BULGARIAN ACADEMY OF SCIENCES
INSTITUTE OF INFORMATION AND
COMMUNICATION TECHNOLOGIES

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OPTIMIZATION OF TRAFFIC IN URBAN ENVIRONMENT

ABSTRACT OF PhD THESIS

Supervisor: **Prof. Todor Stoilov, DSc**

Sofia, 2020

The PhD thesis was discussed and allowed to be defended during an extended session of the Department of Distributed information and control systems at IICT-BAS, which had been held on 01.12.2020.

The full volume of the dissertation is 132 pages. It consists of an introduction and three chapters. The list of references contains 122 items. The text of the dissertation includes 11 tables and 37 figures.

The defense of the PhD thesis had been held on .... at .... in Room ………, Block ………, IICT-BAS.

Approved by Supervising Committee:

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Author: ***Yordanka Lyubomirova Boneva***

Title: **OPTIMIZATION OF TRAFFIC IN URBAN ENVIRONMENT**

INTRODUCTION

Actuality of the problem:

Actuality of the problem of optimizing the traffic in the urban environment globally is related to urban development. Actuality of problem regarding Bulgaria is related to the expansion of the capital, where more people are gathering, respectively there is greater need of cars and need of more effective and efficient traffic management. Traffic management in urban environments is performed mainly by traffic lights, which divide the flow of cars as well as pedestrians over time.

Object and field of research:

The object of research in the dissertation is a network of intersections regulated by traffic lights along Shipchenski Prohod Blvd. in Sofia. The field of research is traffic in urban environments.

Dissertation content:

Chapter 1 discusses basic concepts in traffic management, as well as various models of traffic management in an urban network. Basic concepts for the dissertation are defined, such as cycle duration, green signal duration as part of the cycle (green split), offset and others. An important part of the chapter is the traffic flow models, one of which uses the principle of store-and-forward, applied to define and solve the tasks in the dissertation.

Chapter 2 presents a bilevel optimization task for traffic management and optimization in urban environments. A previous study in the field of bilevel optimization for the purposes of traffic optimization is presented. The essence of the bilevel problem is also described.

Chapter 3 describes experiments conducted for modeling, simulation, optimization of urban traffic on a selected part of the urban transport network. Each experiment is briefly described in summary, the results of the respective study are presented and conclusions are drawn. More than 6 experiments for traffic optimization with different accents were performed: application of optimization with TRANSYT software product, application of results from two bilevel problems in Aimsun software product, assessment of traffic indicators in the performed simulations, assessment of fuel consumption and air pollutants, complicating the computer model by adding the effect of tram stops and parking and the street, etc.

Chapter 4 presents a comparison between the research and experiments performed in Chapter 3. Chapter 4 demonstrates the optimization of traffic on certain indicators. This chapter compares the results of bilevel optimization problems with the results of the simulation with real data and with the results of TRANSYT. As a result of the comparisons, the relevant conclusions were made.

The conclusion summarizes the main aspects of the dissertation.

The contributions of the dissertation work are defined, the future directions of work, the scientific publications on the dissertation are presented, as well as the research projects, on which the research on the dissertation work and the cited works has been done.

Aim and tasks of the dissertation:

The aim of the dissertation is to develop a formal model for solving a research problem for optimizing road traffic in an urban type of transport network.

The object of the study is a network of four connected intersections regulated by traffic lights, located on Shipchenski Prohod Boulevard in Sofia, Bulgaria.

The following tasks are set for solving in connection with the specification of the purpose of the dissertation:

- Development of a formal model of urban transport network.
- Development of a bilevel problem for management of a network of intersections;
- Defining and solving bilevel optimization problems;
- Building a computer model and simulations in the Aimsun software package;
- Testing of results without and with data from the solved optimization problem in Aimsun simulation environment;
- Evaluation of the obtained solutions by comparison with TRANSYT - a software product that is used worldwide for evaluation of management strategies in the field of road traffic.

Approbation of the results:

Some of the results included in the dissertation are presented at the following international conferences: Automatics and Informatics’2019 - Sofia., CompSysTech’20 - Ruse, TechSys 2020 - Plovdiv, etc.

List of publications on the dissertation

1. **Boneva Y.**, Split and Queue Optimization in Transport Network through Bi-level Optimization, CompSysTech '20: ACM International Conference Proceeding Series, Ruse, June 2020 г., ISBN: 978-1-4503-7768-3, Association for Computing Machinery (ACM), New York, USA, pp. 175-179, SJR(SCOPUS) 2019: 0,2, https://doi.org/10.1145/3407982.3407995, **Best**

paper award certificate

2. **Boneva Y.**, Cycle Length Optimization through Bi-level Optimization, 9TH International Scientific Conference "TechSys 2020" – Engineering, Technologies and Systems, Technical University of Sofia, Plovdiv Branch, 14-16 May 2020, IOP Conference Series: Materials Science and Engineering, ISSN:1757-8981E-ISSN:1757-899X, Volume 878, Published online: 21 July 2020, Published under license by IOP Publishing Ltd, ID: 012024, pp. 1-6, Paper OPEN ACCESS, SJR (SCOPUS) 2019: 0.2, https://doi.org/10.1088/1757-899X/878/1/012024, https://iopscience.iop.org/article/10.1088/1757-899X/878/1/012024/pdf
3. **Boneva Y.**, T. Stoilov, Simulation of Tram Stops and their Influence on Traffic – Case Study in Sofia, Bulgaria, Journal "Information Technologies and Control", Online Print ISSN 1312-2622, ISSN: 2367-5357, Issue 3, SAI, 2019, pp. 19-25, DOI: 10.7546/itc-2019-0013, http://www.aksyst.com:8081/Sai/Journal/Docum/Vol_3_03_2019.pdf
4. **Boneva Y.**, Fixed-Time Signal Timing Versus Actuated Control of Traffic Lights – Case Study of Shipchenski Prohod Blvd. in Sofia, Bulgaria, Proceedings for International Conference AUTOMATICS AND INFORMATICS'2019, 03-05 October 2019, ISSN 1313-1850, CD: ISSN 1313-1869, John Atanasoff Society of Automatics and Informatics, Sofia, Bulgaria, 2019, pp. 53 – 56.
5. **Boneva Y.**, Optimization of car traffic flow on intersections regulated by traffic lights through the simulation environment Aimsun, Journal Mechanics, Transport, Communications, ISSN 1312-3823 (print), ISSN 2367-6620 (online), vol. 16, issue 2, art. ID: 1663, Todor Kableshkov University of Transport, 2018.pp. I-1 – I-9, https://mtc-aj.com/library/1663.pdf

Citation:

Cited paper

Boneva Y., Optimization of car traffic flow on intersections regulated by traffic lights through the simulation environment Aimsun, Journal Mechanics, Transport, Communications, ISSN 1312-3823 (print), ISSN 2367-6620 (online), vol. 16, issue 2, art. ID: 1663, Todor Kableshkov University of Transport, 2018.pp. I-1 – I-9, https://mtc-aj.com/library/1663.pdf

Citing papers

1. Ilchev Svetozar, Rumen Andreev, Zlatoliliya Ilcheva, Ekaterina Otsetova-Dudin, Three-channel laser diode driver for multimedia laser projectors, International Journal of Circuits, Systems and

Signal Processing, ISSN: 1998-4464, Vol. 14, 2020, pp. 451-459, DOI: 10.46300/9106.2020.14.60, (SJR (SCOPUS) 2019: - 0.16, Q4)

2. Ilchev S, Andreev R, Ilcheva Z., Display of Computer-Generated Vector Data by a Laser Projector, CompSysTech '20: ACM International Conference Proceeding Series, Ruse, June 2020 г., ISBN: 978-1-4503-7768-3, Association for Computing Machinery (ACM), New York, USA, pp. 11-18, https://doi.org/10.1145/3407982.3407990, SJR (SCOPUS,) 2019: 0,2

Participation in projects:

1. Project: “Modelling and optimization of urban traffic in network of crossroads”, Contract: КП-06-Н37/6, 6.12.2019 of the Bulgarian National Science fund, Project coordinator: Prof. Krasimira Stoilova, D.Sc.

