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OPTIMISATION OF SIGNAL-CONTROLLED INTERSECTION CAPACITY

ABSTRACT

Road traffic safety is a complex system which combines movement of entities in precisely determined space and time dimension. Each of the entities, with their different properties, sets different requirements to road traffic system, including also other entities. Due to the large number of entities and their characteristic requirements, their interaction results in extremely complex relations which determine the behaviour of the road traffic system. The entities are combined according to their common features into certain groups, the movements of which usually result in conflicts. In such situations it is necessary to ensure the movement of a group of entities. This method of insurance necessarily creates negative consequences for all the entities that participate in road traffic system. In order to mitigate as much as possible these consequences, it is necessary to find an adequate method of optimising road traffic system according to a given criterion. The paper uses the results of the analysis of more than 100 road traffic system models and presents the methodology of determining the level of their interconnection. The level of influence of the basic traffic values on the final effect, i.e. the possibility of optimising signal-controlled intersections has been found and described.

KEYWORDS

traffic flow, signalized intersection, pretimedsystem, optimization, 2-phase system, 4-phase system, volume-to-capacity, lost time

1. INTRODUCTION

Considering the complexity of road traffic system and its significance in the development of human society, it is perfectly logical that humans are trying to acquire knowledge necessary to understand the method of its functioning, in order to optimise the controlling process. The basic problem in road traffic system management is the large number of vehicles (with continuous annual increase), which are usually in some kind of conflict, and how to let them through within minimum time interval, always along the same spatial traffic area. Points in road traffic system at which vehicles which participate in the creation of road traffic system get into conflict are called intersections.

Signalized method of managing the conflicting space, i.e. intersections, apart from positive effects regarding increasing the safety of the participants, brings along also some negative consequences. For each traffic participant considering subjectively, the closest notion of such a negative consequence is the length of the travelling time from their origin to their destination. That is, technically, the value of lost time. Considered from the technical and technological aspect, the comparative notion would be represented by the value of the vehicle-to-capacity ratio. The relation between the mentioned two values is usually inversely proportional and crucial for successful traffic process management at intersections. The mentioned notions and issues are the basic objective of this paper, attempting to use scientific base to determine the existence of their interrelation, and to find whether there is possibility of measuring it, i.e. of quantification.

The area of research and analysis of this paper is limited to the area of a single intersection in spatial and time dimensions. According to its traffic and technological properties, the observed intersection represents a symmetric intersection with four equal approaches. The analysis of the basic values of road traffic system is used to try to confirm the set hypothesis about the possibility of determining their interconnection regarding the set traffic and technological conditions, description of their interconnections and interactions, their analyses in order to reach an optimal solution according to the given criterion, and finally providing conclusions. The presented intersection model has been analysed in laboratory conditions, in order to mitigate maximally the undesired influence on the model, increase the credibility of the comparison of results obtained by simulations of different model variations, and to increase the flexibility of the model to the study of its different states.

Analyses carried out in this paper rely on the use of simulation tools for road traffic, as the basic and verified means for the analysis of the road traffic system and its basic concepts. The simulation tools represent a logical choice for the analysis of road traffic system mostly due to the impossibility of performing the analysis in actual conditions (real intersection), since the safety of road traffic participants could be greatly endangered, which represents an absolutely unacceptable choice of performing the research.

2. MODELLING

The model based on which the analysis is to be carried out, was developed using the simulation package Synchro Studio of the Trafficware Company which represents a verified and validated simulation tools recommended for the development of road traffic models by Federal Highway Administration (FHWA), as an umbrella institution referenced for all the issues of road traffic in the USA. The basic characteristic of this simulation tools is the possibility of simulation (analysis) of each simulation model in the same manner, i.e. derivation of models with different traffic and technological elements with always the same order of occurrence of vehicles in the model. This method of analysing the traffic system enables obtaining of high-quality results, suitable for intercomparison, necessary for deriving conclusions.

The model is loaded with entities in three intervals in the total duration of 60 minutes:

1. starting interval,
2. peak interval, and
3. interval with usual volume.

The starting interval equals the longest travelling time that is required by a vehicle in order to appear in the model, and then leave the model, or a maximum of three minutes. In this interval the initial loading of the model with vehicles begins, and during this time no information on the model status are collected, and therefore this time is not added to the overall time of model simulation. The volume of vehicles that appear equals the input volume of vehicles for each traffic lane per each approach. The purpose of this interval is to create a stable traffic flow in the model.

The peak interval takes 15 minutes and during this time the volume values for single lanes on all approaches are multiplied by the peak hour factor (0.92). The purpose of this interval is credible modelling of the creation of the fifteen-minute peak interval effect within the peak hour.

The interval with the usual volume takes 45 minutes and during this time the volume values at all approaches are determined so that the vehicle volume value during the 15-minute interval is subtracted from the total value of the volume for all traffic lanes on all approaches. This step is necessary so that in the end the total number of vehicles that appear in the model with the modelled 15-minute peak interval would be equal to the total number of vehicles input while determining the basic properties of the model. The purpose of this interval is the modelling of time necessary to empty the queuing lines formed during the 15-minute peak interval.

2.1 Basic intersection models

The basic intersection model used to perform laboratory tests is graphically shown in *Figure 1*. It consists of four traffic and technologically identical approaches – eastern (WB), western (EB), northern (SB) and southern (NB), each with one segregated lane for vehicles turning left and right, and two lanes for straight-moving vehicles. The presented models will be used to gather data of all the lanes at all approaches. However, the western (EB) approach has been determined as the reference approach which will be used to quantify the obtained results, i.e. the level of change regarding the change in the traffic and technological conditions.

The selected traffic and technological properties of the basic model make it possible to carry out various tests, i.e. to determine the impact of the changes in cycle duration, intersection geometry, and methods of controlling the traffic-light devices on the intersection capacity. The derived models that were used for testing the changed traffic and technological elements will be presented subsequently, in the order in which they were used in the tests.

The basic values of the traffic flow and of introducing traffic lights at the intersection described by the basic and the derived intersection models are presented in Tables 1 and 2.

Table 1 - Basic notions of the traffic flow describing the basic intersection model

The basic values of the traffic flow	
Maximum allowed vehicle running speed at approaches	50 km/h
Saturated traffic flow (along each lane)[1]	1,900 veh./h
Lane width	3.5 m
Peak hour factor	0.92
Share of cargo vehicles in traffic volume	2%

Table 2 - The basic notions of introducing traffic lights at the intersection which describe the basic intersection model

Basic values of introducing signalisation at intersection	
Minimal green phase duration	4 s
Yellow phase duration	3.5 s
All-red phase duration	0.5 s

The values crucial for deriving the required conclusions that are monitored both in tables and graphs presented through laboratory testing of the model are the following:

– vehicle-to-capacity ratio - v/c, and
– lost time– LT (s).

Graphical presentation is based on the absolute change in the cycle value regarding the starting cycle (C=40 seconds in two-phase operation mode, i.e. C=80 seconds in four-phase operation mode), and the relative change in the mentioned values between two successive cycles.

