Analysis of Vehicles Electromagnetic Emissivity for Vehicles Classification Application

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Abstract. The article deals with analysis of personal vehicles electromagnetic emissivity, which is one of the possible characteristics useful for vehicles classification and recognition. Since the recent vehicles are equipped with a great number of communications – information systems, sensors, actuators and electronic devices with maximally suppressed electromagnetic emissivity, the nature of emitted signals is rather ultra-wide band noise. The signals analysis, based upon emissivity measurement in anechoic chamber, is investigated in the frequency range of 100 kHz to 35 MHz, concluded with some specific classification characteristics.

Keywords: vehicle, electromagnetic emissivity, classification, recognition, vehicle

1 Introduction

Electromagnetic security based on electromagnetic compatibility (interference - emissivity and susceptibility) theoretical basis is recently becoming fundamental task for car producers in conjunction with increasing number of used information technology (IT) and automation. Since IT-based parts of every new innovation have to be implemented on an Electronic Control Unit, there is an increasingly complex basis of ECUs contained in each car meanwhile building a core part of its electronic interior. While simple recent cars are equipped at least with 10 ECUs and several hundreds of m of cables distributed over the whole vehicle, some luxury vehicles currently have up to 80 ECUs.

Primaryaimof the car producers from the EMC point of view is to guarantee the safe functionality of the car in standard environment (electromagnetic emissivity EMI) and not to be electromagnetically harmful to surrounding technology (electromagnetic susceptibility EMS) [1], [2], [3]. Those regulations are expressed in several international and EU regulations (CISPR 12, CISPR 25, EN 301 489-1, EN 50498, ISO 16750-2, …). On the other hand there is some radiofrequency emissivity that can be measured and some external electromagnetic field conditions under which particular car will perform with errors of IT and control systems. This recent research is primarily performed in parallel with so called electromagnetic (or radiofrequency) weapons which are capable of remote electromagnetic disruption of electronic. Both emissions and external electromagnetic field characteristics are car trade mark, car construction, car engine and model dependent. From this point of view the
electromagnetic characteristics of the cars are necessary in order to enable required car classification and further proper and human being safe external electromagnetic interference for potential external car control.

Car electronic systems are operating in frequency range from zero to several GHz with power levels of units of mW to several tens of W.

Fig. 1. Examples for electronic systems in modern car (purple – audio-video system, phone, GPS…; green – ABS, ESP, automatic lights, Airbags, wipers, …; orange – motor part)[4]

Majority of the stationary stochastic signals (communication systems) are very well EMC perfected, however it should be considered, that there are very short non-stationary signal or transient ones.

Electromagnetic emissivity is produced from four main areas of the vehicle:

- The ignition system - it is the largest source of electromagnetic emissivity, voltages up to 30 kV are now common and the peak current for a fraction of a second when the spark plug fires can peak in excess of 100 A, frequency range is above 30 MHz and the energy can peak, for fractions of a second, of the order of 500kW;
- The charging system produces electromagnetic emissivity because of the sparking at the brushes and electronic regulators produce little problems but regulators with vibrating contacts can cause trouble.
- Motors, switches and relays produce some electromagnetic emissivity. A wiper motor and a heater motor are the most popular sources.
- Static discharges are due to friction between the vehicle and the air, and the tyres and the road [6].

Above mentioned precondition and potential scenario, where vehicle is approaching check point with electromagnetic recognition system (some other sensors for data fusion are expected too) and electromagnetic disruptive system give us condition for measurement.

Time for measurement of electromagnetic emissivity is the critical requirement. It is very short up to several tens of milliseconds, due to the speed limit of the vehicle is
established at 50 kph (14 m/s) in build-up areas and vehicle detection distance 10 m. This acquisition time will ensure the preservation of stationary stochastic signals and also several engine revolutions and related non-stationary signals. One part of the sensor system is antenna with bandwidth from 100 kHz to 35 MHz, which is omnidirectional. In real situation it is expected stationary electromagnetic scene except standard communication signals.

2 Signal analysis

It is known a signal is a physical quantity, it brings some report. This report can contain a lot of information, but how much information contains, it depends on the receiver. The signal can be represented by the description of one parameter depending on other parameter or parameters. The analysis of signals is based on this fact. The signals can be processed within the time domain, frequency domain, time-frequency (spectrogram) domain. Each process in one domain has a corollary to the others, however time domain is the best for the transient signals representation, frequency domain with proper selection of correlation interval for the stationary stochastic signals and spectrogram for general overview. In the processing of measured data is necessary reduction of data redundancy and suppress unwanted interference. This process occurs before analysing the data in one of the domain. The most common tool is the filtration and downsampling.

