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Vehicle Influence on the Earth's Magnetic Field Changes

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***Abstract*—Anisotropic magneto-resistive sensors (hereinafter - AMR) react to the Earth's and vehicles' magnetic field, whereas variation disturbances of magnetic field allow detecting the vehicles in the parking space. Having known exactly how the magnetic field varies in the parking space and having measured it with sensor LSM303DLH AMR, an assumption can be made about the presence or absence of a vehicle in the parking space. The article covers analysis of a vehicle's influence on the Earth's magnetic field and possibilities to detect the vehicle. The car constructional model has been mathematically described. The experiment has been performed and compared with the theoretical considerations. Three static detection criteria of the vehicle have been formulated.**

***Index Terms*—Vehicle detection, Earth's magnetic field, magnetic sensor, detection criteria.**

I. INTRODUCTION

As it is known from the previous studies (1), a vehicle influences the uniformity of the Earth's magnetic field (EMF) configuration. Suppose that the Earth's magnetic field vector has all three non-zero components in an empty parking space at the chosen coordinate system, i.e.

$$\vec{H}_0 = H_{x0} \cdot \vec{i} + H_{y0} \cdot \vec{j} + H_{z0} \cdot \vec{k}, \quad (1)$$

where $\vec{i}, \vec{j}, \vec{k}$ - axes vectors of the coordinate system.

The Y-axis of the coordinate system points to the front of the vehicle, Z-axis – points down perpendicularly to the surface of the Earth and X-axis – corresponding to the requirements of the right coordinate system [1]–[3].

It is assumed the vehicle model is a shaped closed parallelepiped rectangular box with walls made of a magnetically conductive material (ferromagnetic) (Fig. 1). Relative permeability of material is quite high μ ~1000 [4].

The Earth's magnetic field vector's direction is directed from the air into the ground in the Northern hemisphere because the South Magnetic Pole is actually situated at approximately the geographical North Pole. Each Earth's magnetic field component magnetises vehicle's walls in the same direction, i.e. a vehicle's wall generates a magnetic field component in the same direction. The total magnetic field component will be calculated as the algebraic sum of the Earth's magnetic field and the vehicle wall's created field components.

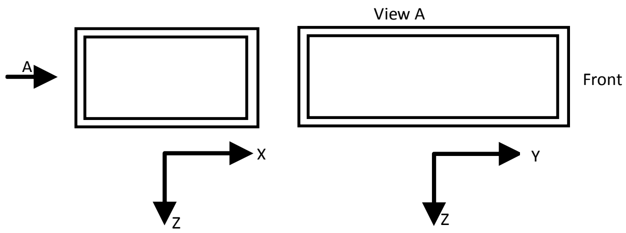

Fig. 1. Simplified physical model of the vehicle and its position.

Further will be used notification k_{ij} meaning impact factor of The Earth's magnetic field *i-th* component for magnetic field generated by the vehicle walls *j-th* component. Assume the sign of these coefficients is positive.

II. STRUCTURAL VEHICLE MODEL

Logical (qualitative) method is used for determination of a vehicle's impact. For example: suppose the vehicle is placed near the magnetic field sensor. Consider the vertical Earth's magnetic field component (Z component) (Fig. 2). Then the vehicle's walls self-magnetize in the same direction and they can be considered as permanent magnets creating an external magnetic field (the wall's magnetic field). Also it is necessary to consider that the external magnetic field created by a permanent magnet is considerably stronger when the magnet poles are located further away from each other (the magnet must be longer) [5].

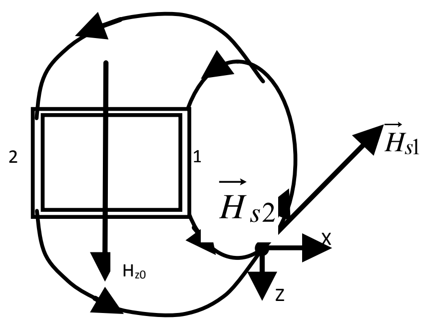

Fig. 2. Magnetic field of vehicle's walls.