2.2 Laboratory research methodology

In order to obtain high-quality and relevant results of laboratory testing each of the developed models was analyzed through the pre-timed traffic light control in the length of cycle duration ranging from 40 to 140 seconds for a two-phase system, i.e. from 80 to 140 seconds for a four-phase system of traffic light control. Different cycle duration intervals for a two-phase and a four-phase system result from the fact that the minimal phase duration was set at 20 seconds. It results from the mentioned rule that the duration of the initial cycle in a two-phase system is calculated by multiplying two phases by 20 seconds, which is 40 seconds. Analogously, the initial cycle of a four-phase system is calculated by multiplying four phases by 20 seconds, resulting in 80 seconds. Each of the mentioned cycles in both traffic light control modes will be analyzed in accordance with the intersection capacity values and the respective vehicle volumes per approaches that are equal for each of the approaches, presented in *Table 3*, i.e. *Figure 1*.

The number of analyzed (derived) models with given conditions:

– intersection capacities (three conditions: below, at, and above capacity),
– number of analyzed systems (two: two-phase and four-phase),
– number of different cycle durations, eleven for a two-phase system (from C=40 seconds to C=140 seconds), and seven for a four-phase system (from C=80 seconds to C=140 seconds).

that is:

– scenario S_01 - 11 models; cycle length from C=40 seconds to C=140 seconds – two-phase system; beow-intersection-capacity, 4 lanes per approach
– scenario S_01_4F - 7 models; cycle length from C=80 seconds to C=140 seconds – four-phase system; beow-intersection-capacity, 4 lanes per approach
– scenario S_02 - 11 models; cycle length from C=40 seconds to C=140 seconds – two-phase system; at-intersection-capacity, 4 lanes per approach
– scenario S_02_4F - 7 models; cycle length from C=80 seconds to C=140 seconds – four-phase system; at-intersection-capacity, 4 lanes per approach
– scenario S_03 - 11 models; cycle length from C=40 seconds to C=140 seconds – two-phase system; above-intersection-capacity, 4 lanes per approach
– scenario S_03_4F - 7 models; cycle length from C=80 seconds to C=140 seconds – four-phase system; above-intersection-capacity, 4 lanes per approach
– scenario S_04 - 11 models; cycle length from C=40 seconds to C=140 seconds – two-phase system; beow-intersection-capacity, 3 lanes per approach

Table 3 - Values of volumes per approaches and intersection capacity

↰	↑	↱	Condition	Value v/c
100	500	100	beow-intersection-capacity	< 0.50
150	750	150	at-intersection-capacity	0.50 ≤ and ≤ 1.00
200	1000	200	above-intersection-capacity (congestion)	> 1.00

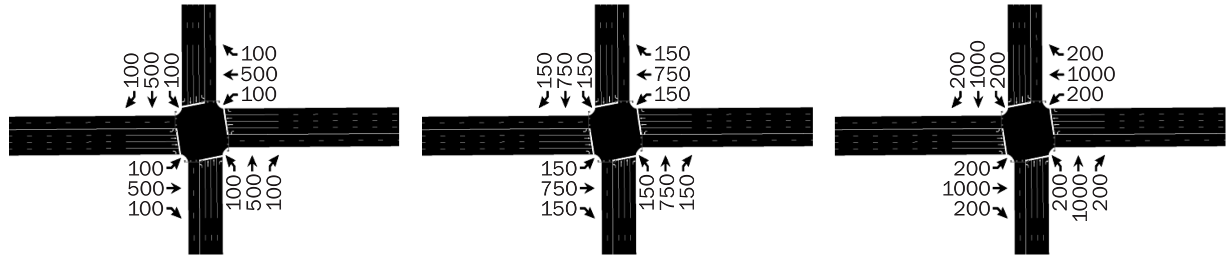


Figure 1 - Vehicle volumes per approaches of the basic model

- scenario S_04_4F - 7 models; cycle length from C=80 seconds to C=140 seconds – four-phase system; beow-intersection-capacity, 3 lanes per approach
- scenario S_05 - 11 models; cycle length from C=40 seconds to C=140 seconds – two-phase system; at-intersection-capacity, 3 lanes per approach
- scenario S_05_4F - 7 models; cycle length from C=80 seconds to C=140 seconds – four-phase system; at-intersection-capacity, 3 lanes per approach
- scenario S_06 - 11 models; cycle length from C=40 seconds to C=140 seconds – two-phase system; above-intersection-capacity, 3 lanes per approach
- scenario S_06_4F - 7 models; cycle length from C=80 seconds to C=140 seconds – four-phase system; above-intersection-capacity, 3 lanes per approach

which yields in total a number of $(11 + 7) \cdot 6 = 108$ analyzed models derived on the basis of the basic model.

Intersection model analyses, as already mentioned, refer to the pre-timed process of traffic light control at intersections, i.e. insensitivity of traffic light operation to current traffic demand at the observed intersection approaches.

In writing this paper there was a possibility of analyzing traffic-dependent control. However, because of the explained traffic and technological design of the basic intersection model (four identical approaches), as well as the selected method of monitoring changes of the traffic values in the model, the analysis of the traffic-dependent control method would not differ from the analysis of the model with pre-timed control. The reason for this fact is easy to explain by knowing that the efficiency of the traffic-dependent control is necessarily based on the existence of at least two differently loaded lanes, which is not the case in the basic model presented in the paper.

Because of the large number of derived models, but also because of the hypothesis which attempts to determine whether there is any interconnection and rule in the method of changing the studied values of the vehicle-to-capacity ratio (v/c) and the lost time (LT), regarding the cycle duration, i.e. the number of phases at the intersection, the pedestrians do not appear either in the basic model, or in the derived models. The analysis of pedestrian impact represents certainly an area that needs to be analyzed in more detail. However, it exceeds the set frames of the scientific research of this paper.

The analyses of the pre-timed traffic control model which proceed in two phases have the phase duration ratio 50:50, which, regarding the equal traffic load of all approaches represents an optimal distribution of the phase duration due to their symmetric traffic load. Exceptions are the models in which signalized intersection operates in four-phase control mode. In these cases the phase duration length (second and fourth phase) for left-turning vehicles is always the same and amounts to 20 seconds, whereas the duration of the first and the third phase ($D_{1st,2nd}$) are determined by the total cycle duration reduced by the duration of the second and fourth phase, i.e.:

$$D_{1^{st},2^{nd}} = \frac{C-40}{2} \qquad (1)$$

Figure 3 shows the order of phases in a two-phase, i.e. four-phase traffic light control at the intersection.

