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# IMPROVING THE CAPACITY OF CROSSROADS WITH TRAFFIC LIGHTS. USING SMART TRAFFIC CONTROL SYSTEMS SUPPORTED BY INNOVATIVE BEAM SENSORS.

**Summary**. The number of vehicles in the streets has been going up every year, which is the main reason leading to traffic congestions. A way to deal with the problem might be the development of an effective system, that would manage the flow of transport vehicles stream through crossroads with traffic lights in congested urban networks. The proposed solution – application of innovative beam sensors – is based on the use of specific light phases periods in traffic light cycles, in a more effective way (effectively reduce the period in which no vehicle is present at the crossroads). Its essence is to improve crossroads capacity in congested metropolitan areas. Any traffic control system supported with the beam sensors would be able to clearly identify if a vehicle has left the crossroad. This way of displaying the green signal for the next phase in a light cycle would be accelerated, while maintaining a very high level of safety. The green period for the phase in which the vehicle was present and the red period for any other traffic lights would be reduced. Thus, the main objective of beam sensors implementation is to reduce the traffic congestions and generally improve the traffic flow, which are certainly great advantages of such solution. They could also contribute to reduction in a vehicle operating costs (related to stop-and-go driving), lower emissions of harmful substances to the atmosphere and finally, to reduced traffic noise.

**Keywords:** traffic congestion; induction loop; high-traffic crossroad; traffic control; beam sensor; vehicles stream; urban network; pre-selection scales

## 1. INTRODUCTION

The 21st century has seen dynamic development of many domains, including passenger and cargo transport. People nowadays want to reach their destinations quickly and comfortably, and often prefer to use their own means of transport rather than public ones. The solution is highly convenient outside large metropolitan areas but becomes a problem in cities/towns with a population over 30,000 people. The number of vehicles in the streets has been going up every year and is among major contributors to traffic congestions [8]. Other important factors include a lack of funds to build collision-free crossroads, inability to develop the existing road infrastructure (e.g. extending narrow, one-lane roads) and a lack of efficient and effective traffic control systems in crossroads with traffic lights. The drivers are those who struggle with the problem of congested streets, not only during peak hours but also in off-peak hours. Despite long time allowed to go over crossroads in off-peak hours, covering the same parts of roads during rush hours may increase by 200% [11, 18].

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Promoting public transport has become a way to reduce traffic congestions. Unfortunately, in the majority of town/cities there are no special bus passes. It means of public transport have to queue to go through crossroads. Therefore a need arises to develop an effective system to manage the flow of public transport vehicles stream through crossroads with traffic lights for congested urban networks [10,12,22]. A new system and traffic control model have to be designed. This becomes particularly important in the most critical parts of cities. The system could be implemented only at some crossroads to support the existing systems or constitute a completely new solution helping to improve efficiency and capacity [19]. One should also remember the need to effectively reduce the period in which no vehicle is present at the crossroads (while maintaining the necessary safety of the transport participants).

This paper aims to present a method to use specific light phases periods in traffic light cycles (called traffic signal cycle) in a more effective way. The essence of the proposed solution is to improve crossroads capacity in congested metropolitan areas. The studies used directly to fulfil the purpose of the paper were carried out at crossroads in selected cities in Poland.

The paper consists of 6 sections. The first section contains a brief introduction and defines the purpose of the paper. The second one presents the rule of induction loops operation, which support traffic light control. The next section describes a sensor that records the parameters of vehicle flows at crossroads (called a beam sensor). The beam sensor can help to optimise the number of vehicles driving through crossroads during a particular traffic signal phase. Section 4 highlights essential differences between induction loops and beam sensors. The main advantages of the sensors are described. Section 5 presents the results of studies (conducted at crossroads in selected Polish cities) including their detailed analysis. The last part of the paper contains a summary describing the contribution of the new type of sensors to improvement and significant increase in the capacity of crossroads with traffic lights in congested metropolitan networks. The paper is supplemented by a list of references.