Thin vehicle's walls are self-magnetized but they almost do not create external magnetic field. In this case both walls create a magnetic field with similar directions in the magnetic sensors environment ($\vec{H}_{s1}$ and $\vec{H}_{s2}$). In addition the Z component of the total magnetic field shall decrease. X

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component may decrease or increase depending on the direction of the Earth's magnetic field X component. Magnetic field created by walls Z component will be $H_{z0} \cdot (-k_{zz})$ and created by X component will be $H_{z0} \cdot (\pm k_{zz})$.

Using this approach it may be pointed that magnetic fields created by the walls will be as follows:

a) A vehicle is directly over the magnetic sensor; no vehicles in the adjacent parking places:

$$H_{sx} = H_{x0} \times (1 - k_{xx}), \tag{2}$$

$$H_{sy} = H_{y0} \times (1 - k_{yy}), \tag{3}$$

$$H_{sz} = H_{z0} \times (1 + k_{zz}). \tag{4}$$

b) A vehicle is parked in an adjacent parking place (in parallel); no vehicle in the main parking place:

$$H_{sx} = H_{x0} \times (1 + k^{/}_{xx}) \pm H_{z0} \times k^{/}_{zx}, \tag{5}$$

$$H_{sy} = H_{y0} \times (1 - k^{/}_{yy}), \tag{6}$$

$$H_{sz} = \mp H_{x0} \times (k^{/}_{xz}) + H_{z0} \times (1 - k^{/}_{zz}). \tag{7}$$

c) Vehicles are in adjacent parking places; no vehicle in the main parking place:

$$H_{sx} = H_{x0} \times (1 + 2 \times k^{/}_{xx}), \tag{8}$$

$$H_{sy} = H_{y0} \times (1 - 2 \times k^{/}_{yy}), \tag{9}$$

$$H_{sz} = H_{z0} \times (1 - 2 \times k^{/}_{zz}). \tag{10}$$

d) Vehicle is directly over the magnetic sensor; a vehicle is parked in an adjacent parking place (in parallel):

$$H_{sx} = H_{x0} \times (1 - k_{xx} + k^{/}_{xx}) \pm H_{z0} \times k^{/}_{zx}, \tag{11}$$

$$H_{sy} = H_{y0} \times (1 - k_{yy} - k^{/}_{yy}), \tag{12}$$

$$H_{sz} = \mp H_{x0} \times (k^{/}_{xz}) + H_{z0} \times (1 + k_{zz} - k^{/}_{zz}). \tag{13}$$

e) Vehicle is directly over the magnetic sensor; there are vehicles in the adjacent parking places (in parallel):

$$H_{sx} = H_{x0} \times (1 - k_{xx} + 2 \times k^{/}_{xx}), \tag{14}$$

$$H_{sy} = H_{y0} \times (1 - k_{yy} - 2 \times k^{/}_{yy}), \tag{15}$$

$$H_{sz} = H_{z0} \times (1 + k_{zz} - 2 \times k^{/}_{zz}). \tag{16}$$

f) Vehicle can be shifted to the side (Δ) or turned at the angle (α) in the parking space. In case there are no vehicles in the adjacent parking places, then:

$$H_{sx} = H_{x0} \times (1 - k_{xx}) + H_{y0} \times (\pm k_{yx\alpha}) + \\ + H_{z0} \times (\pm k_{zx\Delta}), \tag{17}$$

$$H_{sy} = H_{x0} \times (\pm k_{xy\alpha}) + H_{y0} \times (1 - k_{yy}), \tag{18}$$

$$H_{sz} = H_{x0} \times (\pm k_{xz\Delta}) + H_{z0} \times (1 + k_{zz}). \tag{19}$$