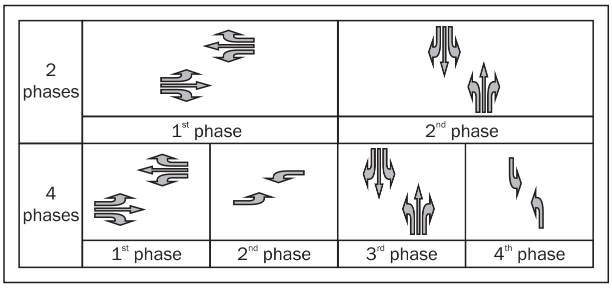


Figure 3 - Order of phases in two-phase and four-phase control mode

As already mentioned, the values of vehicle-to-capacity ratio and the lost time at the intersection have been taken as reference values and their changes are monitored and analysed in order to determine their interrelationships and to try to quantify them. For the easiest possible determination and description of their relations, the values of these two parameters will not be exclusively compared between each other, but all the analyses will be performed through the derived values in the form of absolute change in the cycle duration regarding the initial cycle duration length (C40) and the relative change between two successive cycles, both expressed in percentages. Such an approach to research has been selected for easier determination of the cause-effect relations between the value of the intersection vehicle-to-capacity ratio and the lost time at the intersection. Also, such approach to value monitoring had not been applied up to now, and the aim was to study the possibility of its implementation. The movement of the mentioned derived values are also presented by adequate graphs, where the X-axis represents the respective cycle duration from C=40 seconds (for a two-phase system), that is, C=80 seconds (for a four-phase system) up to C=140 seconds, and Y-axis represents the calculated percentage values. Among the derived values, the primary role in the analysis of relations belongs to the absolute change in the cycle duration regarding the initial cycle duration, whereas the relative change only additionally explains and describes the direction of movement (trend) of values of the resulting changes between two cycle durations represented by the absolute change. The values presented on Y-axis on both graph types appear both in the positive and in the negative area of the graph. In the graphs that show the absolute change between different cycle durations, the movement of the value in the positive field of Y-axis represents less favourable capacity and waiting time values, and their movement in the negative field of Y-axis represents their more favourable values. Contrary to this, in the graphs which show the movement of relative change between two successive cycles, the movement of the value in the positive field of Y-axis represents more favourable values of the capacity and waiting time, and their movement in the negative field of Y-axis represents their less favourable values.

Additional analysis of the relation of the values referring to the vehicle-to-capacity ratio and the lost time will be expressed by the index of absolute distance (2) and the index of relative distance (3). The index of absolute distance DA(LT, v/c), expresses the distance along Y-axis between the value of lost time and the vehicle-to-capacity ratio for the cycle duration of C=140 seconds. The index of relative distance DR(v/c, LT), expresses the distance along Y-axis between the value of the vehicle-to-capacity ratio and the lost time for the cycle duration of C=140 seconds. The indices are calculated according to the following formulae:

$$D_{A(LT,v/c)} = LT - v/c \quad (2)$$

$$D_{R(v/c,LT)} = v/c - LT \quad (3)$$

Using the mentioned indices an attempt will be made to analyse and find the connection between the various scenarios and the traffic and technological conditions of traffic flows on the models of the analysed intersections.

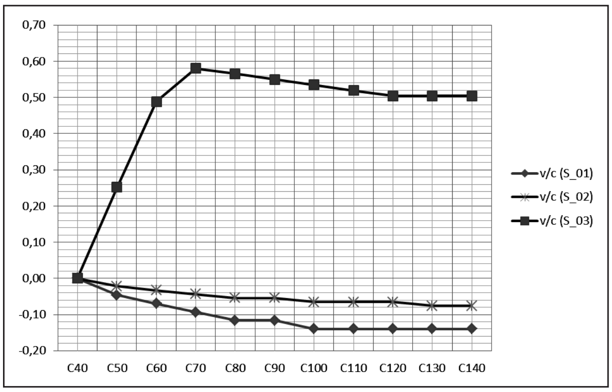
3. DISCUSSIONS OF THE OBTAINED RESULTS

3.1 Discussion of the obtained values of the scenario in two-phase traffic light operation mode

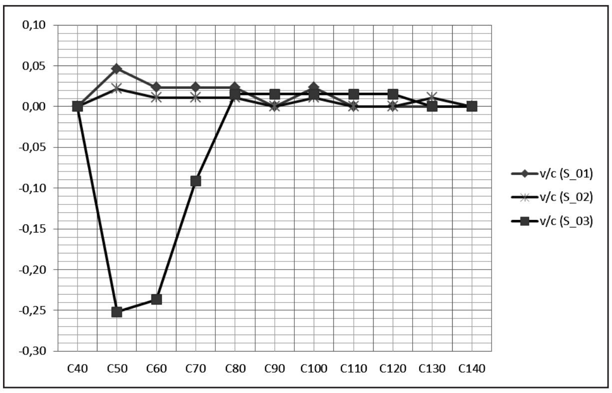
Further in the text there is a summary and a comparison of the results obtained from the analysed scenarios in the two-phase traffic light operation mode by means of graphs. Graphs describe visually the comparative change of the absolute and relative values of the vehicle-to-capacity ratio, as well as comparative change in the absolute and relative values of the time lost at the intersection. These comparisons are presented for two groups of scenarios, depending on the common characteristics of the model. In the first group the same characteristic of the traffic area is shared by scenarios S_01, S_02 and S_03, whereas in the second group the same characteristic is shared by scenarios S_04, S_05 and S_06.

Graphs 1 and 2 clearly show that in scenarios S_01 and S_02, in which the traffic flow proceeds in the conditions below or at-intersection-capacity, the value of vehicle-to-capacity ratio changes in the negative direction (falls) with the increase in the cycle duration. The curve that describes the flow of the percentage change in the vehicle-to-capacity ratio in scenario S_02 (at-intersection-capacity) in *Graph 1*, shows a slightly smaller angle of inclination than the curve that describes the movement of the percentage change in the vehicle-to-capacity ratio of scenario S_01 (beow-intersection-capacity), which indicates that due to the increased vehicle volume the change of values in scenario S_02 proceeds in smaller increments than is the case in scenario S_01.

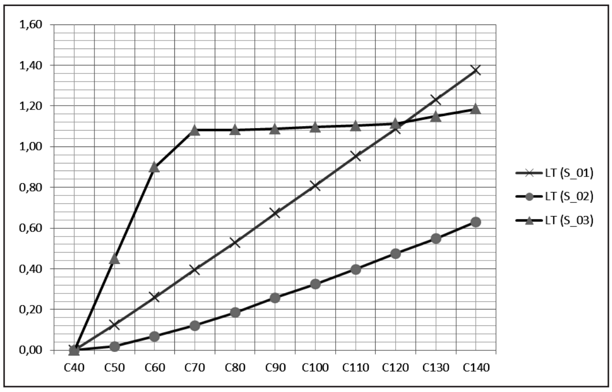
On the other hand, in scenario S_03 in which the traffic flow occurs in above-intersection-capacity conditions, the value of vehicle-to-capacity ratio changes in the positive direction (grows) with the increase in the cycle duration. In scenario S_03, it can also be seen that this increase occurs in big increments up to the cycle duration of C=70 seconds, followed by a decline in the value, but in small increments. This clearly shows that it is possible to describe the traffic flows in above-intersection-capacity conditions numerically. However, such a situation could never be described in the actual conditions of the traffic flow, since already in case of capacity values equal, and particularly greater than 1,