2. Project: “Contemporary digital methods and tools for exploring and modeling transport flows”, Contract: КП-06-М27/9, 17.12.2018, National Science Fund, Competition for financing of scientific researches of young scientists – 2018, Project coordinator: Assistant professor Vladimir Ivanov, Ph.D.

Chapter 1

TRAFFIC CONTROL MODELS

Regulation of intersections by traffic lights is one of the most effective and flexible ways to control traffic. Emerging conflicts from the movement of traffic in different directions is resolved by the principle of separation of flows over time. The advantages of regulation by traffic lights include the increased capacity of intersections and requires a simple geometric design (Teodorovic and Janic, 2017).

The city crossroads consists of a set of approaches and a common crossing area - a crossroads. The approach is part of a street consisting of one or more lanes. An approach is leading to the common intersection area of the intersection, so that the traffic on it has an advantage (r.o.w. - right of way) at the same time and a vehicle in the respective queue can expect to pass during the signal at approximately the same time, whatever band you choose. Crossroads traffic is divided into streams. Two streams are called compatible when they can safely cross the intersection at the same time; otherwise, they are called incompatible or conflicting. The signal cycle is a repetition of the main series of combinations of signals at an intersection. Its duration is called the cycle length or simply a cycle. A stage (or phase) is part of a cycle during which a set of flows takes turn. Constant lost times of several seconds are located between stages to avoid conflict between incompatible flows in successive stages (Diakaki et al., 2002).

Cycle Length

Figure 1.3.e shows the duration of the traffic light cycle (Mathew, 2014).

Fig. 1.3. Cycle length

Green split

Part of the green signal from the cycle is the distribution of the effective green time in each of the phases.

Store-and-forward model

The store-and-forward model was initially proposed by Gazis to represent the state of traffic at congested intersections and has since been used in various traffic management papers. (Gazis, (1964), Papageorgiou, (1995)). The concept is adopted from the theory of communication networks.

Link z is presented, which connects two intersections i - 1 and i (figure 1.4.), The traffic dynamics of link z is given by the conservation equation (equation 1.22.), (Aboudolas et al., 2009). The queues are represented by Equation 2-8. During periods of heavy traffic, this restriction can automatically lead to an appropriate accumulation of cars in a link in order to protect the following areas of congestion. The inflow of cars to link z is represented by equation 1.23.

$$xz(k+1) = xz(k) + T[qz(k) - sz(k) + dz(k) - uz(k)] \qquad (1.22)$$

$$0 \le xz(k) \le xz, max$$

$$q_z(k)= t_i,z_{ui}(k) \qquad (1.23)$$

where: T is discreet time step

k = 0, 1, …., discreet time index

$x_z(k)$ = vehicles in link z during period kT

$q_z(k)$, $u_z(k)$ = the inflow and outflow from link z during the period [kT, (k+1)T]

$d_z(k)$, $s_z(k)$ = the intensity of the arriving, respectively the intensity of the cars leaving the link z

x_z, max = the maximum permissible length of the queue, in number of vehicles

$t_{i,z}$ = ratio of turns to link z entering junction *i*

In Figure 1.4. an example of the store-and-forward model is shown (Liu, 2015).

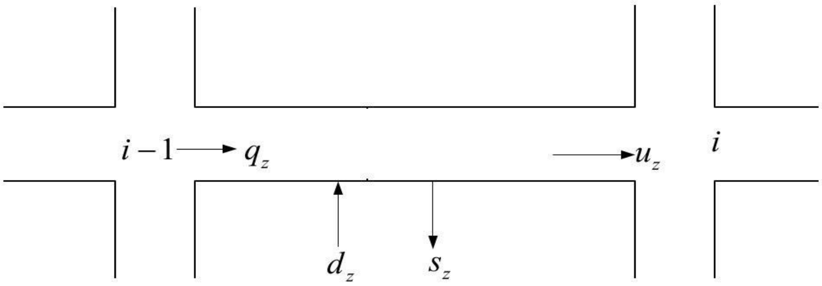


Fig. 1.4. Store-and-Forward model

Conclusion

In the first chapter an overview of some significant concepts and theoretical formulations in the field of urban traffic was made, which would lay the groundwork for further consideration of the topic. In this regard, the concepts related to regulation by traffic lights are clarified. The mathematical basis of the regulation by traffic lights is described, which is important for the definition of the optimization problems in the dissertation.

The store-and-forward model is considered, which is the basis for the formulation of a traffic model and the solution of an optimization problem for a selected network of intersections.

Chapter 2

ANALYSIS OF HIERARCHIC OPTIMIZATION TASKS AND MODELS

Bilevel Optimization

The idea of a bilevel management strategy refers to solving two optimization problems that are interrelated (Fig. 2.2), (Stoilova and Stoilov. 2020).

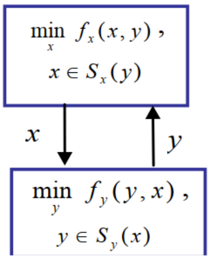


Fig. 2.2. Bilevel optimization

The problem at the upper level accepts the values of y = y * as known parameters and finds the optimal solution x * (y) by solving the problem

$$f_x(x, y^*), \qquad (2.11)$$
$$x \in S_x(y^*).$$

The solution x * (y) is a function of the parameter y. Accordingly, the problem with the lower level accepts x = x * as known parameters and finds a solution y * (x) as a function of x.

These two interrelated optimization problems provide a solution to the global problem.

$$f_x(x, y), \qquad (2.12)$$
$$x \in S_x(y),$$
$$y \in arg\{f_y(y, x) \in S_y(x)\}$$

which means that xopt is the solution of the optimization problem, where y changes the basic function fx (x, y) and the allowable domain Sx (y). Also, y is a solution of the low-level problem, which in turn is influenced by x. For the classical case of optimization, the objective function is only one - fx (x).

Conclusion

The second chapter discusses the achievements in the field of defining and solving bilevel optimization problems in the field of optimization of urban traffic in a network of intersections.

The formulation of a bilevel optimization problem is presented. The same formal statement was presented in the context of car traffic in urban environments, i.e., junctions controlled by traffic lights. This is important from the point of view of laying the foundation for the defined and solved bilevel problems in the same field of application in the present dissertation.

Chapter 3

DEVELOPMENT OF HIERARCHIC MODELS FOR OPTIMIZATION OF TRANSPORT TRAFFIC

Used software packages for traffic modeling and optimization

The dissertation uses three software packages - Aimsun, TRANSYT 15 and MATLAB. Aimsun and TRANSYT 15 are specialized packages for simulating and optimizing car traffic (Aimsun, (2013), Binning, (2015)). MATLAB was used for mathematical simulation of the considered group of intersections, as queues were described based on a store-and-forward model and bilevel optimization was applied. The results obtained by MATLAB for cycle duration and for green split were entered in Aimsun to check their validity.

Aimsun (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks), (Aimsun, 2013). It is able to reproduce the real features of the traffic of each network transport. It is used for the design and testing of traffic control systems, traffic management rules, access controls, location of toll devices, public transport networks, roads, the ability to work with traffic management systems tools and other real-time applications.

The software environment for optimization of fixed time signal plans - TRANSYT 15 has also been applied in the research on the task of optimizing traffic in urban environments.

The operation model of TRANSYT 15 is presented in Figure 3.1. (Binning, 2015). The software calculates and optimizes a target, a function called Performance Index, part of which is the time delay and the number of car stops, the goal is to keep these two indicators to a minimum for the network so that a "green wave" is formed. In a green wave, the plateau of cars from a previous traffic light reaches the traffic light at the next intersection on a green signal and this can happen for several consecutive intersections.