The expressions in general case are following:

$$H_{sx} = H_{x0} \times (1 - k_{xx} + k^{/}_{xx} + k^{//}_{xx}) + \\ + H_{y0} \times (\pm k_{yx\alpha}) + H_{z0} \times (\pm k_{zx\Delta} + k^{//}_{zx} - k^{/}_{zx}), \tag{20}$$

$$H_{sy} = H_{x0} \times (\pm k_{xy\alpha}) + H_{y0} \times (1 - k_{yy} - k^{/}_{yy} - k^{//}_{yy}). \tag{21}$$

$$H_{sz} = H_{x0} \times (\pm k_{xz\Delta} - k^{/}_{xz} + k^{//}_{zx}) + \\ + H_{z0} \times (1 + k_{zz} - k^{/}_{zz} - k^{//}_{zz}), \tag{22}$$

where $k^{/}$ evaluates the influence of the vehicle at the left side parking place and signification $k^{//}$ – evaluates the influence of the vehicle at the right side parking place.

Having analysed these expressions only one unequivocal conclusion emerges: a vehicle located above the magnetic sensor always increases the Z component of the magnetic field and a vehicle situated in an adjacent parking place always decreases the Z component. Furthermore, the Z component of the Earth's magnetic field is 2–3 times greater than the geometric sum of the horizontal components observed in the Lithuanian geographical latitude. Therefore, the Z component of the Earth's magnetic field is the main component for detecting the status of parking space.

III. VEHICLE INFLUENCE ON THE DISTRIBUTION OF THE EARTH'S MAGNETIC FIELD

A real vehicle's constructional-magnetic model is only similar to a closed rectangular parallel piped model discussed above. A vehicle's underside is often magnetically open. A magnetic partition wall is situated between the engine compartment and interior. A similar partition wall is also placed between the cabin and luggage compartment. As it is shown in Fig. 2, depending on the distance between the partition wall and magnetic sensor it can act as a vehicle situated in an adjacent parking place or as a vehicle parked over the sensor, i.e. total magnetic field and its separate components, where the partition wall is near the magnetic sensor, could increase or decrease. Assumption that Earth's magnetic field Z component increases under vehicle is not always correct. This complicates the detection status of parking places.

In order to verify hypotheses described above, the Earth's magnetic field measurements were made employing different vehicles (Renault "Laguna", Toyota "Avensis", Skoda "Fabia") and using four different sensor angles in respect of the Earth's magnetic poles (in respect to the North direction): 0, 45, 90 and 135 degrees, turning from the North to the East (Fig. 3). Vehicles are moved towards the magnetic sensor with engines off – forward and backward until the distance between the magnetic sensor and the vehicle front or rear will be about 1 meter. The horizontal axis marks relative time, designation $|B|$ means magnetic field induction change (when vehicle moves forward) module, B_x, B_y, B_z – induction alternation components, as illustrated on charts in Fig. 3–Fig. 5.