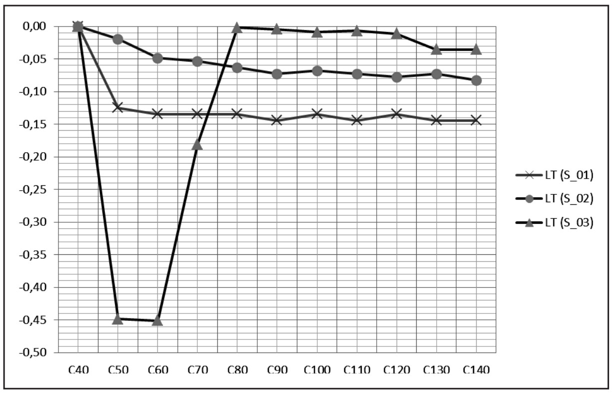
Graph 1 - Absolute change of v/c (%) for scenarios S_01, S_02 and S_03



Graph 2 - Relative change of v/c (%) for scenarios S_01, S_02 and S_03



Graph 3 - Absolute change of LT (%) for scenarios S_01, S_02 and S_03

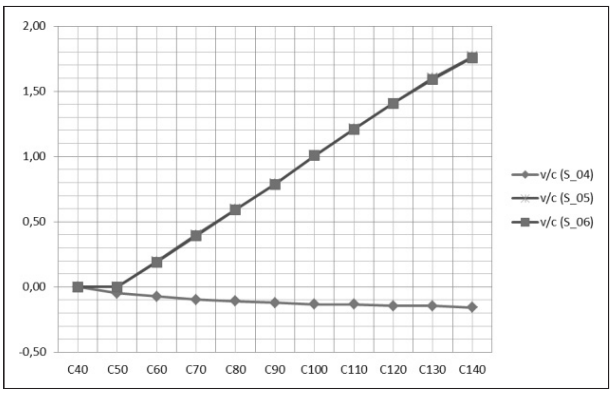


Graph 4 - Relative change of LT (%) for scenarios S_01, S_02 and S_03

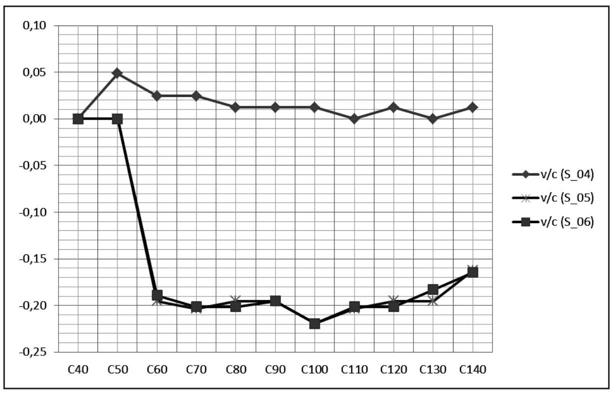
long queues start to form and they start to "spill over" between the adjacent intersections.

On the same basis, Graphs 3 and 4 present changes in the values of time lost at the intersection. *Graph 3* shows that in below-intersection-capacity conditions, by increasing the cycle duration, the value of lost time increases almost linearly, i.e. the curve which represents the movement of its value assumes the form of a line. The curve that represents the movement of the value of lost time in at-intersection-capacity conditions has a somewhat smaller angle of inclination compared to the previously described curve and it is of a slightly concave shape. Its shape shows that the increase in the value of lost time in at-intersection-capacity conditions occurs in smaller increments than is the case in below-intersection-capacity conditions. The third curve which describes the movement of the value of lost time in above-capacity conditions has a bigger angle of inclination than both up to now described curves and it is of convex form. This curve also clearly shows that it is possible to describe mathematically the traffic flow in the conditions of above-intersection capacity. In above-intersection-capacity conditions the value of lost time increases in larger increments than in the up to now described conditions of traffic flow at intersections, all the way to the point of convergence, i.e. until achieving the maximum intersection capacity, followed by saturation, so that the increase in the cycle duration causes almost no change (increase) any more in the value of lost time. This phenomenon clearly shows complete congestion of the intersection.

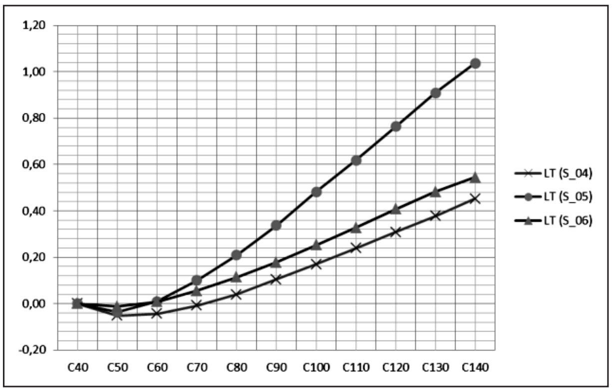
The comparison of the percentage change in the level of vehicle-to-capacity ratio of the second group comprised by scenarios S_04, S_05 and S_06 is presented in Graphs 5 and 6. *Graph 5* shows that only scenario S_04 describes the traffic flow in the below-intersection-capacity conditions. This is confirmed by two facts in the graph. The first shows that only the curve of vehicle-to-capacity ratio for scenario S_04 is falling in the 3rd quadrant, and the second one which shows that the movement of the percentage change of the vehicle-to-capacity ratio for scenario S_04 proceeds in small increments. Unlike scenario S_04, in scenarios S_05 and S_06 the curves that describe the percentage change of vehicle-to-capacity ratio represent ascending lines in the 2nd quadrant, and the movement of the percentage change in the vehicle-to-capacity ratio occurs in larger increments than in scenario S_04. In conclusion, it may be noticed that in the below-intersection-capacity conditions of the traffic flow, in two-phase traffic light control mode, the value of the vehicle-to-capacity ratio is always reduced by increasing the cycle duration. On the contrary, in above-intersection-capacity conditions of the traffic flow, the



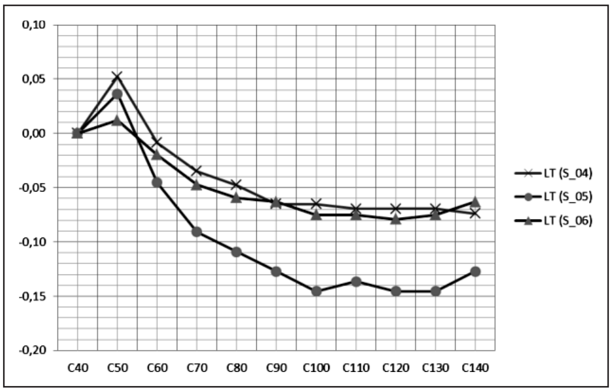
Graph 5 - Absolute change of v/c (%) for scenarios S_04, S_05 and S_06



Graph 6 - Relative change of v/c (%) for scenarios S_04, S_05 and S_06



Graph 7 - Absolute change of LT (%)
for scenarios S_04, S_05 and S_06



Graph 8 - Relative change of LT (%)
for scenarios S_04, S_05 and S_06

Table 4 - Change in the indices of absolute and relative distances for two-phase intersection control mode

	S_01	S_02	S_03	S_04	S_05	S_06
$D_{A(LT,v/c)}$	1.52	0.71	0.69	0.61	-0.72	-1.21
$D_{R(v/c,LT)}$	0.14	0.08	0.04	0.08	-0.03	-0.10

value of vehicle-to-capacity ratio always increases with the increase in the cycle duration.