## 2. INDUCTION LOOPS AS A STANDARD SOLUTION SUPPORTING TRAFFIC CONTROL SYSTEMS

Traffic lights are used at high-traffic crossroads. They are intended to systematise and coordinate the flows of mechanical vehicles and pedestrians, by improving traffic efficiency and safety [4]. By displaying signals of different colours, frequencies and duration they give clear signals to the traffic participants. The signals inform how the traffic participants should behave in a particular cycle phase [17]. Contemporary traffic lights use a number of sensors and microprocessors. The items are responsible for fully automated changes in the signals displayed, and altogether form integrated traffic control systems [1, 7].

The most popular traffic control and traffic lights coordinating systems in Poland include SCOOT, UTOPIA-SPOT and SCATS [3, 15, 20, 21]. The systems use different kinds of detectors which record various traffic parameters at crossroads. The detectors adapt the traffic lights setting parameters to current conditions on the road. They operate in a manner opposite to fixed-time traffic signals when the particular light signal duration is set in advance. It means that even if no vehicle is present in a lane, the particular light phase needs to be displayed. The systems can be modified and adapted to nearly any conditions. They can be used at one or more crossroads, creating a system which optimises traffic in a larger area. The systems vary for their data processing method [5, 16].

An induction loop is the most popular device used nowadays in all abovementioned traffic control systems (traffic lights) at crossroads [6, 25]. A ferromagnetic effect in the loop can detect a vehicle in a lane due to the fact that the vehicle conducts electric current. A vehicle within the loop's reach causes interference in the loop eddy currents. This way the traffic control system is able to read information about the presence of a vehicle and its basic parameters such as e.g. the speed. Traffic lights with induction loops do not activate the green phase in a cycle for a lane with no vehicle. The solution is good for off-peak hours. Then the system allows a vehicle within the induction loop's reach to enter the crossroads nearly immediately (unless the same message has been read for the mutual collision direction). Unfortunately during rush hours the solution is completely inefficient because vehicles are always present on the lanes and every loop reads signals about their presence. This way the system is not able to support traffic lights signalling (the duration of the phase periods in a signal cycle is according to the pre-programmed minimum duration of the particular light signal, for the reference traffic light and lane) [2]. Remembering the functional aspects of induction loops one shall not forget their technical disadvantages. Induction loops can be easily damaged by high temperatures. They are usually installed right below or in the asphalt wearing course. On hot days, as a result of asphalt operation, they are broken (interrupted) and no longer fulfil their functions. In order to avoid frequent damage and further time-consuming repairs, the loops are installed in deeper layers of the road. This, however, entails a risk that not all vehicles will be detected. Moreover, in the case of multi-lane roads, two induction loops in adjacent lanes can fall within the impact field of one vehicle. It means that e.g. a big truck, bus or public transport vehicle near the lane edge can interfere with the signals recorded by the neighbouring loop. In such a case a green light phase can be unnecessarily activated for the adjacent lane [9].

## 3. INNOVATIVE BEAM SENSOR SUPPORTING TRAFFIC CONTROL SYSTEMS OPERATION

Pre-selection scales have become increasingly popular. They are used for detecting and weighing of vehicles. They help to record the approximate axle load, and specify the number or even the speed of vehicles passing. Pre-selection scales often operate based on resistance strain gauge measurements. A vehicle driving onto a horizontal beam in the driveway increases the installed circuit resistance. This way the system gets information that a vehicle axle crossed the device.

Pre-selection scales can also support traffic lights management and control systems at crossroads. Once installed before the crossroads entrance they could provide information about presence or absence of vehicles. It seems a much better solution to use systems with similar characteristics and functions but much simpler and with a lower total cost. A sensor, which needs to record many parameters for pre-selection scales, can be modified in such a way that the sensor reads only one parameter – a presence or absence of a vehicle at the crossroads. The device would come in a form of a horizontal beam (hence the name: beam sensor) consisting of a number of smaller sensors no longer than 2 cm (the shorter the sensor, the more accurate the system). Resistance-based sensors would provide information to the system about vehicle presence in a lane. It would also help to identify if a vehicle has already left the crossroads (if a sensor is also installed at the crossroads exit). Any traffic control system supported with beam sensors would be able to clearly identify if a vehicle (with the particular length, axle spacing and vehicles entering the crossroads before and after the vehicle) has left the crossroads. This way displaying the green signal for the next phase in a light cycle would be accelerated while maintaining a very high level of safety. The green period for the phase in which the vehicle was present and the red period for any other traffic lights would be reduced.