2.1 Time domain

Time domain investigation of signals and systems is one of the most essential tool of electrical engineering. It is useful in short time, transient several times repeated signals. for vehicles EMI analysis we expect those kind of signals emitted from ignition system, especially sparks from petrol engines, fuel injectors from diesel engines eventually petrol engines too. Signal acquisition and triggering synchronisation is with such signals driving process for whole signal acquisition and signal analysis process.

In recognition process cross and autocorrelation is very often used. Correlation is based on similar period of time of investigated processes and in our case it is repetitive ignition between 800 and 2000 rpm (Fig.2). It is known crosscorrelation function (between two signals $f_1(t)$ and $f_2(t)$) and can be written [5]

$$K_{12}(\tau) = \int_{-\infty}^{\infty} f_1(t)f_2(t-\tau)dt$$

and autocorrelation function given by [5]

$$K_{12}(\tau) = \int_{-\infty}^{\infty} f_1(t)f_2(t-\tau)dt,$$  \hspace{1cm} (1)

where $\tau$ is time moving one signal over the other and $T$ repetition period;
\[ K(\tau) = \int_{-\infty}^{\infty} f(t)f(t-\tau)dt \quad K(\tau) = \int_{-\frac{L}{2}}^{\frac{L}{2}} f(t)f(t-\tau)dt. \] (2)

2.2 Frequency domain

Frequency domain refers to analysing a mathematical function or a signal with respect to the frequency. This method is optimal for stationary stochastic signal analysis. The most common transformation is the discrete Fourier transformation commonly used in digital signal processing, software defined radios defined in [5].

\[ X[k] = \sum_{n=0}^{N-1} x[n] e^{-j2\pi nk/N} \] (3)

where \( x[n] \) represents n-th sample in time. Final spectral resolution depends on number of samples, method and windowing, averaging, overlapping and sampling quality (bits number, sampling frequency). Those parameters became very important in situation, where signal to noise ratio (SNR) is very low and wanted signal is unknown. In our situation SNR it is below 15dB, in real situation with background noise below 5dB. Each car situation sampled signal was83886606 points vector, sampling frequency 125 MHz, counting 16 bit resolution, noise threshold -110dB. During the test we examined also some other methods, MUSIC, Covariance, Burgh estimator. Those methods are very effective for narrow band signals compound. The best resolution results we obtained with Welch’s method, which is built on the averaged periodograms of 256 points overlapped, 2048 and 4096 Hamming windowed segments of a time series of signal.

\[ P[k] = 20 \log_{10} \left( \frac{1}{N} \sum_{n=1}^{N} \sum_{l=1}^{L} x[l+n] e^{-j2\pi nk/N} \right) \] (4)

It is good to know one attribute of Fourier transform. If used a long period of signal in time domain, it has an impact on the amplitude of non-stationary frequency components of \( X[k] \) are relative values and are reduced. Thus transient signals are rarely visible in such interpretation.

2.3 Time - Frequency domain

The Fourier transform allows visibility only frequency components in the whole signal and it does not give a view about frequency components occurrence in time. For this view it is suitable to use spectrogram, also called waterfall.
The common tool for spectrogram is modification of the Fourier transform calls Short Time Fourier Transform (STFT) with the window shifted over time gradually. We used it with two different parameters. In general signal characterization with 1024 points overlapped 16384 Hamming windowed segments of a time series of signal. Second option for finding transients (ignition mainly) was 256 points overlapped, 2048 Hamming windowed segments of a time series of signal.

3 The vehicle measurement and analysis of measured data

Configuration of the workplace the measurement of shielding emissivity of personals vehicles was performed according to EMI standard MIL STD-285 and IEEE-299. The whole measurement was done in the Anechoic chamber that was prevented by the influence of other sources of electromagnetic fields. Anechoic chamber was with certified attenuation above 90 dB. The test bed consisted of spectrum analyzer Anritsu MS2667C, signal analyzer Agilent Infinium DSO 80804B and receiving antenna SAS-550-1B with antenna factor 0 in whole spectrum range. There were seven vehicles under the test: Škoda Yeti (diesel engine); Škoda Octavia (diesel engine), Škoda Octavia (petrol engine), Ford Focus (diesel engine), Ford Mondeo (diesel engine), Fiat 500 (petrol engine) and Honda Civic (petrol engine).