Graph 7 shows parallel movement of the absolute change in the value of lost time for scenarios S_04, S_05 and S_06. According to this, it is clear that the value of the lost time at intersections in all conditions of traffic flows at intersections always increases. However, the value of shift is determined by the traffic flow conditions so that by increasing the value of the vehicle-to-capacity ratio, the increase in the lost time changes in larger increments. That is, the greater the value of the vehicle-to-capacity ratio, the lost time value will increase in larger increments than in case when the vehicle-to-capacity ratio is of lower value. After having reached the point of convergence, the curves that describe the value of lost time at intersection in all conditions of traffic flows assume the form of ascending lines in the 2nd quadrant.

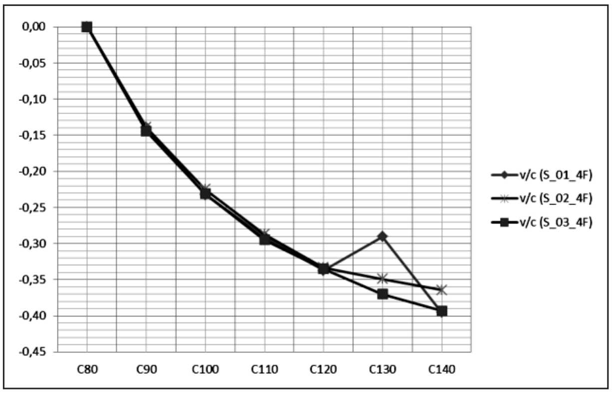
Considering the changes of introduced index of absolute distance $D_{A(LT,v/c)}$ and the index of relative distance $D_{R(v/c,LT)}$, presented in Table4, it can be observed that the value of both indices in the scenarios is reduced with the increase in the value of the vehicle-to-capacity ratio. The reduction in the index value is not proportional to the increase or the decrease in the value of the vehicle volume i.e. traffic area capacity. It is, thus, obvious that 50% increase in the vehicle volume between scenarios S_01 and S_02 will cause a decline in the value of index $D_{A(LT,v/c)}$ by 53.29%, whereas index $D_{R(v/c,LT)}$ will fall by 42.86%. The decline in the value of index $D_{A(LT,v/c)}$ i.e. index $D_{R(v/c,LT)}$ between scenarios S_02 and S_03 is significantly lower, since the traffic at the intersection in scenario S_03 occurs in the above-intersection-capacity conditions.

The reduction in the number of traffic lanes for straight-moving vehicles by 50% between scenarios S_01 and S_04 causes reduction in the value of index $D_{A(LT,v/c)}$ by 59.87%, i.e. index $D_{R(v/c,LT)}$ by 42.86%. This means that even in the case of reducing the traffic area capacity the change of the mentioned indices will not be proportional to the change. This phenomenon proves once again that the traffic flow is of stochastic nature and its change of state cannot be fully forecast and described by mathematical formulae. The mentioned indices in scenarios S_05 and S_06 assume negative values, which again proves that the traffic flow at the intersection in such conditions of vehicle-to-capacity ratio can be described exclusively mathematically, whereas these are not possible in actual traffic flow conditions.

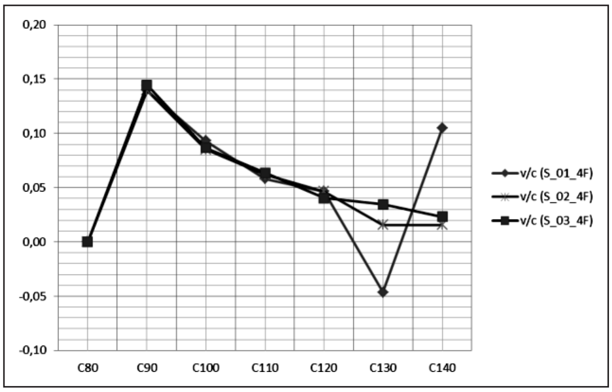
3.2 Discussion of obtained scenario values in four-phase traffic light control mode

Next, a summary and comparison of the results of the analyzed scenarios in the four-phase traffic light control mode will be presented. Like in the case of two-phase control mode, graphs are presented that visually describe the parallel change of absolute and relative value of the vehicle-to-capacity ratio, as well as parallel change of absolute and relative value of the lost time at the intersection. The mentioned comparisons are presented for two groups of scenarios, depending on the common characteristics of the model. In the first group the same characteristic of the traffic area is shared by scenarios S_01_4F, S_02_4F and S_03_4F, whereas in the second group the same characteristic is shared by scenarios S_04_4F, S_05_4F and S_06_4F.

Graphs 9 and 10 clearly show that in scenarios S_01_4F, S_02_4F and S_03_4F the movement of the percentage change in the vehicle-to-capacity ratio



Graph 9 - Absolute change of v/c (%) for scenarios S_01_4F, S_02_4F and S_03_4F



Graph 10 - Relative change of v/c (%) for scenarios S_01_4F, S_02_4F and S_03_4F

is almost identical up to the cycle duration of C=120 seconds. This is followed by a slight increase in the value of the percentage change in scenario S_01_4F, due to the traffic flow in below-intersection-capacity conditions for all cycle durations. Up to the mentioned point of the cycle duration of C=120 seconds, all the curves that describe the movement of the absolute percentage change in the vehicle-to-capacity ratio in the mentioned scenarios represent concave curves in the 3rd quadrant.

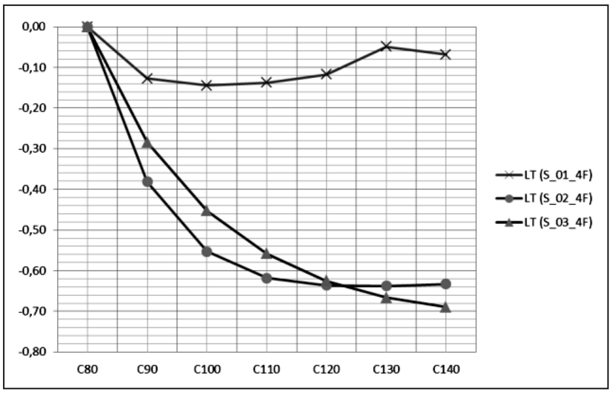
Comparing the movement of values of vehicle-to-capacity ratio in scenarios S_01 and S_01_4F one may notice that under the same traffic and technological conditions and the same traffic load, in below-intersection-capacity conditions of the traffic flow, an optimal solution is the two-phase traffic light control mode at the intersection. The movement of the lost time value in the mentioned scenarios also confirms this fact. A justification for the application of the four-phase control mode under the mentioned traffic and technological conditions would lie only in a large number of left-turning vehicles. It is exclusively on the indicated lane that lower values of the lost time in the four-phase control mode are obtained. This represents an expected situation, since in the four-phase control mode the left-turning vehicles perform their action in their protected phase, without conflict with the straight-moving vehicles from the opposite direction.

