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# VEHICLE DETECTION SYSTEM USING MAGNETIC SENSORS

**Summary.** The paper describes an attempt of using magnetic detectors as an effective alternative to existing vehicle detection systems, which are a key factor in intelligent transportation systems (ITS).

The detectors created within the project use the phenomenon of anisotropic magnetoresistance to report about the appearance of vehicles on the basis of Earth's local magnetic field distortion caused by them passing. This paper presents utilized and developed technologies, advantages and disadvantages of magnetic detection in comparison to other detection systems and problems that arose during the project implementation.

# SYSTEM DETEKCJI POJAZDÓW Z WYKORZYSTANIEM CZUJNIKÓW MAGNETYCZNYCH

**Streszczenie.** Artykuł opisuje próbę zastosowania czujników magnetycznych jako skutecznej alternatywy dla istniejących systemów detekcji pojazdów w ruchu ulicznym, będących kluczowym czynnikiem inteligentnych systemów transportowych (ITS – Intelligent Transportation Systems).

Czujniki stworzone w ramach projektu wykorzystują zjawisko magnetooporu anizotropowego do raportowania o pojawieniu się pojazdu na podstawie zakłóceń, jakie wywołuje on w lokalnym polu magnetycznym Ziemi. Praca prezentuje wykorzystane i stworzone technologie, wady i zalety detekcji magnetycznej na tle innych systemów detekcyjnych oraz problemy, które wyniknęły przy implementacji projektu.

## 1. INTRODUCTION

A significant increase in the number of cars and intensification of traffic proved to be the reason why functioning in large urban areas is becoming more and more difficult. Deepening communication problems associated with widespread traffic jams have effectively reduced the quality of life in city centers [15]. Therefore, advanced control systems developing becomes a crucial task in the process of improving the flow of vehicles through the city. The main and quite natural concept is carrying out continuous analysis of traffic intensity in different directions and customizing the operation of traffic lights to the observed needs. Subsequently, there is an idea of immediate reaction to the data being collected, which enables more efficient and more flexible traffic management [9].

Accordingly, for the last few decades many researchers' attention were focused on developing systems dedicated to detecting vehicles on the road. However, among many well-known methods, it is impossible to find a flawless one, which motivates engineers to look for new solutions.

### 1.1. Solutions in Use

Currently used methods are based mostly on the detection of different phenomena associated with vehicles passing by. The most commonly used are induction loops, videodetection, acoustic detection and radiodetection [11, 15].

Probably the most popular method is an induction loop [11], introduced in the 1960s. Passing car changes inductance of a loop thus rise and fall constantly are different from the steady-state condition [15]. Fluctuations in energy levels make it possible to determine the number of emerging vehicles and their speed. The main problem associated with induction loops is the complexity of their installation. Loops are mounted relatively shallow under the road surface. On one hand this requires an appropriate foundation of the road, on the other – loops often get damaged due to stresses occurring in asphalt when heavy vehicles decelerate. As this system is usually located under the whole intersection, its repairs are associated with the necessity of whole junction temporary shutdown and additionally hinder traffic.

Videodetection systems consist of one or more cameras collecting images of the junction area and a processing module, which analyses the provided data [1]. Videodetection capabilities are quite large. Suitable software allows it to effectively determine size and speed of emerging vehicles. Additionally, images from cameras may be used to get a real-time preview of the intersection [3, 7].

The main drawback of videodetection is its fallibility in the face of changing weather conditions. Fogs or heavy precipitation sometimes block this way of gathering information about the situation on the road. Another vital problem is underexposure [2]. According to a research conducted in 2005 by the TTI (Texas Transportation Institute), night tests of videodetection indicated the presence of up to 40% more vehicles than the control system showed [10]. This may have resulted from counting cars together with shadows coming from low-angled incident light (e.g. street lanterns light).

In the acoustic detection systems, a network of microphones provides traffic information based on the noise generated by passing vehicles. The main problem of this method is making a distinction between vehicles on the adjacent lanes when they generate noise at various levels of intensity. Interferences caused by rain cause trouble as well.

Radiodetection is based on the analysis of data provided by radars placed on poles along the road [5]. Radiowaves are reflected from a moving object and then used to determine the direction and speed of it. However, radiodetection is unsuitable for determining the length of specific vehicle and detecting stationary vehicles. For larger intersections it is also impossible to clearly distinguish which lane the detected vehicle is moving on. In addition, this method is sensitive to the wind, which may falsify the results by moving the poles on which the radars are mounted.

### 1.2. Magnetic Detection

In the face of all of the disadvantages of technologies described beforehand, an idea based on Earth's magnetic field observation has emerged.

The system is based on detectors that measure parameters of the magnetic field in their vicinity. They are mounted in the roadway at intersections equipped with traffic lights. As a vehicle approaches, the magnetic field around the detector is disrupted, which is detected by an electronic sensor. An exemplary Earth's magnetic field distortion is shown in fig. 1.