The proposed solution addresses the issue of the ever growing vehicle traffic. The solution is innovative and allows the use of the traffic signal cycle time when no vehicle is present at crossroads.

The abovementioned solution involving an innovative beam sensor is patent pending according to a procedure carried out by the Patent Office of the Republic of Poland. The procedure was initiated on request of the authors of the study.

## 4. MAJOR DIFFERENCES BETWEEN AN INDUCTION LOOP AND BEAM SENSOR

A beam sensor as a detector of traffic control systems can be adapted in any kind of crossroads. The sensor mounting time and method will be similar to the time and method for the induction loop. The installation cost shall not exceed significantly the induction loop installation cost, either. Other advantages of the solution include its much higher reliability. Geometrical changes in the asphalt surface do not affect the sensor operation (formation of ruts in a lane interrupt the loops and cause the need to make frequent repairs and/or replacements). The sensor has compact dimensions. It can be installed in any place of the crossroads, with any road infrastructure. Induction loops, to the opposite, must not be mounted at the crossroads entrance. It is due to presence of e.g. bicycle lanes, traffic separators etc. A beam sensor may come in any length (measured perpendicularly to the roadway axis). This way it can be installed at the entire crossroads length, which means that no vehicle can drive through the crossroads without driving onto the sensor (drivers often do not "drive onto" the induction loops in the right way). Contrary to induction loops a beam sensor can be installed in a non-hardened part of a road, for instance in the roadside that drivers use to overtake or pass by other vehicles. There is another advantage to using beam sensors, apart from reducing traffic congestions and improving traffic flow. They could contribute to reduction in vehicle operating costs (related to stop-and-go driving), lower emissions of harmful substances to the atmosphere and reduced traffic noise [13, 14, 23, 24].

## 5. STUDYING A FLOW OF VEHICLE STREAM THROUGH CROSSROADS WITH TRAFFIC LIGHTS

Traffic measurements were carried out for the needs of the study between 14 December 2018 and 4 February 2019 at selected crossroads in Poland. They involved recording the time in which no vehicle was present at the crossroads. The measurements were made during afternoon rush hours, i.e. between 3.30 p.m. and 5.30 p.m. The studied crossroads were located in the centre of Warsaw – Marszałkowska St. and Świętokrzyska St., and Aleje Jerozolimskie St. and Marszałkowska St., and in Lodz – Al. Włókniarzy St. and Lutomierska/Wielkopolska St., and Uniwersytecka St. and Jaracza St.. Fixed-time traffic lights were installed at the studied crossroads in Warsaw (each phase lasts the same in subsequent cycles). In Lodz the flow of the stream of vehicles was supported by induction loops.

The results of the studies are presented below, in Figures 1-4 and Tables 1-4, respectively. The results characterise the light signal phases at the studied crossroads. The green period values presented in the tables stand for the green light display time (for the particular phase) when no vehicle was present at the entrance to the crossroads, no vehicle was approaching the crossroads and each vehicle driving through the crossroads has already left it. It means that by shortening the green period for the phase can accelerate and/or extend the green period for another phase. The red periods presented in the Tables are the periods between subsequent phases when no vehicle was present at the crossroads.