Comparing the movement of the vehicle-to-capacity ratio value in scenarios S_02 and S_02_4F, one may notice that under the same traffic and technological conditions, and the same traffic load, under the traffic flow conditions below (S_02) and at (S_02_4F) intersection capacity, the optimal solution is still in the two-phase traffic light control mode at intersections. However, the vehicle-to-capacity ratio becomes equal in both scenarios for the cycle duration of C=120 seconds. Like in the case of comparing scenarios S_01 and S_01_4F, if the movement of the straight-moving vehicles represents the first criterion of finding an optimal solution, this solution will be the two-phase control system. If the first optimisation criterion encompasses the left-turning vehicles, the optimal solution regarding the values of vehicle-to-capacity ratio and of the lost time will be the four-phase traffic light control mode at intersections.

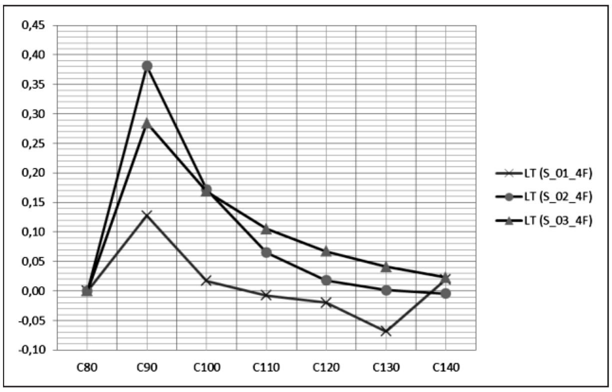
Comparing the movement of values of the vehicle-to-capacity ratio in scenarios S_03 and S_03_4F, it may be noticed that under the same traffic and technological conditions, and the same traffic load, under the conditions of traffic flow above (S_03 and S_03_4F) and at (S_03_4F) intersection capacity, the optimal solution lies in the four-phase traffic light control mode at intersections. This is indicated in the lower value of the vehicle-to-capacity ratio for all the cycle durations, and mostly for the cycle duration of C=140 seconds, where the vehicle-to-capacity ratio has almost half the value in scenario S_03_4F as compared to scenario S_03. Using the four-phase control mode under the given traffic and technological conditions, for the cycle duration of C=140 seconds, a traffic flow in the actual conditions can be achieved, which would be impossible if the two-phase traffic lights control mode were used.

The value of the lost time at the level of the entire intersection increases in the four-phase as compared to the two-phase control mode, as consequence of a special phase for the left-turning vehicles. Such control mode increases the value of lost time for straight-moving and right-turning vehicles, i.e. those vehicles that share the same phase for vehicles moving straight through or turning right. However, lower values of the vehicle-to-capacity ratio for the entire intersection fully justify the use of the four-phase traffic light control mode.

Graphs 11 and 12 show a very significant difference between the two-phase and the four-phase control modes. The values of the lost time in the four-phase control mode decrease with the increase in the cycle duration, which is contrary to the phenomenon that occurs in the two-phase control mode. Furthermore, the "less favourable" the conditions of the traffic flow



Graph 11 - Absolute change of LT (%) for scenarios S_01_4F, S_02_4F and S_03_4F



Graph 12 - Relative change of LT (%) for scenarios S_01_4F, S_02_4F and S_03_4F

in the four-phase system, i.e. at- or above-intersection-capacity, the reduction in the values of lost time occurs in larger increments.

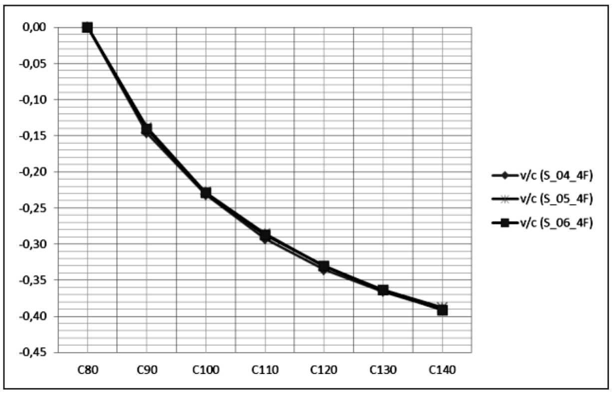
Looking at Graphs 13 and 14, it may be noticed that the movement of the absolute change in the value of the vehicle-to-capacity ratio is almost identical in all the three scenarios, S_03_4F, S_05_4F and S_06_4F. As already mentioned, these scenarios, and particularly scenarios S_05, S_06, S_05_4F and S_06_4F represent purely laboratory scenarios that exist nowhere in the actual traffic system. However, here their significance is great since they can be mathematically described using the laboratory computer model, in order to prove the advantages and the drawbacks of the two-phase and the four-phase traffic light control modes at intersections.

Comparing the value of the vehicle-to-capacity ratio in scenarios S_04 and S_04_4F, as well as in scenarios S_01 and S_02 as compared to scenarios S_01_4F and S_02_4F, because of the achieved value of the vehicle-to-capacity ratio the optimal solution lies in the application of the two-phase control mode. An exception, as already mentioned, is the case in which the first optimisation criterion refers to left-turning vehicles, when the optimal solution regarding the values of the vehicle-to-capacity ratio and of the lost time is in the four-phase traffic light control mode at intersections.

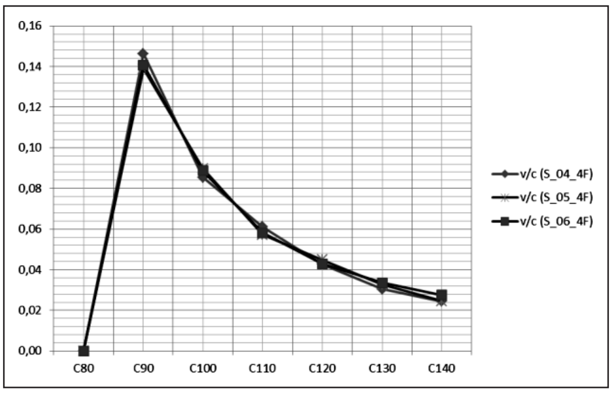
Scenarios S_05_4F and S_06_4F confirm theoretically the already mentioned fact that the use of the four-phase control mode represents the optimal solution under the at- or above-capacity traffic flow. Here also the lost time for vehicles moving straight and turning right will be somewhat bigger than in the case of two-phase control mode. However, the value of the vehicle-to-capacity ratio for the entire intersections justifies the application of the four-phase traffic light control mode at intersections.