Based on the noise level, it is possible to define size of an object and conclude how fast it is moving. This allows the system to distinguish the type of vehicle and the optimize decisions about how to control the traffic lights. For example, a heavy vehicle - a truck or a bus – which is moving quickly will have a higher priority than a small car, which can be stopped and re-accelerated with lower costs causing less severe damage to the road surface.

The system proper operation requires installing at least several detectors, depending on the size of the intersection. The data collected from the detectors should be transmitted to the controller, which analyses the traffic in each direction and acyclically controls the streetlights on many intersections.

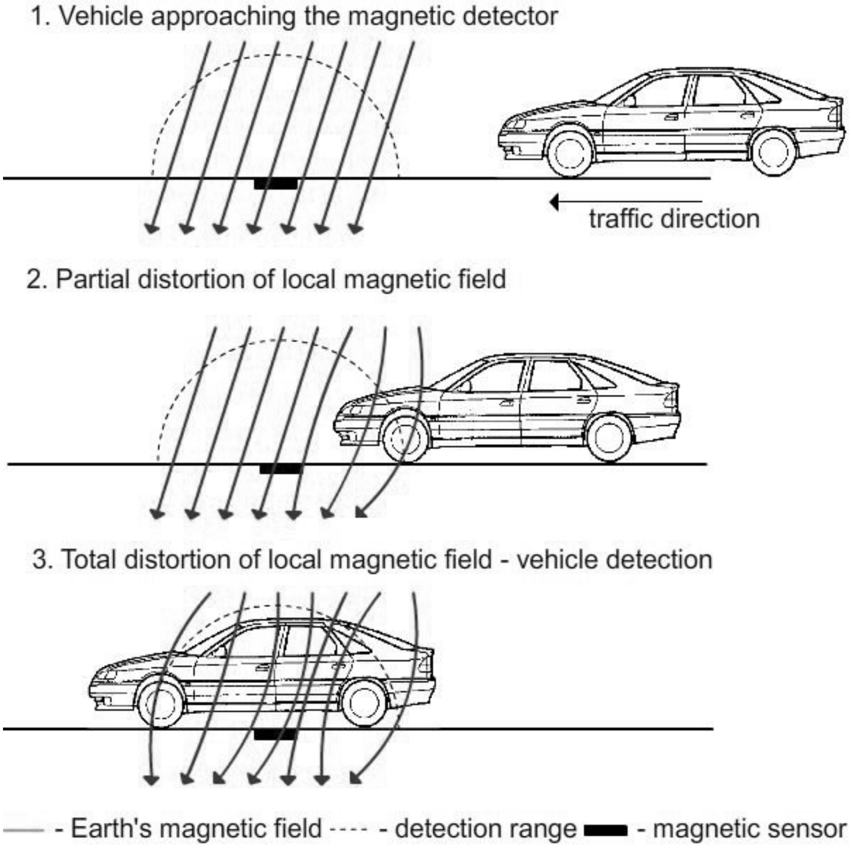

Fig. 1. Earth's magnetic field distortion caused by a moving vehicle
Rys. 1. Zaburzenie pola magnetycznego Ziemi przez poruszający się pojazd

Devices embedded in asphalt often get damaged as a result of pressure exerted on the ground by heavy vehicles passing. Small sensors have therefore an advantage over those like large inductive loops, as their re-installation is associated with lower costs. What is more, the independence of each individual sensor does not require closing the whole crossing to carry out repairs. Compactness of the devices also eliminates the problem of transmission lines being interrupted or destroyed as a result of asphalt deforming. In addition, weather conditions are irrelevant here, as they do not alter the Earth's magnetism deformation [15].

The idea of using the geomagnetism phenomenon in the detection of vehicles is not a new concept on a world-scale. Devices operating on the same principle have been the subjects of research conducted in the United States in particular [10]. Anyway, it should be noted that it is still a novel idea and the implemented systems are not flawless, problems being connected mostly with complicated setup procedures and “hanging” of the detectors.

## 2. CREATED SENSOR CHARACTERISTICS

The place of magnetic detector in the vehicle detection system is shown in fig. 2.

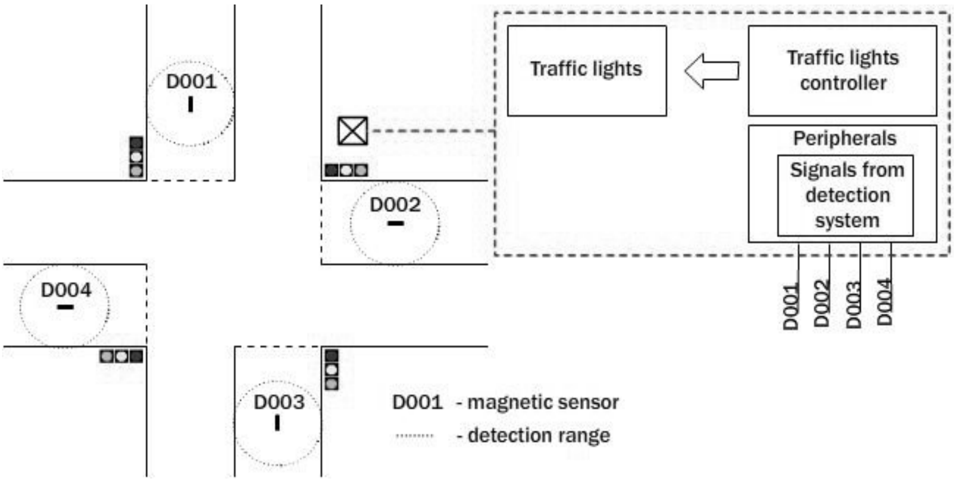

Fig. 2. Block diagram of magnetic detection system
Rys. 2. Schemat blokowy układu detekcji magnetycznej