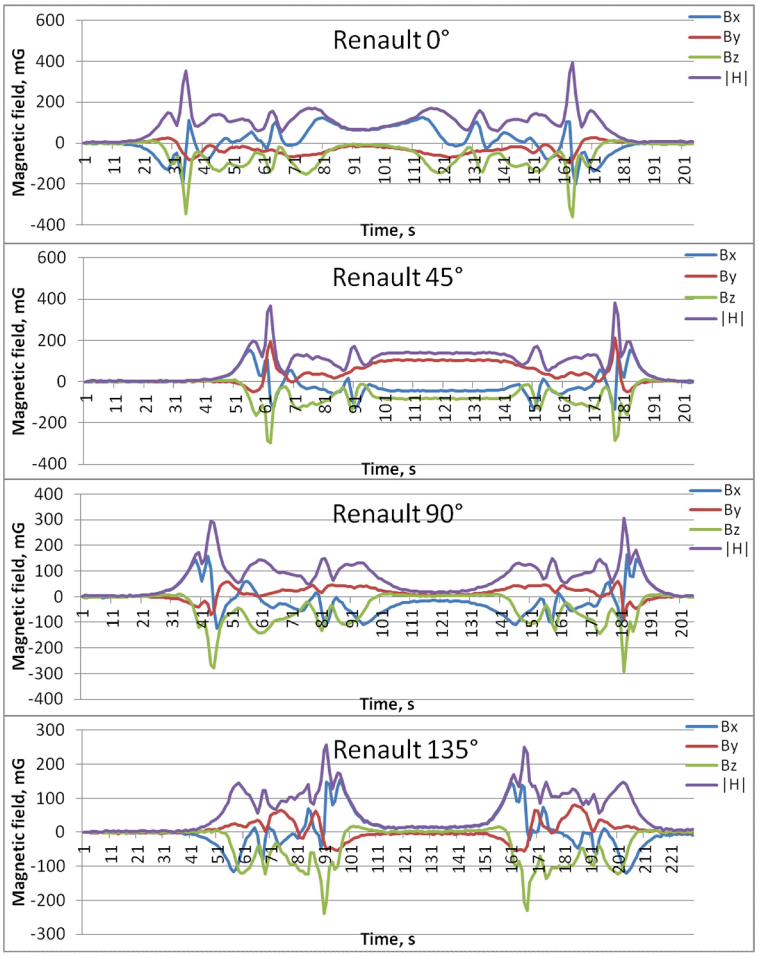

Fig. 3. Magnetic field module |B| and components B_x, B_y, B_z variations in case of Renault.

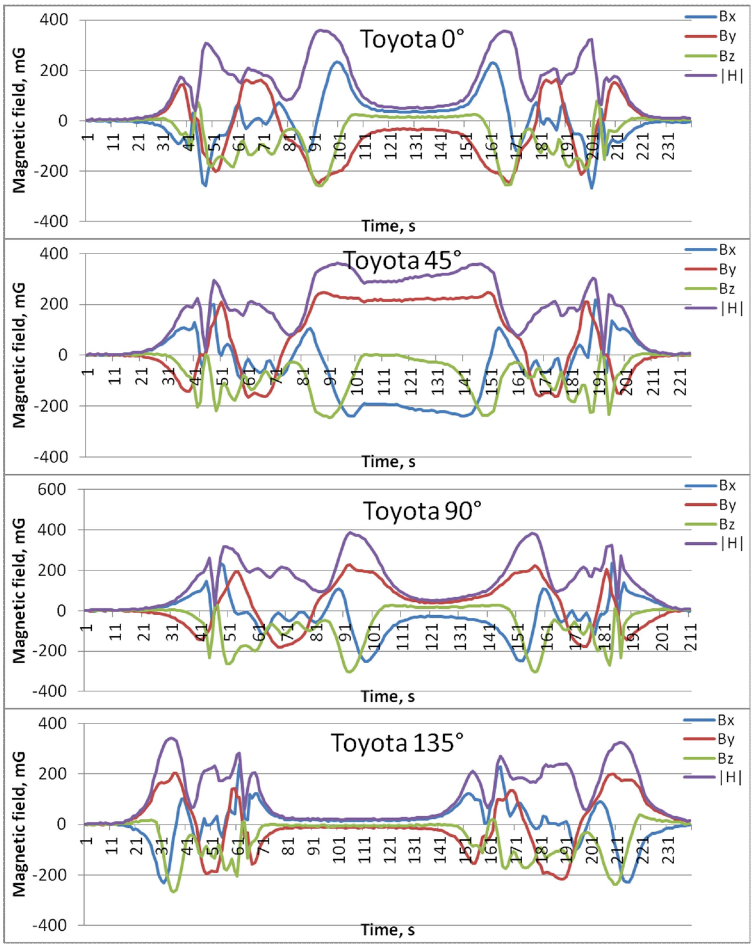

Fig. 4. Magnetic field module $|B|$ and components B_x, B_y, B_z variations in case of Toyota.

As it could be expected, there are variations in the magnetic field module and each single component varies during the vehicle's movement over the sensor depending on the vehicle's model. Particularly strong influence of the wall partitions was observed specifically in case of Toyota. Influence from wall partitions also can be seen in other vehicle models – only in in the case of the Skoda, this influence is not so noticeable. In Toyota's case – in 45 point of the relative time scale B_Z component changes sign when induction module's variation is close to zero. Other induction components (B_x, B_y) have minor changes.