Graphs 15 and 16 show that an increase in the cycle duration at the intersection results in the change of the percentage value of the lost time in ever decreasing increments with the decrease in the vehicle-to-capacity ratio.

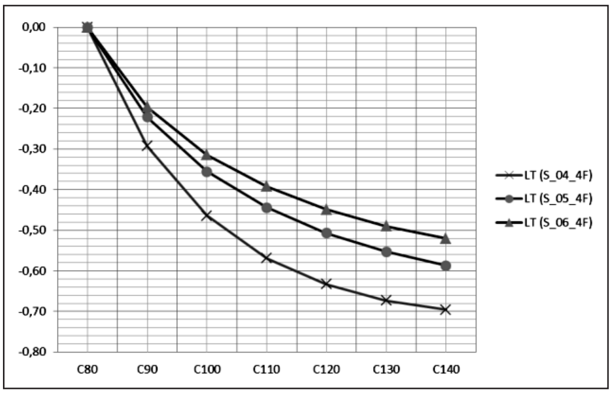
Looking at the changes of the introduced indices of the absolute distances $D_{A(LT,v/c)}$ and indices of the relative distance $D_{R(v/c,LT)}$, presented in *Table 5*, one may notice that the increase in the value of the vehicle-to-capacity ratio in the scenarios results in the decrease of the values of both indices. The decrease in the value of indices is not proportional to the increase or decrease of the vehicle volume i.e. the number of traffic lanes. Thus, it may be noticed that the 50% increase in the vehicle volume between scenarios S_01 and S_02 will cause a decline in the value of index $D_{A(LT,v/c)}$ by 53.29%, whereas index $D_{R(v/c,LT)}$ will fall by



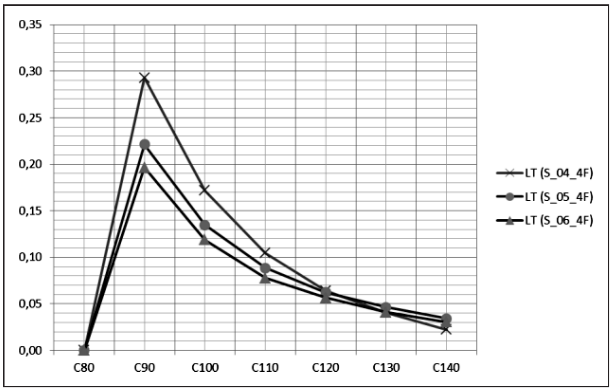
Graph 13 - Absolute change of v/c (%) for scenarios S_04_4F, S_05_4F and S_06_4F



Graph 14 - Relative change of v/c (%) for scenarios S_04_4F, S_05_4F and S_06_4F



Graph 15 - Absolute change of LT (%) for scenarios S_04_4F, S_05_4F and S_06_4F



Graph 16 - Relative change of LT (%) for scenarios S_04_4F, S_05_4F and S_06_4F

42.86%. The decline in the value of index $D_{A(LT,v/c)}$ i.e. index $D_{R(v/c,LT)}$ between scenarios S_02 and S_03 is significantly lower, since the traffic at the intersection in scenario S_03 occurs under the above-intersection-capacity conditions.

The reduction in the number of traffic lanes for the straight-moving vehicles by 50% between scenarios S_01 and S_04, results in the reduction of the value of index $D_{A(LT,v/c)}$ by 59.87%, that is, of index $D_{R(v/c,LT)}$ by 42.86%. This shows that even in the case of reducing (changing) the number of traffic lanes the change of the mentioned indices will fail to be proportional to that change. This phenomenon proves once again that the traffic flow is of stochastic nature and that its change of state cannot be fully described by mathematical formulae. The values of the mentioned indices in scenarios S_05 and S_06 assume negative values, which yet again confirms that the traffic flows at the intersection under the indicated conditions of the vehicle-to-capacity ratio can be described exclusively mathematically, whereas these are not possible under the actual conditions of traffic flows.

Based on the analyses carried out and described in this chapter, the relation between the two-phase and the four-phase control mode of the signal-controlled intersection is presented in *Graph 17*. The arms of the graph represent a certain value of the cycle duration length from C=40 seconds to C=140 seconds. The concentric lines that connect these graph arms represent the value of the vehicle-to-capacity ratio v/c.

The orange (two-phase) and the reddish (four-phase) marked areas of the graph represent the recommended cycle duration[2] for a certain mode (two-phase or four-phase) of controlling the signal-controlled intersection. The light-green area of the graph represents an acceptable value of the vehicle-to-capacity ratio in the interval from 0 to 1.

The lines that connect the graph arms represent the movements of the values of the vehicle-to-capacity ratio in scenarios that describe the two-phase control mode, S_01, S_02 and S_03, that is, the movement of the value of the vehicle-to-capacity ratio in scenarios S_01_4F, S_02_4F and S_03_4F that describe the four-phase traffic light control mode at intersections.

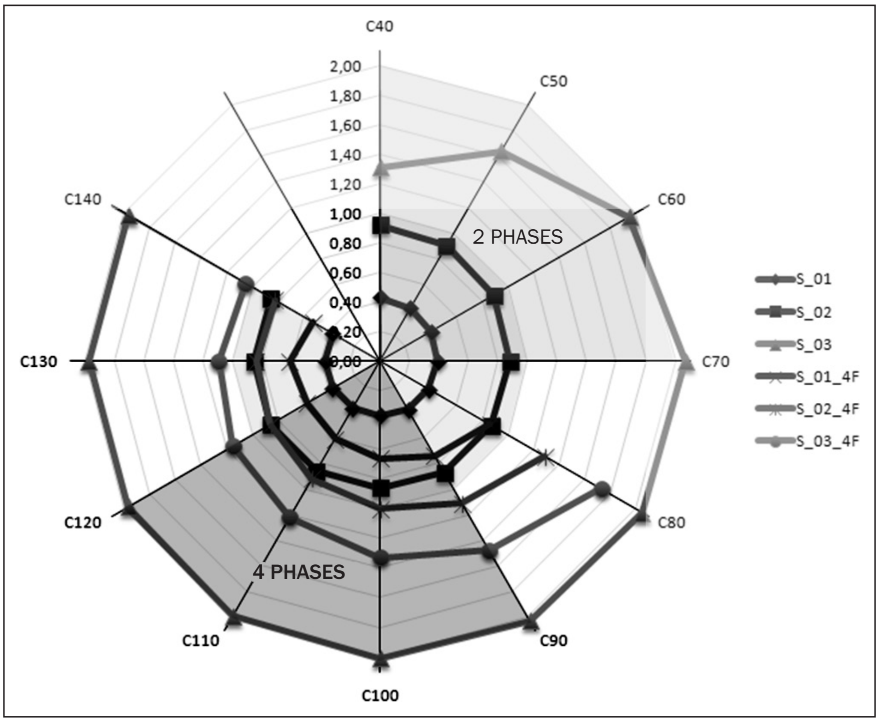
Regarding the method of presenting the information in *Graph 17*, the methodology of its interpretation is simple – the closer the studied value of the vehicle-to-capacity ratio to the central point of the graph for a certain cycle duration, the vehicle-to-capacity ratio in whose area it is located represents the “engineering” higher-quality, i.e. optimal solution.