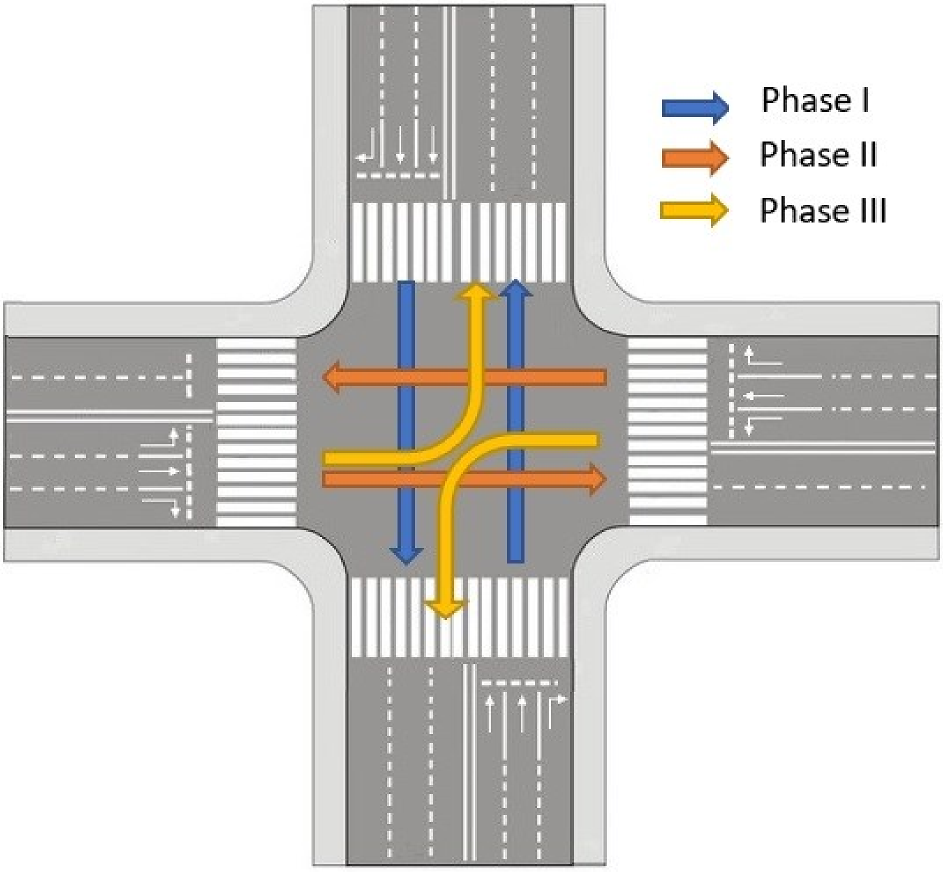


Fig. 1. Marszałkowska St. crossroads with Świętokrzyska St., Warsaw

Tab. 1

Marszałkowska St. crossroads with Świętokrzyska St.- measurement results

| No. | Marszałkowska St. crossroads with Świętokrzyska St., Warsaw | | | | | | Cycle |
|---|---|---|---|---|---|---|---|
| | Phase I | | Phase II | | Phase III | | duration: |
| | green | red | green | red | green | red | 2:01.45 |
| 1 | 6.02 | 7.01 | 6.03 | 1.46 | 0 | 0 | 2:02.10 |
| 2 | 24.02 | 7.38 | 0 | 2.22 | 0 | 0 | 2:00:89 |
| 3 | 8.43 | 6.34 | 0 | 1.99 | 0 | 0 | Mean: |
| 4 | 7.77 | 5.88 | 3.33 | 2.73 | 1.1 | 0.94 | **2:01.00** |
| 5 | 6.5 | 4.4 | 3.95 | 2.34 | 1.43 | 1.36 | |
| 6 | 6.2 | 4.89 | 1.22 | 1.94 | 2.67 | 1 | |
| 7 | 8.3 | 5.2 | 2.2 | 3.2 | 1.7 | 1.2 | Total |
| Mean | 9.61 | 5.87 | 2.39 | 2.27 | 0.99 | 0.64 | **20.14** |