Thus, in case the Toyota stops at this point, it will become problematic to detect the vehicle. This interval where components and module have constant values is named 'hole'; in case of Toyota it is not big (distance between two adjacent positions – about 20 cm). It's quite optimistic since the probability of getting into such a "hole" isn't very high.

Next tests have been done in cases where the vehicle enters a parking space at centre and shifts to the edge of the parking space, also when vehicle enters an adjacent parking space shifted from sensor with distance of 1 meter and 1.7 meters. The measurements' results of three cars – Peugeot, Skoda and Toyota are presented in Fig. 5 and Fig. 6. The results confirm the theoretical considerations about the magnetic field Z component alternation dependencies from various magnetic field X and Y components variation patterns and also possibilities of "hole" occurrence. In addition, these results provide information about magnetic field module and components alternations values and signs.

When a vehicle enters a parking space and shifts closer to the edge, most changes occur in the magnetic field induction X and Y components – they even change sign, while z component and module has no changes.

Magnetic induction module will decrease, while z component has no changes when the distance shifts from 1 m to 1.7 m between the magnetic sensor and the vehicle in adjacent parking spaces. This shows a decreasing influence of the adjacent vehicles by increasing the distance.

IV. Complex Vehicle Detection Criteria

It is necessary to formulate the state criteria to determine whether the parking space is free or occupied. The following assumptions and limitations will be used for criteria:

1. Sensors can be oriented according to the compass;
2. In a parking lot vehicle can be parked in any direction;
3. Time for vehicles entrance to (and departure from) the parking space is very different (in the range of 2 to 100 and more seconds);
4. Magnetic field variation when a vehicle is moving over magnetic sensor is almost unpredictable;
5. Vehicles in the adjacent parking spaces influence magnetic field of particular parking spaces;
6. Variation of magnetic field when vehicle is parked can be very small and have unpredictable sign;
7. Magnetic field sensors LSM303DLH have a large scale of scattered parameters – sensitivity about 50 %, the initial displacement (offset) up to 20 %, temperature coefficient of sensitivity ranges from -5 % °C to +2 %/ °C [6], [7];
8. Vehicle may be parked at any parking space in a parking lot;
9. Magnetic field variation does not affect values of the field components when vehicle stops before its parking.

When a vehicle is parked over a sensor, all three magnetic field components can be measured and only the latter information can be used for statistic criteria formation.

Square deviation is very simple criterion calculation of which requires computing capacities of a very small microcontroller. Square deviation is defined as follows

$$K = \sqrt{(B_x - B_{x0})^2 + (B_y - B_{y0})^2 + (B_z - B_{z0})^2}, \quad (23)$$

where B_x, B_y, B_z – measured values of the magnetic induction at a given moment, B_{x0}, B_{y0}, B_{z0} – magnetic induction values of a free parking space at a given time temperature. This criterion is easily implemented in a microcontroller but there are some disadvantages:

– Big criterion dispersion due to high offset and sensitivity scattering;

– Very high sensitivity to temperature's influence (it is needed to measure temperature coefficients of all three axes and calculate B_{x0}, B_{y0}, B_{z0} values);

– Low resistance to the vehicles located in the adjacent parking spaces .

Vectorial deviation is a simple criterion defined as:

$$K = |\cos\alpha - \cos\alpha_0| + |\cos\beta - \cos\beta_0| + |\cos\gamma - \cos\gamma_0|, \quad (24)$$

where $\cos\alpha$, $\cos\beta$, $\cos\gamma$ – cosines of magnetic field vector's angles in parking space with vehicle, $\cos\alpha_0$, $\cos\beta_0$, $\cos\gamma_0$ – cosines of magnetic field vector angles in free parking space at a given time temperature. $\cos\alpha = B_x / M$, $\cos\beta = B_y / M$, $\cos\gamma = B_z / M$, $M = \sqrt{B_x^2 + B_y^2 + B_z^2}$ – magnetic field module at any vehicle position in the parking space. The advantages of this criterion are: very high sensitivity and significantly better resistance to temperature effects, compared to the "square" deviation. The magnetic field induction component ratios were used for creation of this criterion. In order to make temperature compensation, it is enough to compensate only one variable-criterion (instead of 3 criteria in case of "square" deviation). Although using this criterion, the vehicles can be detected at a 2 m distance, however a vehicle which is located in adjacent parking space (especially – vehicle of higher dimensions), can cause wrong decision.