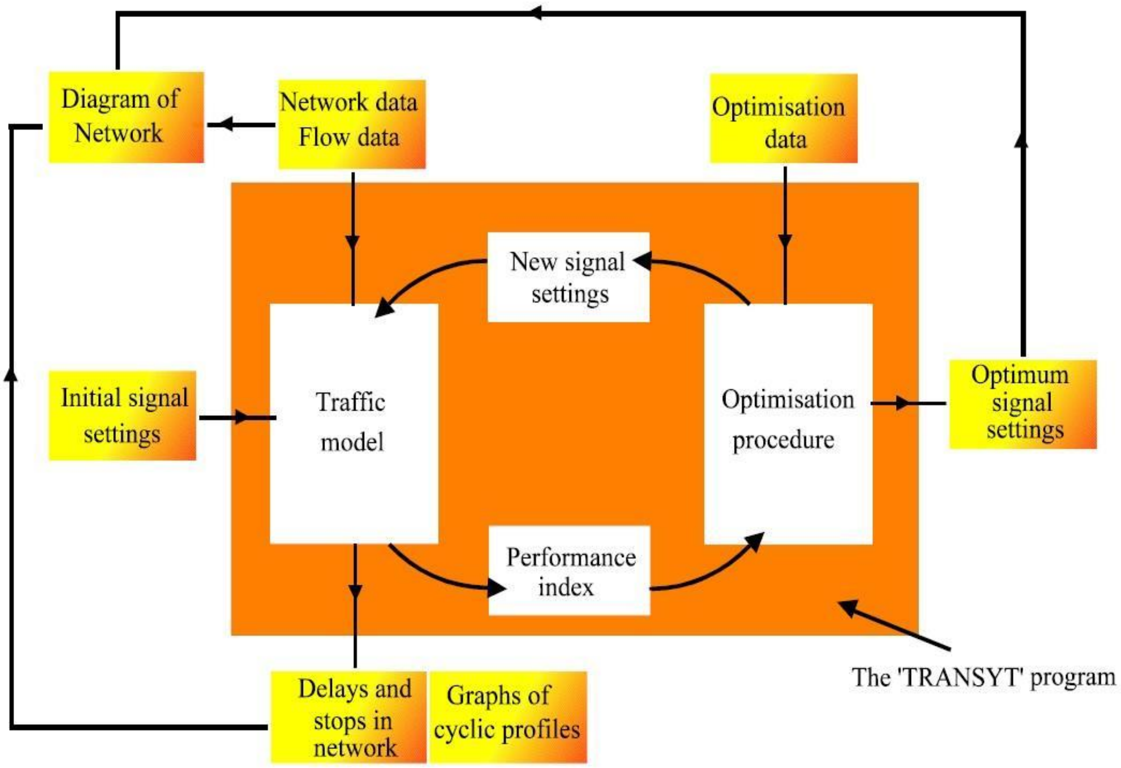


Fig. 3.1. TRANSYT 15 optimization procedure

The processes described in the darker part of Figure 3.1 take place in the TRANSYT environment. Processes marked in bright rectangles are in another software package. In the case of research, this is the Aimsun software package.

Initially, a model of the transport network was created in the Aimsun package, where the initial settings of the light signaling were introduced. The created transport network is exported to TRANSYT 15. The initial Performance Index is calculated and the first iteration of an optimization procedure for reducing this Performance Index is performed. This optimization procedure leads to new traffic light settings, which are introduced in the initial model and thus the circle is closed and begins with a new iteration of Performance Index calculation, optimization, new traffic light settings and their introduction into the traffic model. The software offers the "Hill Climb" method as an optimization method.

A special program script must be written for use in a bilevel problem. The problem with bilevel optimization is solved in MATLAB environment. A special additional tool for solving bilevel tasks is included in MATLAB. The additional tool is called YALMIP. YALMIP is a free tool (https://yalmip.github.io/). A detailed description of this tool is given in (Lofberg, 2004).

Object of the simulation

In Figure 3.2. a view of the city network of four intersections taken from Google Maps is shown. It shows the names of some streets, shops and other sites and gives the overall impression of a dense population in terms of buildings.

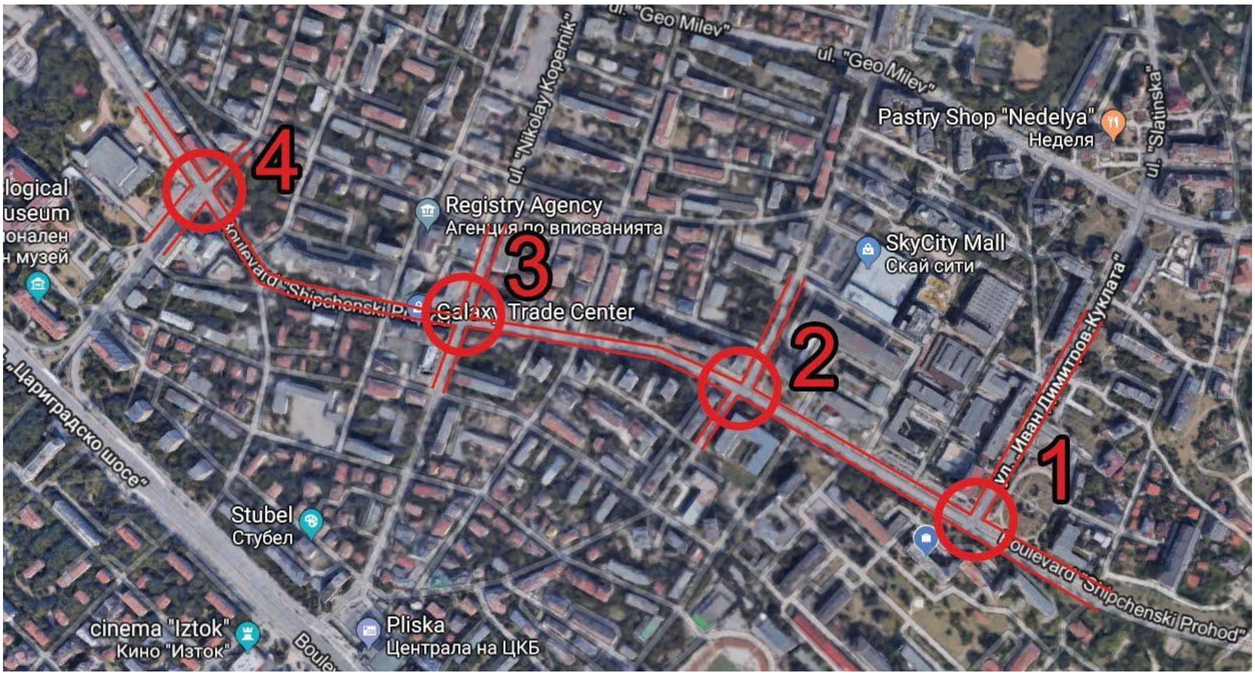


Fig. 3.2. Image of the four connected intersections from Google Maps

In Figure 3.3. four connected traffic-light-controlled junctions modeled in the Aimsun software environment are shown. The intersections are located along Shipchenski Prohod Blvd. in the city of Sofia. The intersections are located at a relatively short distance from each other, which is a good prerequisite for reaching a green wave. The total length of the considered section is 1.5 km.

Fig. 3.3. Four connected traffic-light-controlled intersections in Aimsun

There are many points of interest (POI) in the area under consideration, such as offices, shopping malls, schools, kindergartens, a polyclinic and others. These points of interest are places that attract people for certain reasons. Traffic is generated in these places, both by the local population and by people from other parts of the city.

During the on-site study of the investigated section in some parts of it, overload conditions were established - queues that cannot pass completely during the green signal from the traffic light cycle and accordingly form a residual queue, which occupies part of the green time of the next cycle to pass through the intersection.