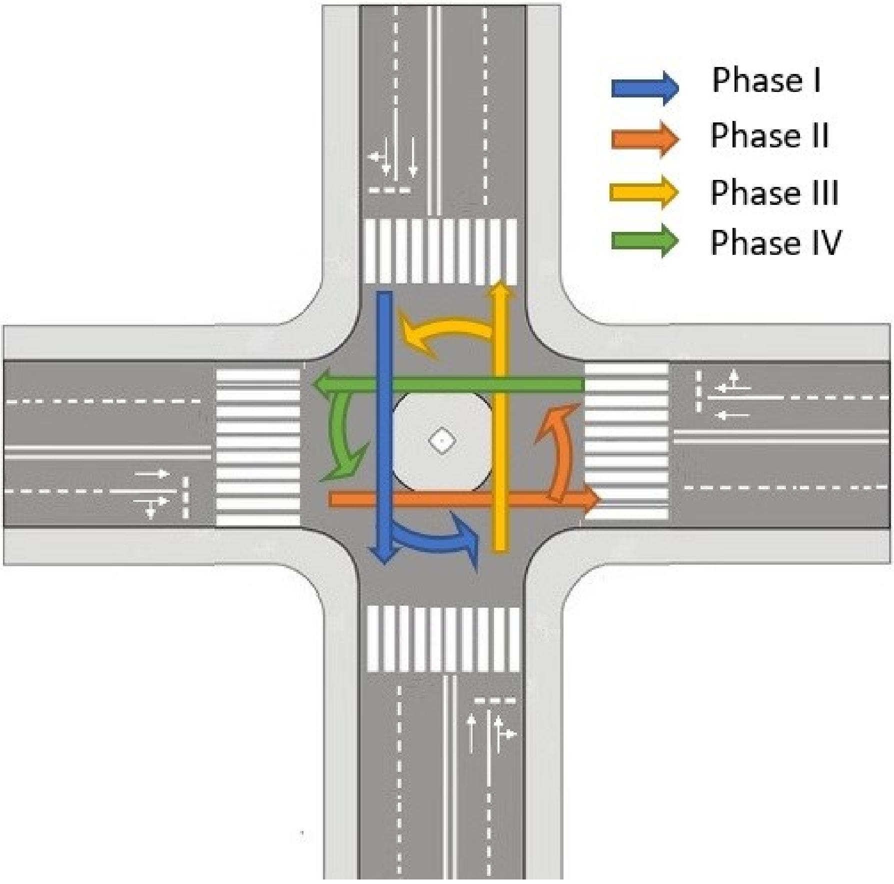


Fig. 2. Al. Jerozolimskie St. crossroads with Marszałkowska St., Warsaw

Tab. 2

Al. Jerozolimskie St. crossroads with Marszałkowska St. - results of measurements

| No. | Al. Jerozolimskie St. crossroads with Marszałkowska St., Warsaw | | | | | | | | Cycle |
|---|---|---|---|---|---|---|---|---|---|
| | Phase I | | Phase II | | Phase III | | Phase IV | | duration: |
| | green | red | green | red | green | red | green | red | 1:51.24 |
| 1 | 0 | 3.05 | 1.3 | 2.23 | 0 | 5.74 | 1.2 | 0 | 1:50.74 |
| 2 | 0 | 0 | 0 | 3.53 | 0 | 5.25 | 1.1 | 14.33 | 1:51.01 |
| 3 | 0 | 1.5 | 0 | 3.14 | 4.02 | 0 | 0 | 9.28 | Mean: |
| 4 | 0 | 0 | 0 | 2.5 | 14.5 | 4,5 | 0 | 11.65 | **1:51.00** |
| 5 | 1 | 0 | 0.8 | 1.89 | 2.9 | 1.22 | 1.43 | 10.4 | |
| 6 | 0.95 | 2.1 | 0 | 2.6 | 3.65 | 3.45 | 0 | 6.6 | |
| 7 | 0 | 1.9 | 1.3 | 4.02 | 5.8 | 2.5 | 1.15 | 5.67 | Total |
| Mean | 0.28 | 1.22 | 0.49 | 2.84 | 4.41 | 3.24 | 0.70 | 8.28 | **18.77** |