### 2.1. Magnetic Detector Construction

The detector consists of the following functional blocks:

- one- and two-axis magnetic sensors detecting changes in the magnetic field,
- accelerometer determining the detector's position,
- filtering and amplifying module,
- microcontroller.

These blocks are shown in fig. 3.

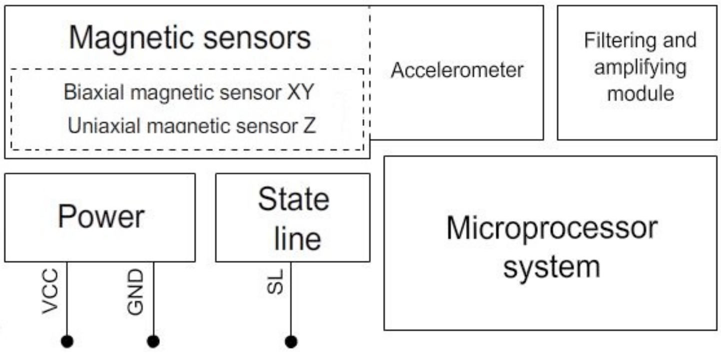

Fig. 3. Functional blocks of the detector
Rys. 3. Bloki funkcjonalne detektora

### 2.2. AMR Sensors Characteristics

Magnetoresistance is a material feature consisting in its resistivity changes resistance upon placing in a magnetic field [4, 6, 14]. To observe this phenomenon in non-magnetic metals, it is necessary to apply a fairly large external magnetic field. The change of material resistivity in a magnetic field of intensity *H*, given $\rho_0$ - the resistivity in zero magnetic field, is depicted in the Kohler's rule [4]:

$$\frac{\Delta\rho}{\rho_0} = F\left(\frac{H}{\rho_0}\right) \tag{1}$$

where *F* represents a function associated with the properties of specific metal.

As has been proven, ferromagnetics are characterised by a particular type of magnetoresistance - anisotropic magnetoresistance (AMR). They change their resistivity depending on the direction of current in relation to the orientation of magnetic field lines, where the metal is located in [8, 12]. As a result, these elements resistivity changes occur even at low magnetic field strengths. This feature improves the sensitivity of sensors.

The change in resistivity $\Delta R/R$ of AMR sensor is expressed as:

$$\frac{\Delta R}{R} = -\frac{\Delta \rho}{\rho_0} \sin^2 \varphi \tag{2}$$

where $\phi$ is the angle between current and magnetisation vector directions, and $\Delta\rho/\rho_0$ is called the magnetoresistivity factor [12].

Recently, the magnetoresistors presenting the GMR (Giant Magnetoresistance) phenomenon has greatly gained in popularity [13,16]. Due to their specific properties, such sensors open up some new measurements possibilities. However, the AMR sensors still have an advantage over them in respect of simplicity and sensitivity [13].

### 2.3. Sensor Configuration

In order to ensure proper work of a detector, it is crucial to configure it appropriately to the environment in which it is installed. Therefore, it was necessary to create software for customising the detectors parameters.

First, it is necessary to collect data from sensors when there are no instantaneous distortions of the magnetic field nearby. These values, called the background level, are obtained by averaging the results of measurements over the specified period. Later on, they become the reference point for subsequent measurements. The time period during which background level data is collected is called the initial averaging time.

The current value of stimulation level is determined as a sum of values read for each axis (X, Y, Z, see fig. 3) and multiplied by the appropriate multiplier for this axis. Such a system allows determining the importance of each axis or even disabling one or two of them. This option may be used for example to protect against detecting vehicles moving in disaccordance with the direction of traffic on the specific lane.

Vehicle detection occurs when the difference between background level and currently read value exceeds the stimulation upper threshold. Hysteresis is used in order to avoid the double counting of long (multi-axle) vehicles.

A summary of configurable sensor parameters is contained in the table hereunder.

Table 1

Detector's configurable parameters

| Parameter name | Description |
|---|---|
| Axis multipliers | determine the sensor axis importance |
| Averaging time | determines the period of data collection for background level calculation |
| Hysteresis thresholds (lower and upper) | determine the parameters of hysteresis loop |

## 3. RESULTS

The aim of the first testing phase has been to investigate the magnetic detector possibilities. It has been necessary to determine parameters such as sensitivity to the passage of vehicles, robustness to noise, ability to classify vehicles and determine speed, minimum excitation times etc. The laboratory tests have shown the designed device main characteristics. Further testing procedures have required permanent installation on the city intersections.