The capacity of the intersection can be exceeded, both in terms of time and space. In terms of time, congestion is observed when the duration of the green signal is not enough to pass all cars that arrived at the traffic light during the red signal, i.e., a residual queue is formed. With regard to the spatial aspect, there is talk of congestion if the queue of cars reaches the previous intersection and thus part of the green signal remains unused again, due to the inability of cars from the previous intersection to pass through it. While temporal congestion can affect an isolated intersection, spatial congestion is a sign of degradation in the network of intersections. A detailed description of the methodology for determining an oversaturated intersection by collecting information from sensors can be found in (Wu and Liu, 2010), which methodology aims to determine the severity of congestion.

Conducted experiments

Figure 3.4. presents experiments conducted in connection with the dissertation. Each of these experiments will be described in detail.

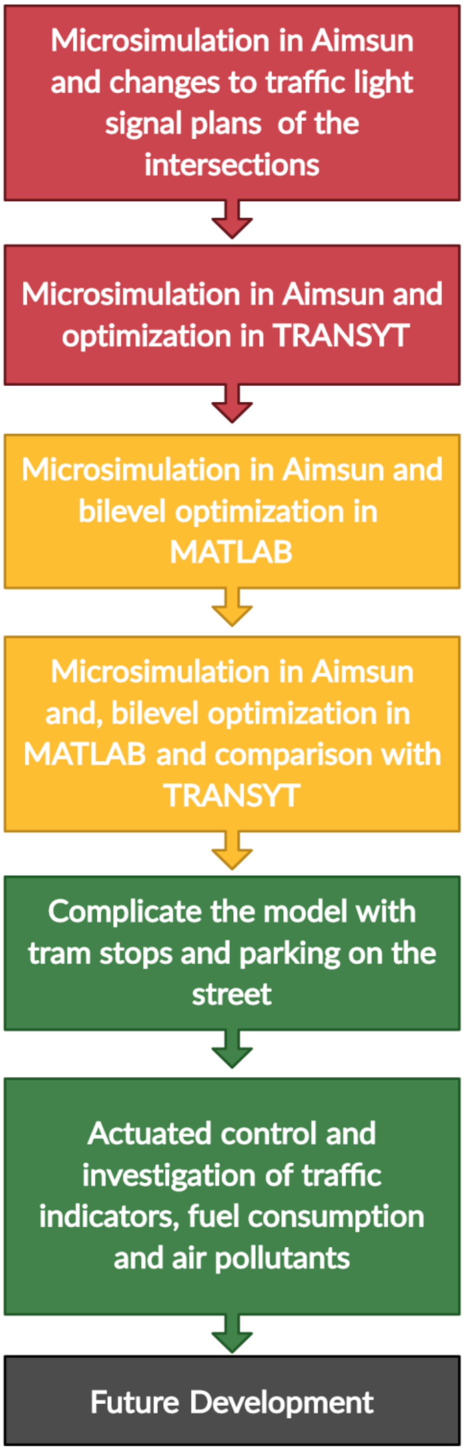


Fig. 3.4. Review of the conducted experiments

The initial experiments put more emphasis on the use of software products, their study and application - these experiments are marked in red on the graph (first and second rectangles). The following are the most significant experiments for the dissertation work, which carry the most significant part of the applied and scientific-applied contribution. These experiments use bilevel optimization and the solvebilevel() function in MATLAB and test the results obtained for traffic light control in specialized software environments for traffic simulation and optimization - in the figure they are marked in yellow (third and fourth rectangles). They are followed by experiments to complicate the model used and bring it closer to real conditions by introducing tram stops and parking on the street (fifth rectangle). Finally, there are experiments for flexible traffic management, which are done entirely in Aimusn. In addition to the good traffic indicators that these studies lead to, the aspects of fuel consumption and environmental pollution are also considered. (sixth rectangle). The directions for future development (seventh rectangle) are presented in the section "Future development", located at the end of the dissertation.

Optimization of car traffic at traffic-light-controlled intersections by means of Aimsun simulation environment

Summary of the experiment

The presented experiment examines the possibility of improving traffic along Shipchenski Prohod Blvd. Dynamic microsimulation is performed. The green signal settings for the traffic lights on the boulevard and the small streets crossing the boulevard are changing. The hypothesis is that there are traffic light settings that are better than the actual ones, which will improve the performance of traffic on the boulevard and can be determined by simulation.

This study is performed solely through the use of the Aimsun simulation software product. Ten traffic indicators were compared for a network of four intersections on Shipchenski Prohod Blvd., for different settings of the green signal for the traffic lights on the boulevard and for the traffic lights on the small streets.

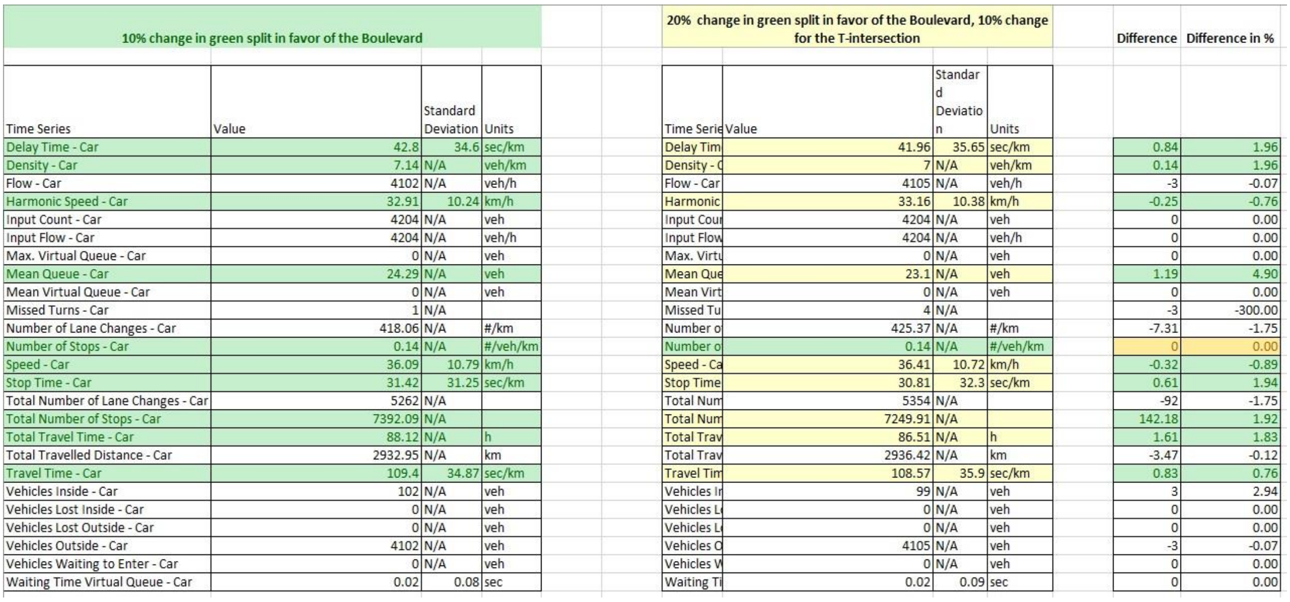
The results prove the hypothesis that there are better settings of traffic lights in order to improve the ten selected traffic indicators for the network of intersections, which settings were found experimentally by simulation. Four cases of traffic light settings are considered.