The method of graphical presentation of the movement of the vehicle-to-capacity ratio value in different scenarios presented by *Graph 17* also allows their easy comparison, as well as a clear presentation of how an equal level of vehicle volume increase causes a much greater increase in the vehicle-to-capacity ratio in the two-phase than in the four-phase traffic light control mode at intersections. The mentioned increase is clearly seen in the distance between the lines that connect the values of the vehicle-to-capacity ratio for different cycle durations. The example of *Graph 17* clearly shows that the distances between the lines that connect the vehicle-to-capacity ratio values in the scenarios with the two-phase control mode are larger than between the lines that connect the values of the vehicle-to-capacity ratio in the scenarios with the four-phase traffic light control mode at intersections.

These facts prove the thesis that the two-phase traffic light control mode represents an optimal solu-

Table 5 - Changes of indices of absolute and relative distance for four-phase intersection control mode

	S_01_4F	S_02_4F	S_03_4F	S_04_4F	S_05_4F	S_06_4F
$D_{A(LT,v/c)}$	0.33	-0.27	-0.30	-0.31	-0.20	-0.13
$D_{R(v/c,LT)}$	0.08	0.02	0.00	0.00	-0.01	0.00



Graph 17 - Comparison of the movement of values of vehicle-to-capacity ratio (v/c) in two-phase and four-phase control mode

tion in cases of below-intersection-capacity, that is, that the four-phase control mode has proven to be an optimal solution under the traffic flow conditions at and above-intersection capacity.

The mentioned graphical presentation of the movement of the values of the vehicle-to-capacity ratio for different values of the cycle duration, allows not only the presentation of the values of the vehicle-to-capacity ratio presented in the paper, but rather allows a general presentation and determination of the optimal solution for the traffic light control at intersections. According to the indicated facts and the past absence of such a method of presentation in the relevant literature, this type of graphical presentation of the indicated values along with the proven hypothesis expressed at the beginning of the paper, represents a direct scientific contribution in the area of technical sciences, field of technology and transport.

4. CONCLUSION

The basic aim of this paper lies in the study of the observed basic values of the traffic flow that describe the movement of vehicles along a segregated area of an intersection in urban environment. The analysis of the indicated values was used in an attempt to confirm the set hypothesis about the possibility of determining their interconnection regarding the set traffic and technological conditions, description of their interrelations and interactions, and finally their analysis in order to achieve the optimal solution regarding the given criterion.

A hundred and eight intersection models were used to show that a seemingly simple road traffic system represents an extremely complex unit, whose behaviour cannot be predicted in advance. This conclusion has resulted from the model analyses that have been based on a controlled change of the following four factors:

- vehicle volumes,
- traffic area capacity (number of traffic lanes),
- cycle durations,
- number of phases within the cycle.

Based on the presented factors, additional analyses have been carried out on the output values of the model, which represent the basic traffic values of the road traffic system:

- vehicle-to-capacity ratio - v/c, and
- lost time - LT.

The indicated values are not the only ones, but they do represent the two most significant values that describe the manner of traffic flows at signal-controlled intersections. Although both are used by the traffic experts for searching for an optimal solution, they are interesting because the vehicle-to-capacity ratio represents exclusively a technical value that is not subject to direct perception of road traffic participants. On the other hand, the lost time represents a value that is directly felt by all the road traffic participants as time they have to spend waiting in order to leave the observed intersections or a certain section of the road traffic network.

The analysis of the movement of the value of the vehicle-to-capacity ratio and the lost time resulted in the knowledge about the connection method between the indicated two values. Their connection depends on the number of phases within the cycle and the cycle duration. In the two-phase control mode of the traffic lights, with the increase in the cycle duration, the vehicle-to-capacity ratio value falls. On the contrary, under the same conditions the value of the lost time increases. In the four-phase traffic light control mode, the increase in the cycle duration results in the fall of both values.

In order to prove the given hypothesis, two indices have been introduced: the index of absolute distance $D_{A(LT,v/c)}$ and the index of relative distance $D_{R(v/c,LT)}$, with the aim of quantifying the levels of change of the vehicle-to-capacity ratio and the lost time, regarding the set traffic and technological conditions.

Based on the movement of the absolute and relative change in the values of the vehicle-to-capacity ratio and the lost time, their graphical presentation as well as the given indices, the methodology has been presented that, without using mathematical calculations, can determine the optimal cycle duration for the overall intersection, or regarding the choice of the right-of-way lane.

The performed analyses have also proven that the two-phase traffic light control mode represents an optimal solution in cases of below-intersection-capacity, i.e. few left-turning vehicles. The four-phase control mode has proven to be the optimal solution under the conditions of traffic flow at and above-intersection-capacity, that is, when there are many left-turning vehicles.

The analysis of various models, in the controlled laboratory environment, has proven that any change within such a system never has any mathematically predictable effects on the monitored values of the traffic flow, regardless of the uniform increase in the value of the model parameters.

Every road traffic system represents in the reality an isolated case with characteristic traffic and technological conditions and safety requirements in which the traffic flows occur. Therefore, the analyses, results and conclusions derived in the paper should only be considered within the framework of the models presented here, and should not be applied to other models without previous verification.

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SAŽETAK

OPTIMIZACIJA PROPUSNE MOĆI SEMAFORIZIRANIH RASKRIŽJA

Cestovni prometni sustav je složeni sustav koji objedinjuje kretanje entiteta u točno određenoj prostornoj i vremenskoj dimenziji. Svojim različitim svojstvima svaki od entiteta postavlja različite zahtjeve prema cestovnom prometnom sustavu, ali i ostalim entitetima. Zbog velikog broja entiteta i njima svojstvenih zahtjeva, njihovim međudjelovanjem nastaju izrazito složeni odnosi koji određuju ponašanje cestovnog prometnog sustava. Entiteti se prema svojim zajedničkim osobinama povezuju u određene grupe, čijim kretanjima vrlo često nastaju konflikti. U takvim situacijama nužno je osiguravanje kretanja određene grupe entiteta. Takav način osiguravanja nužno stvara negativne posljedice za sve entitete koji sudjeluju u cestovnom prometnom sustavu. Kako bi se te posljedice što više ublažile, nužno je pronaći odgovarajući način optimizacije cestovnoga prometnog sustava prema zadanom kriteriju. U članku je na temelju rezultata analize više od 100 modela cestovnog prometnog sustava, prikazana metodologija određivanja stupnja njihove međusobne povezanosti.Pronađena je i opisana razina utjecaja osnovnih prometnih veličina na konačan učinak, odnosno mogućnost optimizacije semaforiziranog raskrižja.

KLJUČNE RIJEČI

prometni tok, semaforizirano raskrižje, vremenski ustaljeni proces, optimizacija, 2-fazni sustav, 4-fazni sustav, stupanj zasićenja, izgubljeno vrijeme

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