### 3.1. Laboratory Tests

Laboratory tests have consisted in assessing the influence of a series of various magnetic field interferences around the detectors on their operation. Subsequently, the received data has been visualized by computer application. The field distortions have been produced by metal objects of different sizes and ferromagnetic properties. Each test started with background level measurement for the specific detector. As a result, the differential characteristics of the field strength for three different directions (X, Y and Z) have been brought to the same level (as shown in fig. 4). The Z-axis has been disabled and is invisible on the graph.

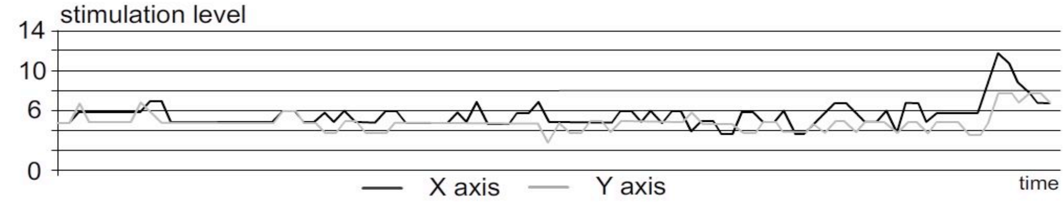

Fig. 4. Background learning: visualisation for two axes separately
Rys. 4. Nauka tła: wizualizacja wartości dla dwóch badanych osi

The actual test has been designed as cyclic sensor stimulation and registration of the results. Each excitation pulse is visible on the real-time graph shown in fig. 5.

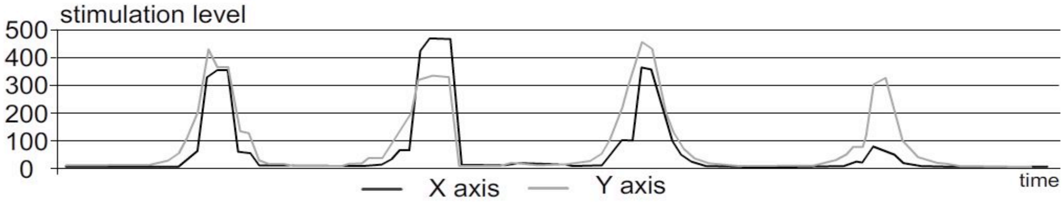

Fig. 5. Registration of detector's stimulation level: visualisation for two axes separately
Rys. 5. Rejestracja poziomu wzbudzenia czujnika: wizualizacja wartości dla dwóch badanych osi

Fig. 6 illustrates the summary level of sensor stimulation for situations described beforehand in relation to the selected thresholds of hysteresis loop.

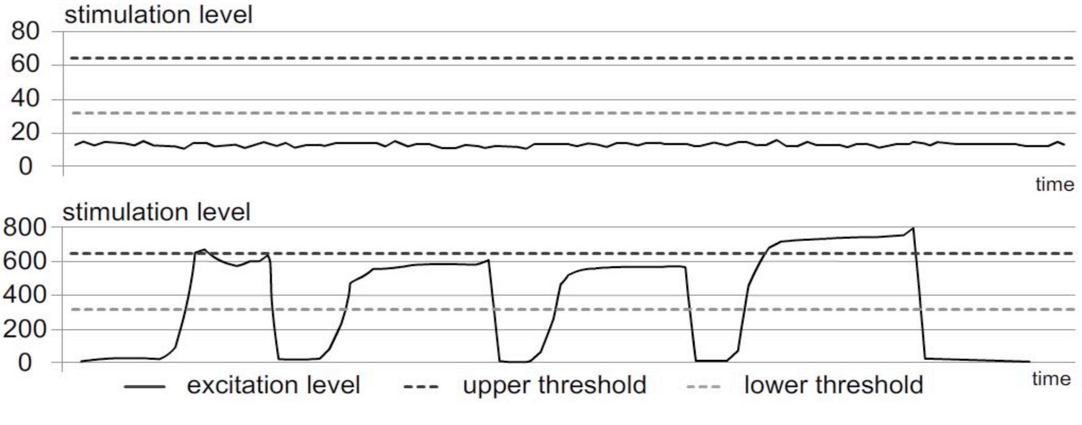

Fig. 6. Registration of detector's stimulation level: visualisation of the sum of axes values
Rys. 6. Rejestracja poziomu wzbudzenia czujnika: wizualizacja wartości sumy wzbudzeń

### 3.2. Outdoor Tests

After a series of successful laboratory tests, the prototype system has been introduced to several intersections for outdoor tests. These tests have allowed for a broader assessment of the devices in terms of ease of use (device configuration) and the quality of information provided. Sometimes, detection systems are installed redundantly for increased reliability. Then it is possible to compare the results obtained from one system with another. However, some of the solutions are designed to provide information more generally than specifically for a certain part of the lane, which makes the comparison with magnetic detectors unreasonable; other ones are known to be vulnerable to weather conditions – those in turn are not a proper reference point as the results will vary inherently. Only one of test intersections is equipped with inductions loops, which are now considered to be one of the most accurate vehicle detection systems. Due to this fact this intersection has been chosen as a numeric data source; the collected information has been subsequently used to carry out a statistical analysis of system efficiency.