Base Case Scenario			10% change in green split			20% change in green split			20% change и 10% change only for T-intersection		
8744			8744			8744			8744		
	Start Time	Duration		Start Time	Duration		Start Time	Duration		Start Time	Duration
Signal 1	0	30	Signal 1	0	33	Signal 1	0	36	Signal 1	0	33
Signal 2	0	30	Signal 2	0	33	Signal 2	0	36	Signal 2	0	33
Signal 3	36	30	Signal 3	39	27	Signal 3	42	24	Signal 3	39	27
8778			8778			8778			8778		
	Start Time	Duration		Start Time	Duration		Start Time	Duration		Start Time	Duration
Signal 1	0	20	Signal 1	0	23	Signal 1	0	26	Signal 1	0	26
Signal 2	26	25	Signal 2	29	22	Signal 2	32	19	Signal 2	32	19
Signal 3	0	22	Signal 3	0	25	Signal 3	0	28	Signal 3	0	28
Signal 4	26	24	Signal 4	29	22	Signal 4	32	19	Signal 4	32	19
8845			8845			8845			8845		
	Start Time	Duration		Start Time	Duration		Start Time	Duration		Start Time	Duration
Signal 1	0	24	Signal 1	0	26	Signal 1	0	29	Signal 1	0	29
Signal 2	0	25	Signal 2	0	27	Signal 2	0	30	Signal 2	0	30
Signal 3	29	23	Signal 3	31	21	Signal 3	34	18	Signal 3	34	18
Signal 4	29	23	Signal 4	31	21	Signal 4	34	18	Signal 4	34	18
14175			14175			14175			14175		
	Start Time	Duration		Start Time	Duration		Start Time	Duration		Start Time	Duration
Signal 1	0	25	Signal 1	0	28	Signal 1	0	31	Signal 1	0	31
Signal 2	0	17	Signal 2	0	20	Signal 2	0	23	Signal 2	0	23
Signal 3	29	28	Signal 3	32	25	Signal 3	35	22	Signal 3	35	22
Signal 4	29	16	Signal 4	32	14	Signal 4	35	11	Signal 4	35	11

*The signals in yellow has been changed

Fig.3.7. Adjustment of traffic lights for different cases

In Figure 3.11. is illustrated by comparing between the second and fourth cases from the total of four cases considered in the experiment.



10% change in green split in favor of the Boulevard				20% change in green split in favor of the Boulevard, 10% change for the T-intersection				Difference	Difference in %
Time Series	Value	Standard Deviation	Units	Time Serie	Value	Standard Deviation	Units		
Delay Time - Car	42.8	34.6	sec/km	Delay Tim	41.96	35.65	sec/km	0.84	1.96
Density - Car	7.14	N/A	veh/km	Density - C	7	N/A	veh/km	0.14	1.96
Flow - Car	4102	N/A	veh/h	Flow - Car	4105	N/A	veh/h	-3	-0.07
Harmonic Speed - Car	32.91	10.24	km/h	Harmonic	33.16	10.38	km/h	-0.25	-0.76
Input Count - Car	4204	N/A	veh	Input Cou	4204	N/A	veh	0	0.00
Input Flow - Car	4204	N/A	veh/h	Input Flow	4204	N/A	veh/h	0	0.00
Max. Virtual Queue - Car	0	N/A	veh	Max. Virtu	0	N/A	veh	0	0.00
Mean Queue - Car	24.29	N/A	veh	Mean Que	23.1	N/A	veh	1.19	4.90
Mean Virtual Queue - Car	0	N/A	veh	Mean Virt	0	N/A	veh	0	0.00
Missed Turns - Car	1	N/A		Missed Tu	4	N/A		-3	-300.00
Number of Lane Changes - Car	418.06	N/A	#/km	Number o	425.37	N/A	#/km	-7.31	-1.75
Number of Stops - Car	0.14	N/A	#/veh/km	Number o	0.14	N/A	#/veh/km	0	0.00
Speed - Car	36.09	10.79	km/h	Speed - Ca	36.41	10.72	km/h	-0.32	-0.89
Stop Time - Car	31.42	31.25	sec/km	Stop Time	30.81	32.3	sec/km	0.61	1.94
Total Number of Lane Changes - Car	5262	N/A		Total Num	5354	N/A		-92	-1.75
Total Number of Stops - Car	7392.09	N/A		Total Num	7249.91	N/A		142.18	1.92
Total Travel Time - Car	88.12	N/A	h	Total Trav	86.51	N/A	h	1.61	1.83
Total Travelled Distance - Car	2932.95	N/A	km	Total Trav	2936.42	N/A	km	-3.47	-0.12
Travel Time - Car	109.4	34.87	sec/km	Travel Tim	108.57	35.9	sec/km	0.83	0.76
Vehicles Inside - Car	102	N/A	veh	Vehicles Ir	99	N/A	veh	3	2.94
Vehicles Lost Inside - Car	0	N/A	veh	Vehicles L	0	N/A	veh	0	0.00
Vehicles Lost Outside - Car	0	N/A	veh	Vehicles L	0	N/A	veh	0	0.00
Vehicles Outside - Car	4102	N/A	veh	Vehicles O	4105	N/A	veh	-3	-0.07
Vehicles Waiting to Enter - Car	0	N/A	veh	Vehicles W	0	N/A	veh	0	0.00
Waiting Time Virtual Queue - Car	0.02	0.08	sec	Waiting Ti	0.02	0.09	sec	0	0.00

Fig. 3.11. Case 2 and Case 4 comparison - Comparison between 10% change of green signal for all intersections and the case of 20% change for all intersections and only 10% for T-intersection

Conclusions from the experiment

Simulating the parameters of the traffic lights saves time and money and makes possible simulations that in real conditions could lead to traffic difficulties, traffic jams, pollution and driver dissatisfaction.

In this chapter, ten traffic indicators were considered. It is clear from the research that sometimes it is necessary to consider the intersection separately within the general model. With this result, the hypothesis was proved that in an empirical way and through computer simulation better settings of the traffic lights can be found than the actual ones.

Improving traffic in urban environments by optimizing traffic lights

Summary of the experiment

This experiment presents the object of study, which is modeled in the Aimsun software environment, then optimized in the TRANSYT software environment and exported back to Aimsun to validate the results. The experiment consists in optimization of the green signal and offset of traffic-light-regulated intersections, which leads to the improvement of eleven selected traffic indicators.

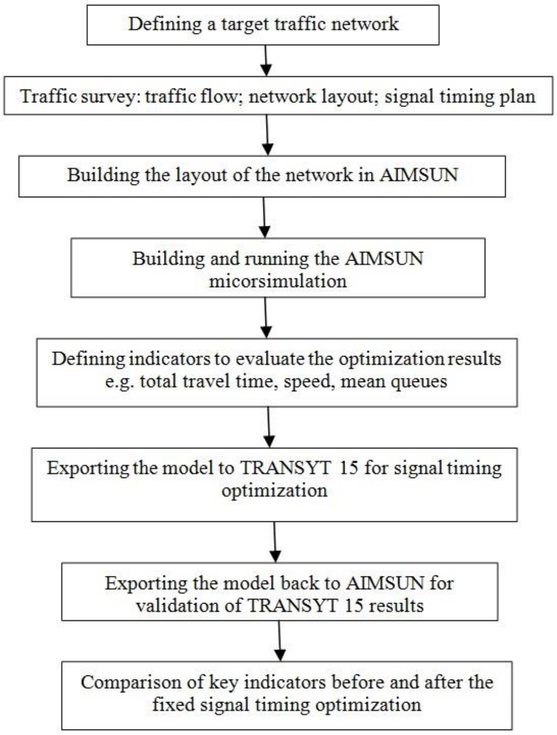


Fig. 3.12. Research workflow

There are improvements in all studied indicators after the optimization with TRANSYT (Table 3.1)

Table 3.1. Traffic indicators "before" and "after" optimization in TRANSYT

Traffic indicators		**Before optimization in TRANSYT**		**After optimization in TRANSYT**			
	Units	**Value**	**Standard Deviation**	**Value**	**Standard Deviation**	**Difference**	**Difference in %**
Delay	sec/km	51.16	40.3	36.33	35.88	-14.83	-28.99%
Density	veh/km	7.69	N/A	6.53	N/A	-1.16	-15.08%
Flow	veh/h	4095	N/A	4126	N/A	31	0.76%
Harmonic Speed	km/h	30.57	10.61	34.97	10.66	4.4	14.39%
Queue	veh	29.85	N/A	19.08	N/A	-10.77	-36.08%
Number of stops	#/veh/km	0.16	N/A	0.12	N/A	-0.04	-25.00%
Speed	km/h	34.25	11.56	38.21	10.37	3.96	11.56%
Stop time	sec/km	38.42	35.17	26.34	32.84	-12.08	-31.44%
Total number of stops		8322.87	N/A	6367.76	N/A	-1955.11	-23.49%
Total travel time	h	94.76	N/A	81.2	N/A	-13.56	-14.31%
Travel time - car	sec/km	117.76	40.53	102.96	35.96	-14.8	-12.57%

Conclusions from the experiment

Optimization improvement is measured by eleven traffic indicators such as queues, speed, travel time, and more. Two cases were compared - before optimization and after optimization of traffic light signals with TRANSYT. The results show that after the optimization the traffic indicators have significantly improved, as some of the indicators reach an improvement of over 30 percent compared to the case before the optimization.