Combined vectorial deviation – is a criterion compiled from the "square" and vectorial deviations. According to the fact that Z component increases when a vehicle is moving over and decreases nearby the vehicle, it can be used to increase the sensor's sensitivity when a vehicle is moving over and, at the same time, suppress the influence of the adjacent vehicles.

$$K = |\cos\alpha - \cos\alpha_0| + |\cos\beta - \cos\beta_0| + (B_z / B_{z0} - 1). \quad (25)$$

At first sight this criterion seems inconsequential because, it adds different dimensions – cosines and ratio.

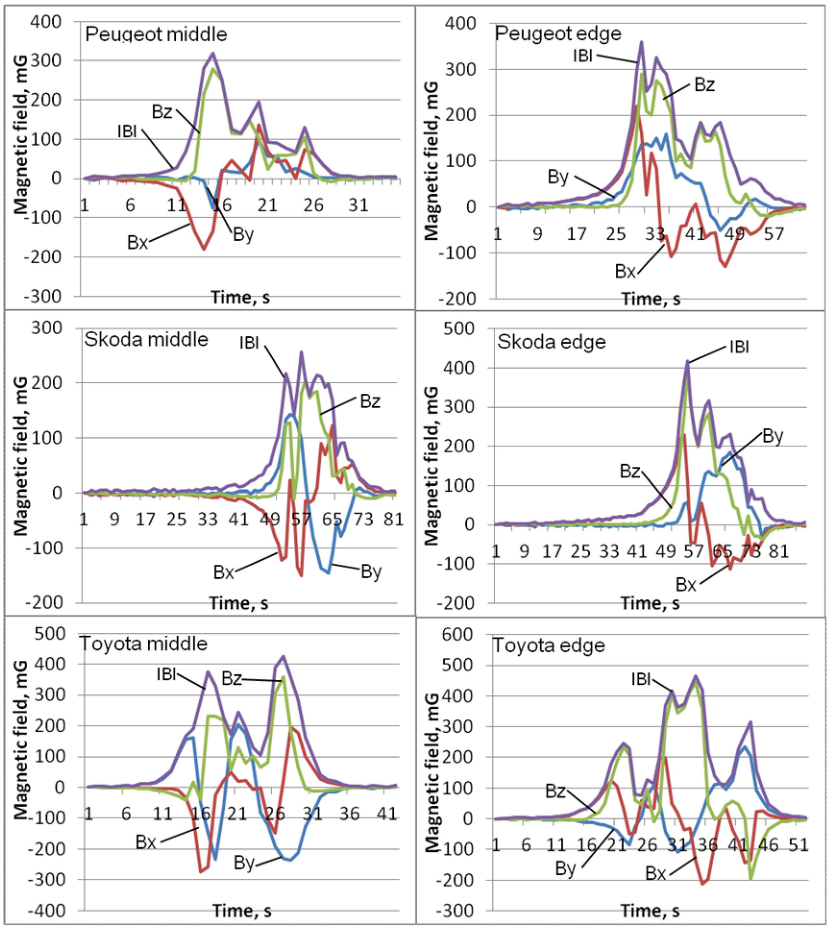

Fig. 5. Magnetic field module $|B|$ and components B_x, B_y, B_z variations vehicles moving the parking space close to the middle and closer to one edge of parking space.