The study has been conducted for four sensors based on the data acquired during the first three months after installation. During this time the detectors settings have not been modified. Fig. 7 shows the location of detectors and corresponding induction loops. Approximate numbers of vehicles crossing the junction using each lane during the week are tagged as well. The system effectiveness has been calculated according to variations in the detection numbers with the induction loops as reference.

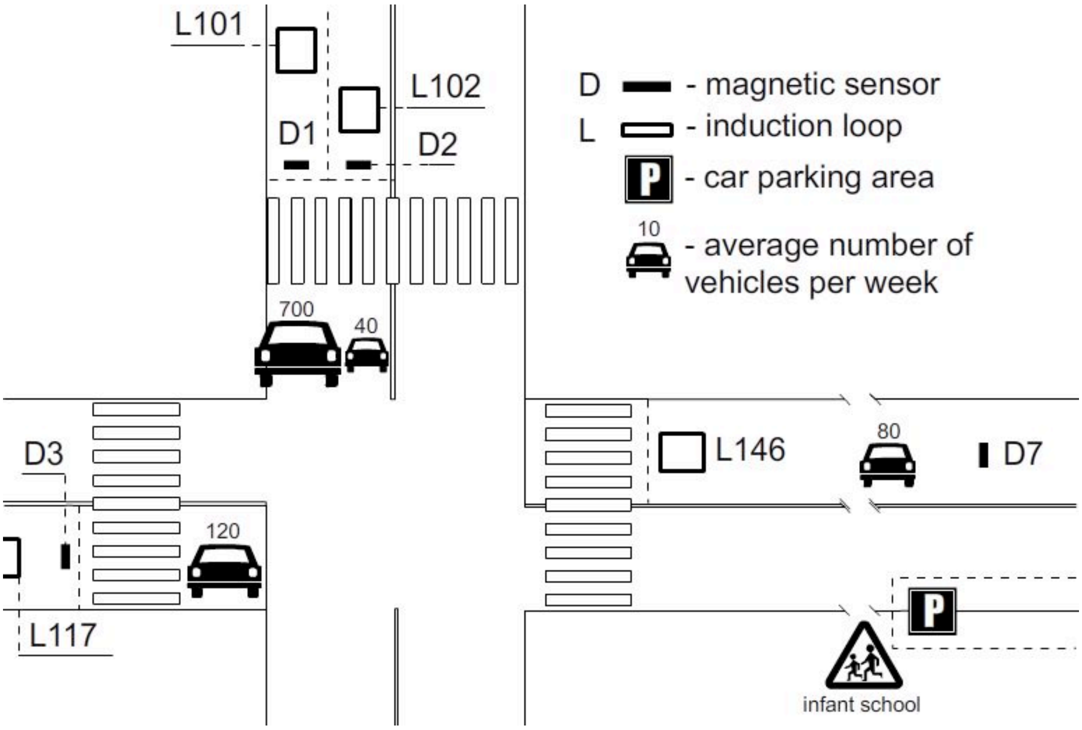

Fig. 7. Location of detectors (D) and corresponding induction loops (L)
Rys. 7. Umiejscowienie detektorów magnetycznych i odpowiadających im pętli indukcyjnych

The collected data has shown that statistically the magnetic sensors and inductive loops are not equally accurate. The effectiveness of the system at the test intersection is 84.81% in general case. Detection relative error in this case is 15.19%. For a bigger number of cars per hour (over 100 for 3 hours), the average relative error is 9.15%, and the efficiency is up to 90.85%. Detection effectiveness is highly dependent on traffic and sensors location.

Table 2 summarises the average relative errors for each sensor per month.

Table 2

The summary of average relative errors for each sensor grouped by month

| **Average relative error [%]** | | | | |
|---|---|---|---|---|
| **Detector number** | **D1** | **D2** | **D3** | **D7** |
| **May** | 4.76 | 18.69 | 5.86 | 23.42 |
| **June** | 13.48 | 28.06 | 4.58 | 22.97 |
| **July** | 7.88 | 25.85 | 4.04 | 22.20 |
| **Average relative error [%] for number of vehicles >100 per 3h** | | | | |
| **Detector number** | **D1** | **D2** | **D3** | **D7** |
| **May** | 5.67 | - | 3.49 | 23.55 |
| **June** | 11.87 | - | 2.74 | 30.91 |
| **July** | 7.47 | - | 4.60 | 28.24 |

The charts below shows a comparison of the average number of vehicles detected by sensors and corresponding induction loops during the test. The data has been grouped and averaged for each day of the week. Individual bars on each day correspond to consecutive three-hour intervals (00:00 – 3:00 a.m., 3:00 – 6:00 a.m. etc.).