3.1 Analysis in the time domain

It is necessary to find signals which are regularly repeated and which are specific for each kind of vehicle in the time domain. Signals, occurred with a certain time period, are a precondition for classification or recognition of the vehicle. Examples can be the communication signals or transients caused by the ignition system, which depends on engine revolutions. It is a spark inside the cylinder for the vehicle with petrol engine and a fuel injection into the cylinders for vehicle with diesel engine [6]. These two facts depend on engine revolutions. It is known if the engine revolutions are 2000 rpm, one of these facts shows every 0.015 seconds in the time domain or every 0.0375 seconds, if the engine revolutions is 800 rpm. There are pulses in Škoda Yeti’s data in time domain (fig. 2), which depend on engine revolutions. The time period is 0.0379 second for 800 rpm and 0.01634 seconds for 2000 rpm (inaccuracy can be caused by fluctuation of engine revolutions or error on the display for engine revolutions in vehicle). However, the pulses are not 100 % identical, which can be caused by reducing transient because of they must show frequently. This fact can cause that the cross correlation it is not 1.
Fig. 2. Škoda Yeti’s data in time domain – up is 800 rpm, down is 2000 rpm

On the other side, there can be also data of vehicle that shows no characteristic pulses or signals without filtering in time domain for example Škoda Octavia’s (with diesel engine) data (fig. 3).

Fig. 3. Škoda Octavia’s (with diesel engine) data in time domain – up is 800 rpm, down is 2000 rpm

The vehicle’s classification in time domain is characteristic for vehicles with petrol engines, there are detectable pulses dependent on engine revolutions after analysis in the frequency domain it is known, they are wideband pulses. It can be appropriate filter out pulses that are compared in the time domain. For example (fig. 4) there are pulses of Škoda Octavia with petrol engine in the time domain before and after filtration in frequency band 3 MHz to 6 MHz.
In the case of Fiat 500’s data (fig. 5) there are pulses that (time period is 0.01 seconds) does not have a connection with engine revolutions, the level of this pulse is low and it might not be possible to ensure a sufficient signal-to-noise ratio for its detection. Pulses, dependent on engine revolutions, are three, one of them changes its time duration with engine revolutions. It is 0.033 seconds time duration at 800 rpm and 0.005s seconds at 2000 rpm.

### 3.2 Analysis in the frequency domain

As it is able to determine some parameters of signals from measured data in the time domain, as well as in the frequency domain, it is possible to identify
specific frequencies for different types of vehicles. The specific for vehicles with petrol engine is broad-spectrum signals with low levels, and the can be problems with a sufficient signal-to-noise ratio for detection. On the other side, vehicles with diesel engine emit signal with a lot of frequency components with sufficient level.

![Image](image1.png)

**Fig. 6.** Fiat 500’s data in frequency domain – up is 800 rpm, down is 2000 rpm

There is amplitude frequency spectrum of Fiat 500’s data on fig. 6. There are some similar frequency spectrums by radio pulse with carrier frequency. Now it is possible to identify frequency range in which can be possible filtering and detect later this vehicle e.g. there are four frequency ranges for Fiat 500:

1. 100 kHz to 600 kHz;
2. 8 MHz to 12 MHz;
3. 15 MHz to 24 MHz;
4. 26 MHz to 30 MHz.

For demonstration there are amplitude frequency spectrums of Honda Civic (fig. 7) with specific frequencies. Fiat 500 and Honda Civic are vehicles with petrol engine, on the fig. 8 there is vehicle with diesel engine.

![Image](image2.png)

**Fig. 7.** Honda Civic’s data in frequency domain – up is 800 rpm, down is 2000 rpm
Fig. 8. Škoda Octavia’s (with diesel engine) data in frequency domain – up is 800 rpm, down is 2000 rpm

Every vehicle emits some signals carried by specific frequencies with any level. We must not forget this is stochastic signals and transients. The table 1 shows the specific frequencies for vehicles with signal levels measured in the anechoic chamber. There are marked frequencies intended for the detection and the recognition of each vehicle, level of signals is higher for vehicles with diesel engine.