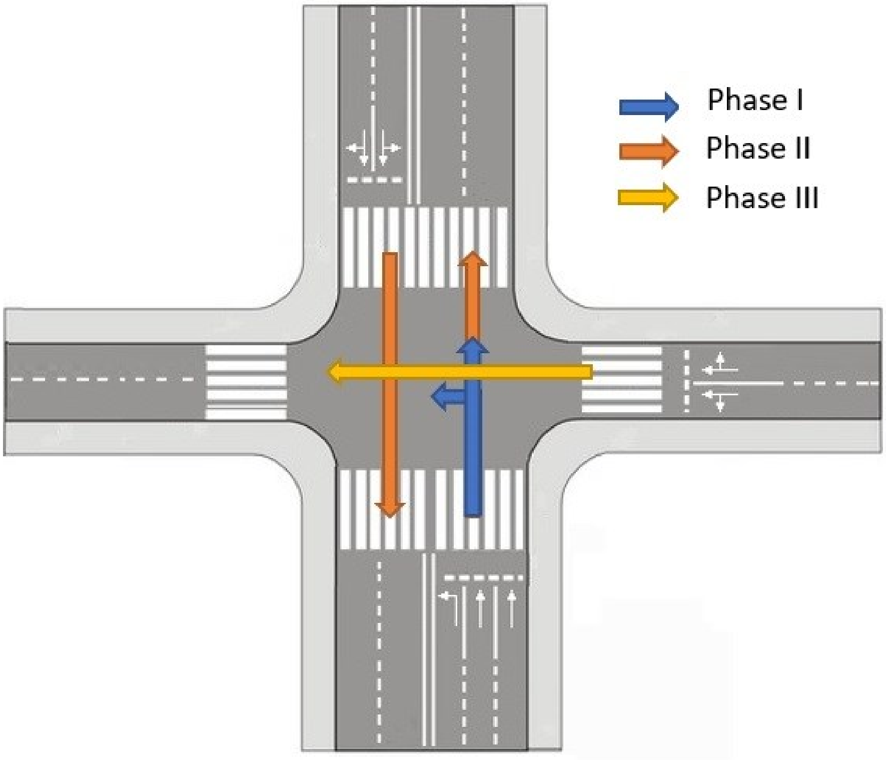


Fig. 3. Uniwersytecka St. crossroads with Jaracza St., Lodz

Tab. 3

Uniwersytecka St. crossroads with Jaracza St.- results of measurements

| No. | Uniwersytecka St. crossroads with Jaracza St., Lodz | | | | | | Cycle |
|---|---|---|---|---|---|---|---|
| | Phase I | | Phase II | | Phase III | | duration: |
| | red | green | red | green | red | green | 1:40.21 |
| 1 | 9.68 | 0 | 3.92 | 3.43 | 9.31 | 2.45 | 1:41.38 |
| 2 | 4.4 | 0 | 5.5 | 4.11 | 8.92 | 3.04 | 1:39.25 |
| 3 | 6.54 | 0 | 8.11 | 1.75 | 7.21 | 2.2 | Mean |
| 4 | 7.44 | 0 | 7.04 | 2.88 | 7.11 | 1.9 | **1:40.00** |
| 5 | 5.5 | 0.9 | 4.43 | 3.1 | 6.92 | 3.9 | |
| 6 | 4.66 | 0.5 | 2.13 | 3.87 | 5.94 | 3.42 | |
| 7 | 3.3 | 1 | 2.2 | 2.5 | 4.12 | 2.6 | Total |
| Mean | 5.93 | 0.34 | 4.76 | 3.09 | 7.08 | 2.79 | **23.65** |