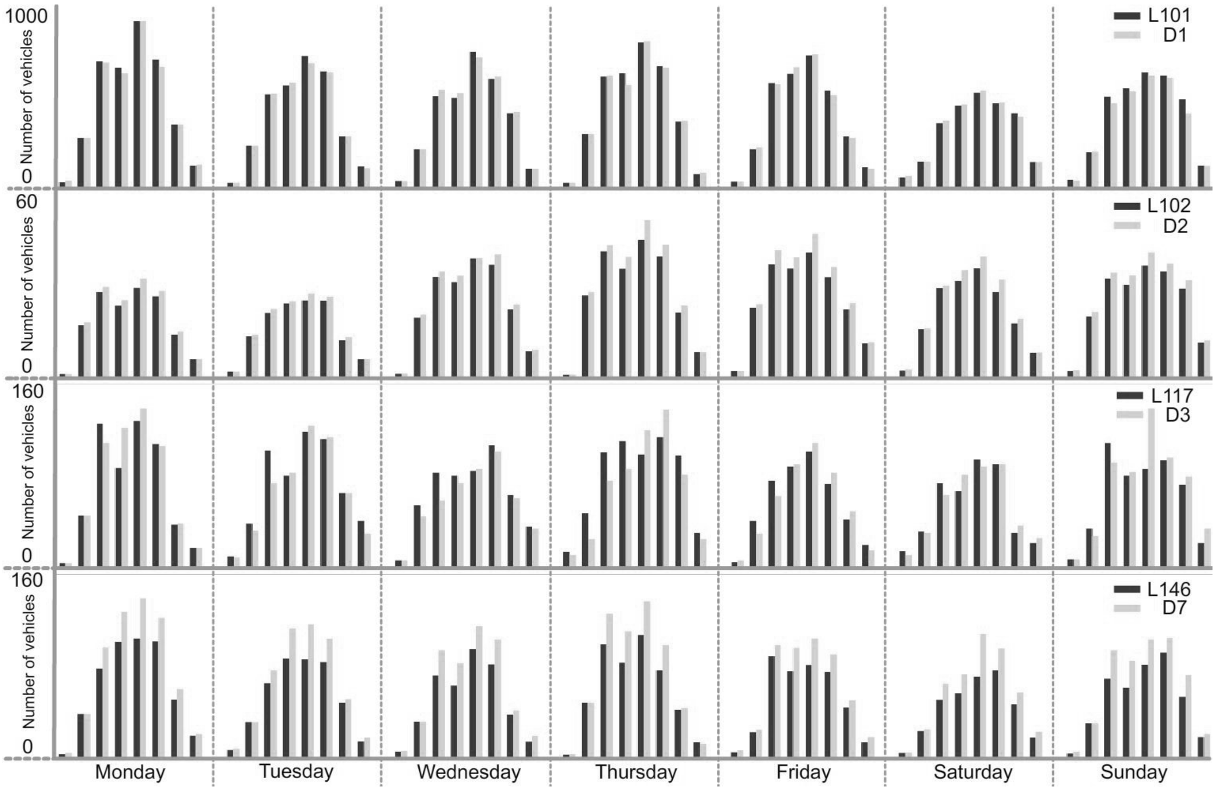

Fig. 8. Average number of vehicles detected by sensors and corresponding induction loops
Rys. 8. Średnia liczba pojazdów wykrytych przez detektory i pętle indukcyjne

The case of detector D2 shows a significantly higher number of reports with respect to the data collected by the loop. The reason of the problem is the detector's location on the left-turn lane. This issue has been more broadly described in section 3.3.1.

Detector D3 demonstrates very high detection efficiency. It is worth noting that this lane was hardly used by multi-axle vehicles (like heavy trucks), which reduces the likelihood of double detection errors. False sensor excitation errors still occur but they affect the overall effectiveness to a lesser extent.

Detector D7 shows the lowest efficiency rate. The errors related to this device significantly affect the overall system effectiveness. The reason is the detector's location. The induction loop and the sensor are not in the same place. Furthermore, there is an infant school alongside the neighbouring lane; vehicles crossing the junction are forced to keep clear of cars parked on the road. Therefore, these vehicles cross the D7 lane and provoke false detection reports. Due to this fact the detection number differences are so conspicuous.

When evaluating the collected results, it is crucial to pay attention to a few things. First, the detectors parameters turned out not to be optimal in some cases. This is one of the reasons why the system efficiency is worse than expected. However, this issue may be justified as this system installation was a pioneering one.

Another problem, which occurred, was connected with the detectors installation technique. The detectors are placed in pipes running under the road surface. They may rotate around its own axis while being inserted, which results in mounting the sensors in unknown orientation with respect to the Earth's magnetic field lines. This fact is not relevant in the context of detecting changes in the magnetic field distortion level (which is the basic functionality of detectors) but makes it impossible to e.g. compare analogue data collected by various detectors placed on the same lane.