Table 1. Characteristic spectral parameters for analyzed car EMI signals

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Frequency Amplitude [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>[kHz] [kHz] [kHz] [kHz]</td>
</tr>
<tr>
<td>Ford Focus</td>
<td>6.75 kHz 24.69 kHz 374.3 kHz 469 kHz</td>
</tr>
<tr>
<td>Ford Mondeo</td>
<td>24.94 kHz 648.2 kHz 1.293 MHz 10.01 MHz 10.31 MHz 21.21 MHz 21.64 MHz 25.36 MHz</td>
</tr>
<tr>
<td>Honda Civic</td>
<td>2.61 MHz 6.41 MHz 7.65 kHz 8.373 kHz 8.61 MHz 8.83 MHz 9.3 MHz 9.589 MHz</td>
</tr>
<tr>
<td>Fiat 500</td>
<td>5.41 MHz 7.67 kHz 13.57 MHz 14.91 MHz 21.42 MHz 21.52 MHz 26.68 MHz 29.94 MHz</td>
</tr>
<tr>
<td>Škoda Octavia diesel</td>
<td>480.1 kHz 660.1 kHz 2.36 kHz 4.2 kHz 4.94 MHz 8.5 MHz 8.824 MHz 19.08 MHz</td>
</tr>
<tr>
<td>Škoda Octavia petrol</td>
<td>4.952 MHz 8.109 MHz 16.1 MHz 17.49 kHz 1 MHz 10.1 MHz 22.17 MHz 24 MHz</td>
</tr>
<tr>
<td>Škoda Yeti</td>
<td>6.56 kHz 2.4 MHz 4.4 Hz 4.94 kHz 8.4 MHz 8.808 MHz 8.4 MHz 8.109 MHz 8.8965 MHz</td>
</tr>
<tr>
<td></td>
<td>7.71 kHz 11.7 kHz 14.21 kHz 13.62 kHz 19.16 kHz 18.32 kHz 9.9994 kHz 11.05 kHz</td>
</tr>
</tbody>
</table>
It can be possible to make classification according to the vehicle manufacturer. For manufacturer Ford there is frequency 3.4 MHz ± 0.2 MHz specific for both type of vehicle. For manufacturer Škoda there is frequency 4.5 MHz ± 0.5 MHz, but the signal level for the vehicle with petrol engine is smaller than for vehicles with diesel engine.

3.3 Analysis in the time frequency domain

The analysis in the frequency domain is suitable for stationary signals or data, in this case it is better to specify the vehicle on frequencies, which are visible in time. It would be determined the frequencies involved on the pulse dependent on the engine revolutions. For this type of analyses it is suitable used spectrogram. There are visible particular features for each vehicle in spectrograms.

As mentioned, vehicles with petrol engine (fig. 9) are formed by wideband pulses and number of pulses changes with engine revolutions and vehicles with diesel engine (fig. 10) are formed with by quantity of frequencies emitted during operation of the vehicle, but there are wideband pulses too, but their frequency bands are narrower than frequency band of pulses of vehicles with petrol engine are.

![Fig.9. Fiat 500’s spectrogram (2000 rpm) - wideband impulse is in the red circle](image)

![Fig.10. FordMondeo’s spectrogram (2000 rpm) - wideband pulse is in the red circle, quantity of frequencies emitted during operation of the vehicle is in the black circle.](image)

Škoda Octavia with petrol engine has wideband pulses dependent on engine revolutions too, but it has a kind of pulses not discovered in the time or frequency domain and independent of engine revolutions. The first kind of pulses (fig. 11) is emitted at 15.95 MHz and 16.1 MHz and the second kind of pulses (fig. 12) is emitted at 20 MHz.
3.4 Conclusion of analysis

As mentioned in previous chapters, the largest source of electromagnetic emissivity is the ignition system. Also should be noted, that there are stationary stochastic signals and very short non-stationary signal. These signals are visible in this analysis (Fig. 2, 3, 4, 5). Petrol ignition signal is ultra-wide band and single, diesel (common rail) injection signal is the group of 2 or 3 similar, with delay characteristic for particular car producer. Frequency filtration of the acquired signals with filters characteristics highlighted in the Table 1 will allow creating matrix and further standard detection processing. It is expected that the recognition of each producer of vehicle and model can be based on a combination of the time and frequency domain characteristics detection or comparison of images formed by spectrograms, which can include peculiar as with Škoda Octavia with petrol engine.

4 Conclusion

Analysis of personal vehicles electromagnetic emissivity is one of the possible characteristics useful for vehicles classification and recognition. There are used typical four vehicles with diesel engine and three vehicles with petrol engine, every with specific electronic systems, for the classification purposes of measurement. The
measurement is investigated in the frequency range of 100 kHz to 35 MHz. Measured data were selectively processed and evaluated in the time, frequency and time-frequency domain with results expressed in Table 1 and analysis conclusion.

For proposed application scenario, with expected recognition time of several tens of milliseconds, selected frequency band allows vehicle classification according to the type of engine diesel - petrol. Classification and engine revolution speed can be detected in selected wide frequency bands, very much the same for all producers of common rail diesel engines and very wide bands for petrol ones. The best fitting bands are around 10MHz and 20MHz. The classification according to a vehicle manufacturer, is possible with use of detailed frequency matrix detection; however the probability of success in real environment might low. The classification of a particular type of vehicle is possible in given scenario only in ideal environment. For slow classification purposes (several seconds) one may use emitted narrow band and low level signals from communication means (like CAN bus) and make interpretation of internal code.

Analytical investigation brought the database, which is primarily expected to be used for following automated car recognition. Algorithms for real time use with software defined radio or more robust recognition tool are the following program. Secondly the database of EMI characteristic have some relation to EMS characteristics of the particular car and knowledge will be used for blocking the particular electronics of the vehicle and further stopping the non-cooperative vehicle by electronic means.

References