Optimization of the green split and the queues in the transport network through bilevel optimization

Summary of the experiment

This section describes the use of bilevel optimization, as well as the well-known store-and-forward approach to optimizing the transport network.

The need for traffic lights and the need to control them optimally have led to many studies and the invention of different approaches. The approach proposed here is based on the popular store-and-forward model. The added value of this study is that the store-and-forward model is formalized in the problem of optimizing a bilevel task. In this way, the additional parameters of the transport system are evaluated with optimal values. This study, through the application of bilevel optimization, finds the optimal duration of green splits as a value from the traffic light cycle. In addition, vehicle queues have been kept to a minimum, but the intensity of traffic through the city network has been increased. Due to its potential advantages, bilevel optimization is used in practical areas such as portfolio optimization, optimization of railway plans, etc., (Pavlova, (2017), Stoilov et al. (2016), Stoilov and Stoilova, (2012)). This study makes a formal development of a bilevel transport model. It is demonstrated how this problem can be solved with appropriate software tools.

This study makes a composition of the store-and-forward model with an additional optimization problem, which is aimed at maximizing the flow of traffic crossing the transport network. The composition of these two problems is integrated into a two-hierarchical formal optimization model.

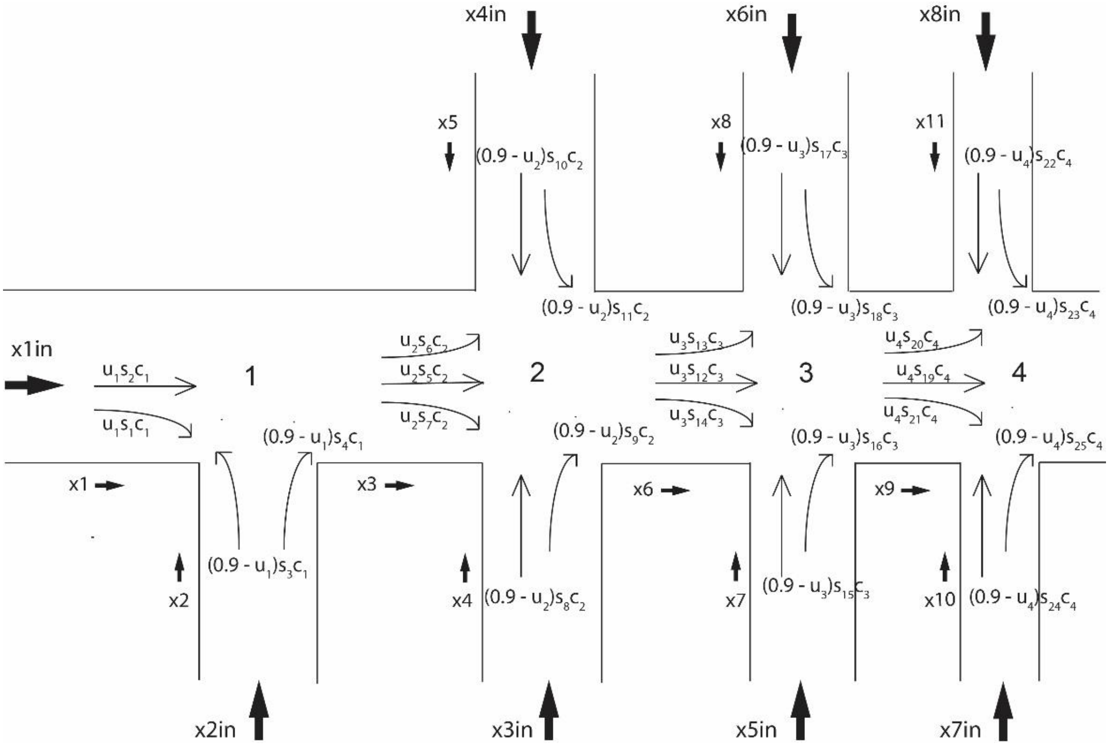


Fig. 3.17. Graphic model of the modeled urban network

The model shown in Figure 3.17. has been used as a constraint on the lower objective function, which aims to minimize queues at traffic lights. The designations of the figure are as follows:

ci - is the duration of the cycle

ui - indicates what part of the cycle is the green split

si - is saturation flow, which is cars per hour that pass in a given direction.

x1in - x8in - are cars entering the hour for the given approach (street)

x1 - x11 - are queues in front of traffic lights, measured in cars for one traffic light cycle

The aim is to minimize the queues in front of the traffic lights, the sum of all queues of x1 + x2 + ... + x11 should be minimal, which is represented by the objective function.

The formula by which the queue in front of a traffic light is calculated is the following for x1 and it is analogous for all queues in Figure 3.17.

x1 <= x10 + x1in - u1 * s2 * c1 - u1 * s1 * c1

The queue is equal to the cars from the previous time period at the traffic light x10, plus the cars that arrive at the traffic light for a given period of time x1in, minus the cars that pass through the intersection during the green signal in the right direction (u1 * s2 * c1) and turning cars (u1 * s1 * c1). The calculation of queues in this way is based on the store-and-forward model used.

The need to minimize the cycle stems from a study that a shorter traffic light cycle in an urban environment leads to better results (https://nacto.org/). The duration of the cycle is defined by law (Ordinance № 17, 2001) within certain limits - for minimum and maximum duration.

In Table 3.2. a comparison of the results of the simulations with a fixed time plan and with bilevel optimization is made.

Table 3.2. Comparison of simulation results

	Current Fixed time plans	*Bi-level optimization results*	
Time Series	Value	Value	Units
Delay Time	51.16	37.23	sec/km
Density	7.69	6.67	veh/km
Flow	4095	4126	veh/h
Fuel Consumption	355.53	300.6	l
Emission - CO2	874077.52	775912.65	g
Emission - NOx	1835.5	1658.83	g
Emission - PM	340.52	274.26	g
Emission - VOC	1131.69	980.42	g
Mean Queue	29.85	21.17	veh
Number of Stops	0.16	0.12	#/veh/km
Speed	34.25	38.98	km/h
Stop Time	38.42	27.73	sec/km
Total Number of Stops	8322.87	6069.72	
Total Travel Time	94.76	82.9	h
Travel Timer	117.76	103.86	sec/km

Conclusions from the experiment

This study develops a new formal model for controlling traffic flows in an urban environment. The problem of bilevel optimization is defined and solved. Defining a bilevel problem allows the use of two objective functions, to expand the control space of the transport task and to include a larger set of constraints.

The results of the bilevel optimization were evaluated and compared in a simulation environment with the currently established fixed plan. The network has been chosen as an important destination in the city of Sofia. The results of the bilevel optimization are compared with a set of traffic parameters. Obviously, the bilevel formalism in transport systems has great potential. All studied transport parameters give preference to the bilevel transport model.

Cycle length optimization through bilevel optimization

Summary of the experiment

This experiment describes the formalization of the store-and-forward model into a bilevel optimization problem. The study finds the optimal cycle length for given green spit durations. Queues in front of traffic lights are kept to a minimum. In this way, the network allows greater throughput and less congestion as a result less pollution and better traffic performance such as density, speed and more.

The results for traffic and pollution indicators are obtained from the Aimsun software product. The optimization is performed using a MATLAB script based on an additional tool called YALMIP, as well as with a modern software product TRANSYT, which is compatible with the Aismun software package. The results show that it is wise to use the traffic optimization script, as TRANSYT only optimizes the green signal duration, but works with the cycle value from Aimsun.