In future, it may be necessary to improve the processing of signals received from the magnetic detectors in order to make the system equivalent to the inductive loops. There is also a need to implement detection of direction in which the vehicle travels. This may help evaluate which cases of sensor excitation are not the relevant ones.

The tests have highlighted a number of serious technical problems. These issues are described in more detail in the next section.

## 3.3. System Malfunction Cases

All types of vehicle detection systems face specific technical problems. Magnetic detection system also has a number of issues that require special considerations and refinement.

### *3.3.1. Detection of Vehicles from Neighbouring Lanes*

The vehicles that cause greater disruption of the magnetic field, such as heavy trucks, are sometimes detected by the magnetic sensors located on the adjacent lanes, as shown in fig. 9A (on the left). To some extent, this problem may be eliminated by reducing the sensors sensitivity.

This kind of problem is particularly common in the case of sensors on lanes surrounded by other ones. Fig. 9B (on the right) shows situation on the left-turn lane. Vehicles passing nearby on their own would not be able to put the stimulation level high enough to report detection on a properly set detector, but if several vehicles come at the same time, the sum of small magnetic field distortions can cause the excitation of the detector.

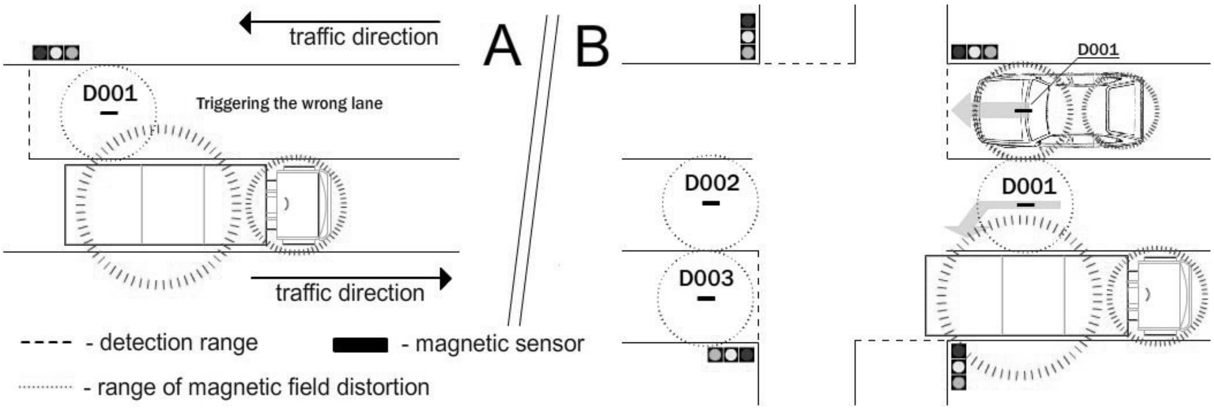

Fig. 9. Two situations of triggering the wrong lane detector
Rys. 9. Dwie sytuacje wzbudzenia detektora na niewłaściwym pasie

### 3.3.2. Crossing the Wrong Lane

The problem of false stimulation occurs also in situations where vehicles are detected while passing the lane unrelated to their route. Fig. 10 shows a situation where a vehicle cuts the corner driving directly over the sensor located on the left-turn lane going in opposite direction. As a result, the sensor reports false detection.

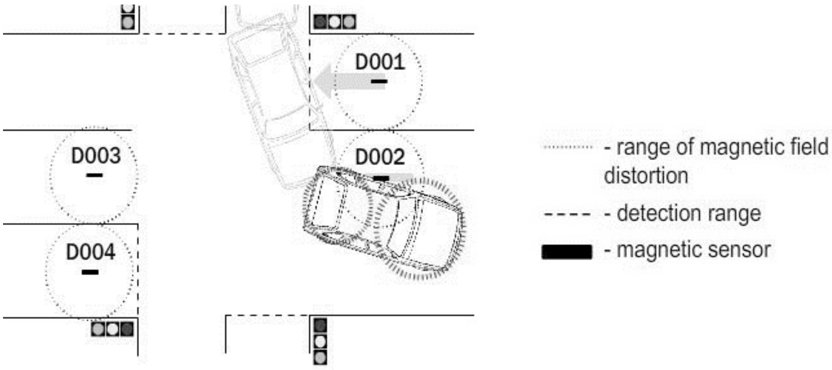

Fig. 10. Vehicle crossing the wrong lane
Rys. 10. Pojazd przejeżdżający po niewłaściwym dla siebie pasie

### 3.3.3. Double Counting

The tests have shown that sensors sometimes record vehicles with a few different points of metal mass concentration, such as trucks or trailers, as two separate detections. The problem is illustrated in fig. 11.

The cabin of the truck passes over the sensor generating a response (the measured level of distortion of the magnetic field reaches a value exceeding the upper detection limit). Then, the signal level drops below the lower limit to detect the vehicle and then rises again signalling the second detection when the sensor is passed by heavy rear of the trailer.