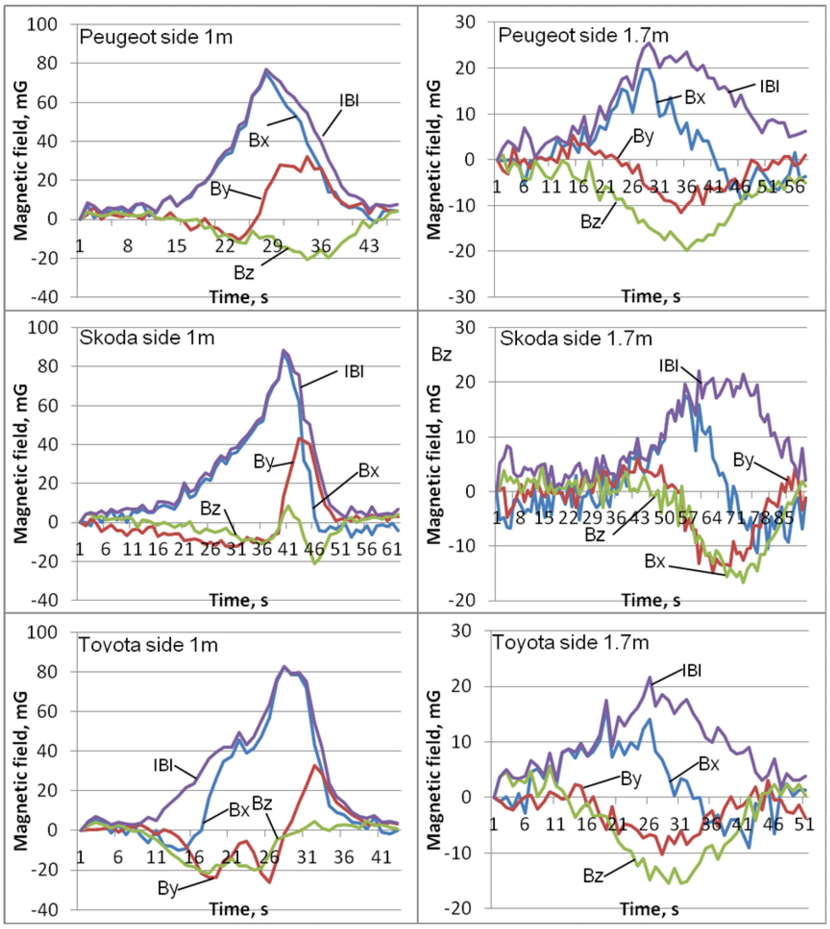

Fig. 6. Magnetic field module $|B|$ and components B_x, B_y, B_z variations by moving vehicles in adjacent parking space when distance from magnetic sensor is 1 meter and 1.7 meter.

However, cosine and ratio are dimensionless. The advantage of this criterion – sensitivity and temperature stability compared with the parameters of vectorial criteria and resistance to vehicles located in adjacent parking spaces.

In some cases when a vehicle moves over we can see that the magnetic field Z component decreases from 20 % to 50 % and even more – falling into a very deep “hole”. In these situations the “square” and vectorial criteria would detect the vehicle correctly, while combined criterion would not detect the presence of the vehicle. This can be resolved quite simply by adding additional logical condition L

$$K = \left|\cos\alpha - \cos\alpha_0\right| + \left|\cos\beta - \cos\beta_0\right| + L(B_z / B_{z0} - 1), \tag{26}$$

where $L = 1$, when $(B_z / B_{z0} - 1) > -Kd$ and $L = -1$, when $(B_z / B_{z0} - 1) < -Kd$, here Kd – “hole” condition (threshold).

One disadvantage of this criterion – necessity to thermo-compensate the sum of cosines and Z component or thermo-compensate criteria to the “left” and to the “right” from the calibration point temperature.

V. CONCLUSIONS

Vehicle constructional model is more complex than the simple geometric shapes given. Experimental measurements have shown that different brands of vehicles have different influence on the Earth’s magnetic field (Fig. 3–Fig. 5).

Magnetic field analysis with mathematical expressions along with experimental study showed that a vehicle, which is standing over the sensor does not always increase the magnetic field Z component and the vehicle standing in an adjacent parking place does not always decrease the Z component.

Variation of the magnetic field when a vehicle is moving above a sensor is almost unpredictable. When a vehicle gets into the “hole” it can be detected only by using the complex detection criteria. Application of all three detection criteria requires the temperature compensation. Currently, there is no one straight answer which of those three detection criteria should be used.

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