In Table 3.3. a comparison of simulation data from a baseline experiment (with actual data collected), an experiment with MATLAB results, and an experiment with TRANSYT results is given.

Table 3.3. Comparison of traffic indicators for three cases

Traffic Indicators	*Base Case*	*MATLAB script*	*TRANSYT Optimization*	*Units*
Delay Time	51.16	36.4	35.51	sec/km
Density	7.69	6.91	6.27	veh/km
Flow	4095	4107	4124	veh/h
Fuel Consumption	355.53	338.06	293.98	l
CO2	875112.07	843316.7	768464.08	g
NOx	1311.3	1250.91	1130.48	g

PM (particulate matter)	223.74	210.73	174.77	g
VOC (Volatile organic compounds)	1107.33	997.88	917.66	g
Mean Queue	29.85	20.88	16.28	veh
Number of Stops	0.16	0.14	0.12	#/veh/km
Speed	34.25	37.59	38.8	km/h
Stop Time	38.42	25.48	25.76	sec/km
Total Number of Stops	8322.87	7404.37	6401.28	
Total Travel Time	94.76	85.44	77.96	h
Total Travelled Distance	2925.17	2939.58	2932.89	km
Travel Time	117.76	102.99	102.13	sec/km

Conclusions from the experiment

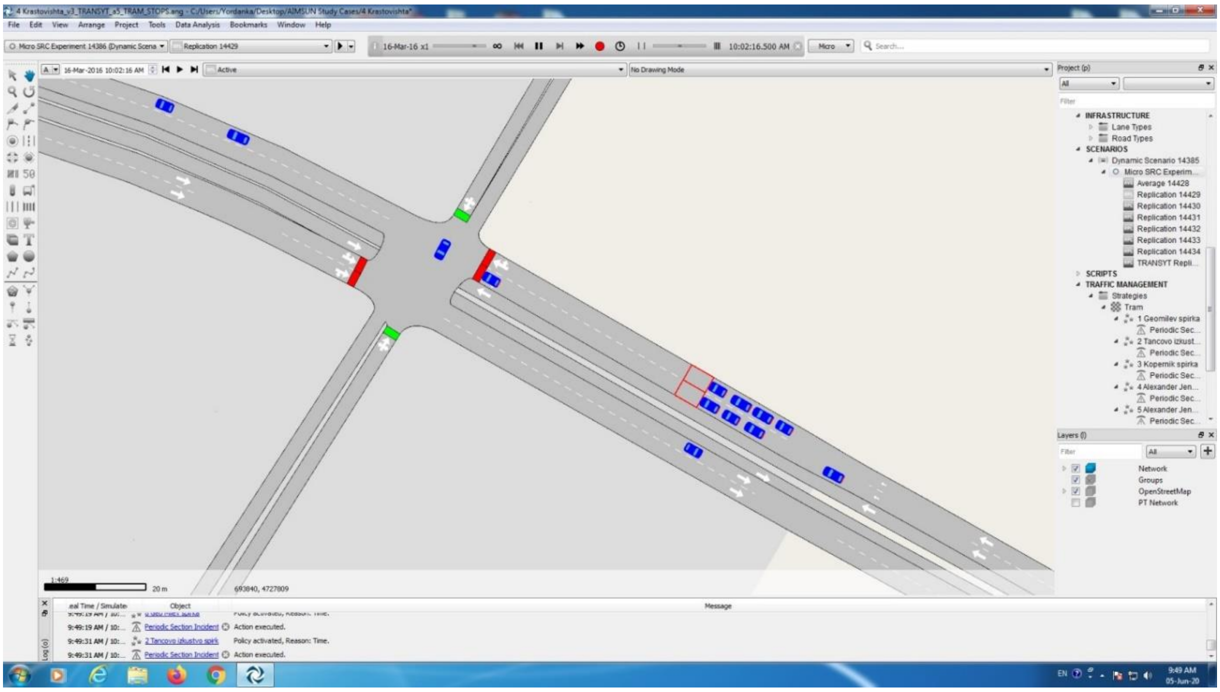
In the experiment, a script was presented in MATLAB for optimizing the cycle length of a network of traffic lights on Shipchenski Prohod Blvd. in Sofia. The script solves a bilevel problem using the store-and-forward model as a constraint on the lower target function. A comparison is made with the results of the most modern TRANSYT optimization software. Three experiments were simulated in the Aimsun software package. In conclusion, based on the result, it can be stated that bilevel optimization has the potential to be studied in more depth as an approach for the purposes of traffic optimization.

Complicating the model. Introduction of tram stops and street parking.

Summary of the experiment

The experiment will result in a study on the impact of tram stops on traffic. The hypothesis is that tram stops will negatively affect traffic. However, it is more important to establish the extent of this impact, as it can serve the purposes of the city government to make informed decisions about tram schedules. Also, in a separate experiment, the computer model is further complicated by including a simulation of street parking - respectively, a comparison is made of cases without and with street parking. The capabilities of the Aimsun software package for measuring various traffic indicators, as well as indicators for fuel consumption and air pollution. The two studies are combined in this common point, as studies that complicate the studied computer model and bring it closer to the real conditions in the road network from the traffic-light regulated intersections.

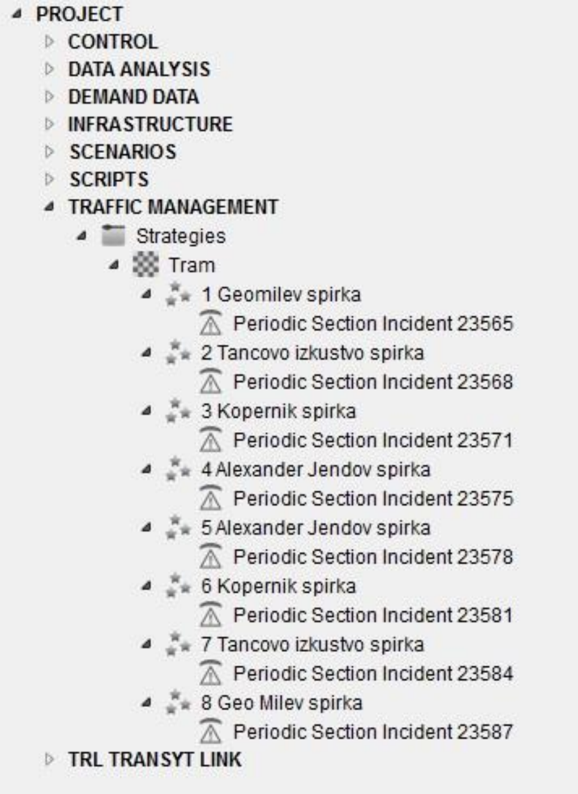
In Figure 3.18. is shown a simulation view from the Aimsun programming environment. The figure illustrates a queue of cars waiting for passengers in getting on the tram on a tram stop.



```
.eal Time / Simulate   Object                          Message
9:49:19 AM / 10:...    Periodic Section Incident       Action executed.
9:49:31 AM / 10:...    2 Tancovo izkustvo spirk        Policy activated, Reason: Time.
9:49:31 AM / 10:...    Periodic Section Incident       Action executed.
```

Fig. 3.18. A queue of cars in front of a tram stop

In Fig. 3.18. the simulations of eight bus stops on Shipchenski Prohod Blvd. are presented.



- PROJECT
  - CONTROL
  - DATA ANALYSIS
  - DEMAND DATA
  - INFRASTRUCTURE
  - SCENARIOS
  - SCRIPTS
  - TRAFFIC MANAGEMENT
    - Strategies
      - Tram
        - 1 Geomilev spirka
          - Periodic Section Incident 23565
        - 2 Tancovo izkustvo spirka
          - Periodic Section Incident 23568
        - 3 Kopernik spirka
          - Periodic Section Incident 23571
        - 4 Alexander Jendov spirka
          - Periodic Section Incident 23575
        - 5 Alexander Jendov spirka
          - Periodic Section Incident 23578
        - 6 Kopernik spirka
          - Periodic Section Incident 23581
        - 7 Tancovo izkustvo spirka
          - Periodic Section Incident 23584
        - 8 Geo Milev spirka
          - Periodic Section Incident 23587
  - TRL TRANSYT LINK

Fig. 3.18. The periodic incidents on the section represent tram stops on Shipchenski Prohod Blvd.