The use of hysteresis prevents from counting two axles of the vehicle as two separate reports. This fact is presented in fig. 11: two trailer axles are recorded as two peaks, but they are so close that the measured level of stimulation does not fall below the lower limit of the hysteresis loop. However, in case of large distance between the parts of the same vehicle the sensor is not able to recognise two distant peaks as one detection.

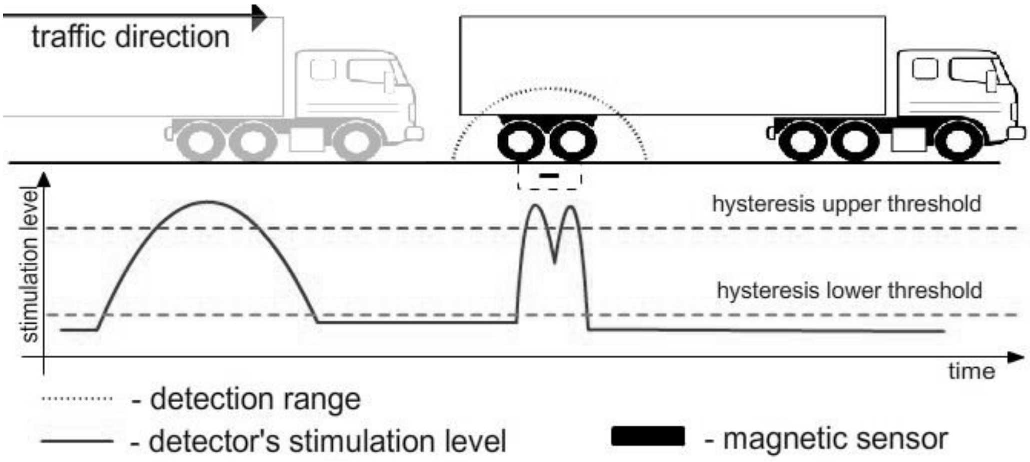

Fig. 11. Double detection of heavy truck
Rys. 11. Podwójna detekcja ciężarówki

### *3.3.4. Undesired Detection of Trams*

A major problem of the magnetic detection is recording trams and reporting them as motor vehicles (fig. 12). Even if the tram is far away from the area of the detector, the voltage induced in tram rails disturbs the magnetic field, which results in improper operation of the detection system.

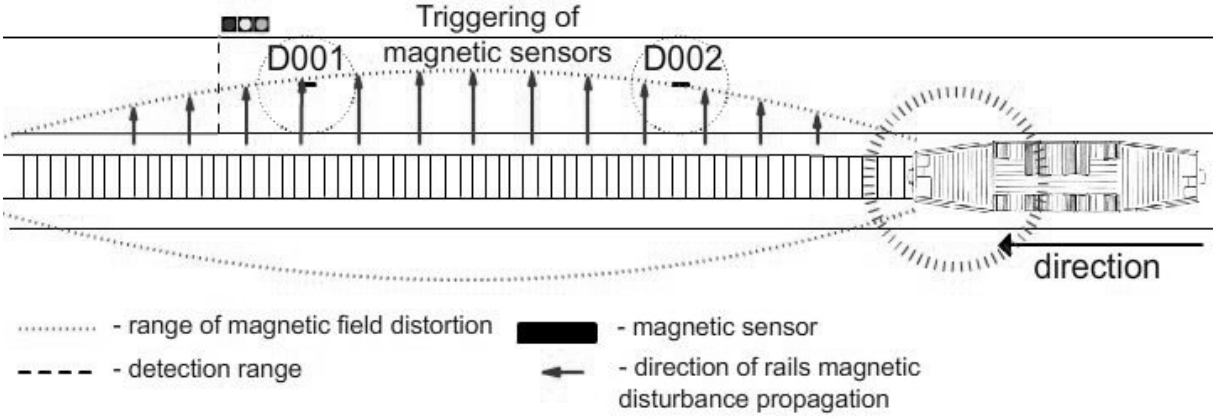

Fig. 12. Detection of a tram
Rys. 12. Detekcja tramwaju

## 4. SUMMARY

Magnetic detection system is constantly being tested and improved. Outdoor tests have shown some serious issues related to the concept of detecting vehicles using magnetic field distortions. The solutions to these problems will probably require more developed analysis of data collected by sensors rather than hardware design changes.

The main idea is to consider whether the detected vehicle is travelling in accordance with the direction of traffic on the particular lane. This would presumably eliminate most of false detection cases. Another way of solving the described problems may be a comprehensive analysis of data from all detectors at the intersection. Both of these concepts are currently being investigated. The system is under observation and amendments are being gradually introduced to increase its detection efficiency.

In some respects, magnetic sensors seem to have advantage over other detection systems. An important feature is the low price of detectors and simplicity of their installation. System maintenance is more convenient and cheaper than in case of e.g. induction loops. Also weather conditions proved not to affect the efficiency of vehicle detection. Taking all these factors into account, the detectors are expected to become applicable for the intelligent traffic control systems in the future.

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