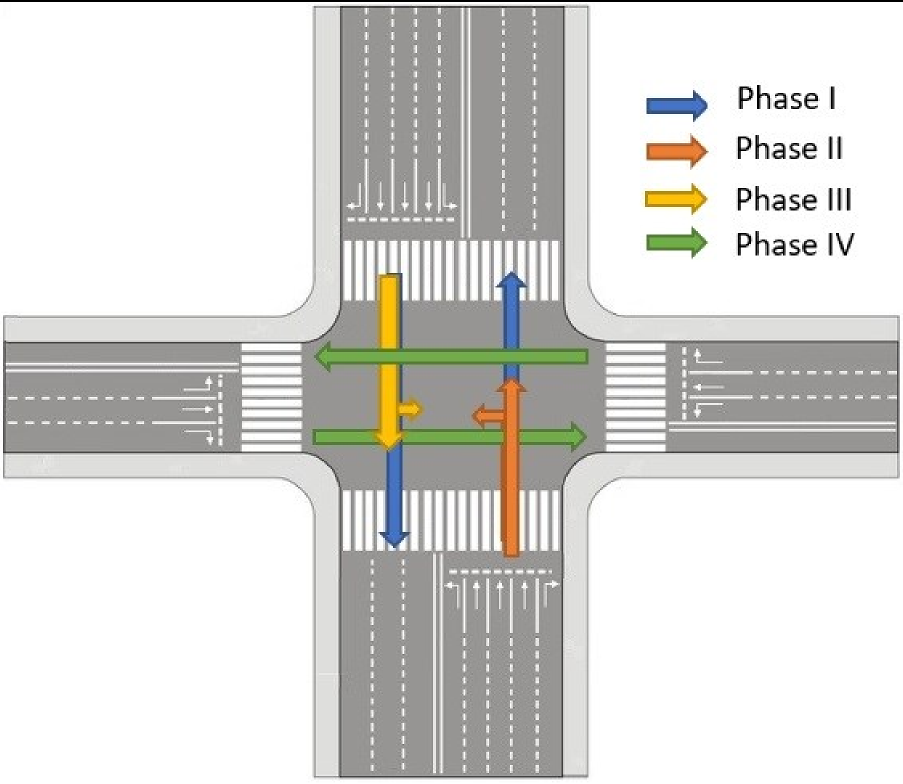


Fig. 4. Al. Włókniarzy St. crossroads with Lutomierska St. and Wielkopolska St., Lodz

Tab. 4

Al. Włókniarzy St. crossroads with Lutomierska St. and Wielkopolska St. - results of measurements

| No. | Al. Włókniarzy St. crossroads with Lutomierska St. and Wielkopolska St., Lodz | | | | | | | | Cycle |
|---|---|---|---|---|---|---|---|---|---|
| | Phase I | | Phase II | | Phase III | | Phase IV | | duration: |
| | green | red | green | red | green | red | green | red | 2:20.36 |
| 1 | 2.7 | 15.25 | 4.3 | 2.41 | 0 | 2.69 | 1.2 | 1.21 | 2:21.56 |
| 2 | 3.9 | 15.62 | 3.5 | 3.54 | 1.21 | 3.14 | 1.1 | 5.45 | 2:21.45 |
| 3 | 0 | 14.5 | 3.71 | 1.26 | 3.02 | 2.11 | 0 | 3.21 | Mean: |
| 4 | 3.4 | 16.49 | 1.19 | 2.36 | 0 | 0 | 0 | 0 | **2:21.00** |
| 5 | 0 | 13.05 | 0.92 | 1.96 | 2.65 | 4.21 | 1.43 | 2.12 | |
| 6 | 2.8 | 14.01 | 3.16 | 3.21 | 1.55 | 3.89 | 0 | 2.36 | |
| 7 | 1.9 | 17.23 | 2.32 | 2.32 | 1.13 | 2.14 | 1.15 | 4.19 | Total |
| Mean | 2.10 | 15.16 | 2.73 | 2.44 | 1.37 | 2.60 | 0.70 | 2.65 | **27.68** |

The mean values for each column in Tables 1-4 (mean time loss in a reference cycle phase) were calculated and presented in the last lines. The "Total" value is the last line sum, i.e. the time not used in each light signal cycle. The results of the studies do not include (in the total of the reference phase mean times) the time values of less than 2 seconds (it can be assumed that a driver's reaction takes 2 seconds). It means that if it was possible to obtain up to 2 seconds in each cycle, the validity of replacing fixed-time traffic signals/ induction loops with beam sensors should be taken into consideration. The studies clearly suggest that every crossroads has significant time resources which are not used. Even greater reserves can be obtained when the time periods of less than 2 seconds not taken into account are included.

Crossroads in the very heart of Warsaw, the capital of Poland, with the heaviest traffic, were studied. Fixed-time traffic lights are installed at the crossroads. It means that every phase in the light signal cycle lasts the same, regardless of traffic intensity. The displayed light signal duration is not adapted to the current conditions.

According to the data in Table 1 (Marszałkowska St. crossroads with Świętokrzyska St.), the mean traffic light cycle duration is 2:01.00. The mean time with no vehicle at the crossroads accounts for ca. 20% of the whole cycle. A similar situation is true for another crossroads studied in Warsaw (Aleje Jerozolimskie St./ Marszałkowska St.). The data in Table 2 show that the mean cycle duration is 1:51.00. On average there is no vehicle at the crossroads for 16.9% of the time (the light signal cycle duration is 111 seconds, while the unused time reserves last 18.77, i.e. 16.9% of the whole cycle duration).

With regard to the above, it seems reasonable to implement a system able to reduce green and red periods in the particular phase and accelerate the green period in subsequent phases by means of horizontal beam sensors. It will help to increase the number of vehicles passing in a column to about 10 – 20. As compared to the current conditions, it means a significant improvement. It is also possible that once the system is implemented at neighbouring crossroads which are connected by a relevant system (e.g. SCATS) the capacity will increase by more than the assumed 10 – 20 vehicles. At night, at lighter traffic, the system with the proposed beam sensor will adapt the displayed signals to the actual conditions. The adaptation will be aimed to obtain as smooth flow of vehicles as possible, without stop-and-go cycles. Besides shorter times of driving through the crossroads, it will be possible to reduce the traffic noise and quantity of exhaust gases released to the environment.

Lodz is the third largest city in Poland (as for the population) and ranked as the fifth most congested city in the world (according to TomTom ranking) [26]. Despite the fact that the city authorities have implemented smart traffic control system in the city, moving around Lodz in peak hours is very difficult. The system is mainly based on induction loop sensors. It does not eliminate traffic phases when no vehicle is present at the crossroads. The same is true for Warsaw, while the per cent share of the phases is definitely much higher. At Aleja Włókniarzy St. crossroads with Lutomierska St./Wielkopolska St. the period with no traffic at the crossroads accounts for nearly 20% of the whole cycle duration (Table 4), while at Uniwersytecka St. crossroads with Jaracza St. it is nearly 25% (Table 3). If a beam sensor was installed at every crossroads, based on the conducted studies it can be concluded, that each traffic phase could be extended by about 1/4 of the whole cycle duration. The solution could contribute to significant improvement in the capacity and would free the crossroads of traffic congestions.

The application of the described system using beam sensors is feasible. It allows the adaptation of current systems and guarantees reasonable green period inter-phase intervals. The solution can be implemented at crossroads in congested city centres (like Warsaw), in roads off the very centre (similar to the studied crossroads in Lodz) and at junctions of national and regional roads with local roads.

## 6. Conclusions

High traffic intensity and poorly adapted traffic lights are the main causes of traffic congestions worldwide. Advanced traffic control systems based on various kinds of motion detectors – mainly induction loops – have been installed in the largest Polish cities. Despite their application, the majority of systems in the very centres of cities are inefficient during rush hours. It makes moving from one place to another extremely difficult. The situation can be improved owing to better use of inter-phase periods. According to the completed studies, on average about 20% of the whole traffic signal cycle at the most congested crossroads is wasted (because there is no vehicle at the crossroads). The use of the proposed horizontal beam sensor solution will help to significantly reduce traffic congestions at crossroads. The system will offer accurate information about the vehicles entering and leaving the crossroads (including the information about the exit way). Observation of traffic at the crossroads leads to a conclusion that if the traffic was by about 10% lower in rush hours, it would be possible to move around smoothly or without any major difficulty. Once the proposed solution has been implemented, extra 10% reserve would still be left. The traffic flow in off-peak or night hours could be fluent or at least more fluent. The solution could not only improve the capacity but also reduce the traffic noise and the quantity of harmful substances emitted to the atmosphere by combustion engines.

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