Conclusions from the experiment

From the performed experiments, which complicate and bring closer to the real conditions the simulation model, it is clear that the tram stops do not significantly affect the traffic indicators and the pollution of the environment, while the street parking leads to more noticeable changes in the traffic indicators and negatively affects the environment.

It can be concluded that all studied traffic indicators deteriorate in the case of street parking compared to the case in which there is no street parking. Another not very obvious result is the increase in fuel consumption and CO_2 emissions, which in a careful analysis is logical due to the reduced capacity of the network and traffic jams that are formed by parking on the street.

Adaptive control and research of traffic indicators, fuel consumption and environmental pollution

Summary of the experiment

There are different approaches related to reducing car pollution. This study focuses on traffic light signaling control policies and their impact on air pollution. A software simulation with the software products Aimsun and TRANSYT was performed. Aimsun uses the ecological model of (Panis et al. (2006), (Panis et al., (2011))). Experiments lead to the conclusion that traffic pollution may be affected by changes in traffic light signal control policies.

In Table 3.8. fuel consumption and harmful emissions by different traffic control policies are presented.

Table 3.8. Fuel consumption and harmful emissions by different traffic control policies

Parameters - Car	*Current signal timing plan*	*Green wave fixed-time plan*	*Actuated control*	*Units*
Fuel Consumption	355.53	307.52	289.86	l
IEM Emission - CO2	874077.52	788275.5	762346.78	g
IEM Emission - NOx	1835.5	1680.73	1614.73	g
IEM Emission - PM	340.52	288.71	271.36	g
IEM Emission - VOC	1131.69	963.57	876.51	g

Table 3.9. presents the relative differences of green wave fixed-time plan and actuated control compared to the current signal timing plan in terms of fuel consumption and harmful emissions.

Table 3.9. Fuel consumption and harmful emissions in different traffic signal policies (relative differences)

Parameters - Car	*Current signal timing plan (in absolute value)*	*Green wave fixed-time plan (change in %)*	*Actuated control (change in %)*
Fuel Consumption	355.53	-13.50	-18.47
IEM Emission - CO2	874077.52	-9.82	-12.78
IEM Emission - NOx	1835.5	-8.43	-12.03
IEM Emission - PM	340.52	-15.21	-20.31
IEM Emission - VOC	1131.69	-14.86	-22.55

Figure 3.20 illustrates the relative changes of the studied indicators for fuel consumption and air pollution depending on the type of control. The current fixed time policy is considered to be the basis (Table 3.8 and Table 3.9). In comparison, a red pole shows a fixed plan optimized for green wave, and a green pole shows actuated control policy. Figure 3.20 shows that actuated control policy leads to a reduction in fuel consumption and air pollutants to a greater extent than the observed reduction in fixed time control optimized for green wave.

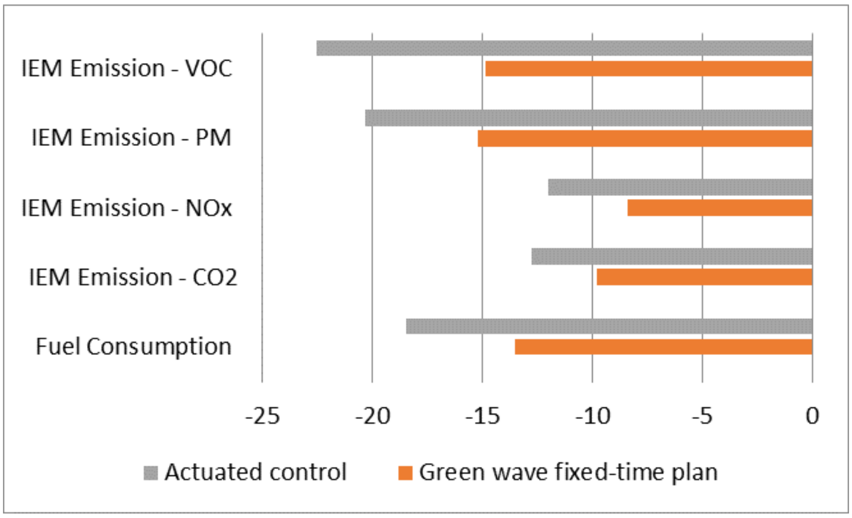


Fig. 3.20. Relative changes in indicators depending on the type of management

Various signal policies affecting air pollution emissions have been evaluated. Microsimulations were performed with Aimsun. TRANSYT is also used to optimize the fixed time signal plan for green wave. The results of the study clearly show that when traffic in real time is taken into account, both air pollution and fuel consumption are reduced.

Conclusion

The third chapter presents the performed experiments for the dissertation. The object of optimization was presented - a network of four traffic-light-controlled intersections. The object is modeled in the Aimsun simulation environment. Description and basic information about the used software products - Aimsun, TRANSYT and MATLAB are also presented in this chapter of the dissertation.

The simulations and experiments performed are described in detail. They are related both to the collection of data on the geometry of the road network and the intensity of traffic in this network, and to the subsequent preparation of computer simulations and a formal mathematical model. Based on the models - mathematical and simulation, and the applied optimization methods, the results are evaluated.

The chapter presents two bilevel optimization problems solved by using the solvebilevel() function. The solutions are implemented in the Aimsun simulation environment and the results were derived in the form of traffic parameters to be compared with the simulation in TRANSYT. The achieved results are related to the increase of the network capacity, the reduction of the queues in front of the traffic lights and the reduction of the traffic jams. Bilevel optimization allows for more objective functions, control parameters and more constraints in the control space.

The object of study has been complicated by additions such as tram stops and street parking, which phenomena are available in real conditions. In this way, the simulation model was brought closer to the real conditions in the road network and will be the subject of more detailed future research.

Attention was also paid to the impact of the optimization of traffic on fuel consumption and indicators of air pollution. This relationship results in reduction of queues and reduction in both harmful emissions and fuel consumption. This reduction benefits society from a health perspective. Therefore, optimization of traffic in urban conditions is important not only for faster movement from one point of the city to another, but also for optimizing unwanted aspects of traffic such as air pollution.

Chapter 4

SIMULATION AND NUMERICAL EXPERIMENTS AND RESULTS

Comparison of results from simulation experiments

This chapter presents, in tabular and graphical form, the results of simulation and numerical experiments. These are the results of the experiments, which are described separately in the previous chapter 3. A comparison is made between the individual experiments, comparing the optimized results with the results of the experiment with basic case scenario and taking into account the improvement of several traffic indicators. In addition to the comparison between the traffic indicators, in the different experiments, a comparison was made of the fuel consumption and two environmental pollutants - carbon dioxide and particulate matter. This comparison aims to show that optimal traffic management also favors indicators of environmental pollution.

The first column of Table 4.1. presents key traffic indicators, fuel consumption and environmental pollutants. The second column of the table presents the results of the simulation of the base case scenario experiment. The third column presents the results of simulation after the introduction of data optimized by bilevel optimization, using the solvebilevel() function in MATLAB for the duration of the green splits of the studied road network. The fourth column presents the results of a simulation in which optimized cycle data is entered after bilevel optimization using the solvebilevel() function in MATLAB. The fifth column is optimization through the TRANSYT software package, which is used as a standard to evaluate a number of traffic management strategies worldwide. The last sixth column presents the units of measurement.

Table 4.1. Comparison of traffic indicators, fuel consumption and environmental pollution in four simulations

	Current settings	*Bilevel optimization with upper objective function green split*	*Bilevel optimization with upper objective function cycle length*	*Optimization of current settings trough TRANSYT*	*Units*
Delay	51.16	37.23	36.4	35.51	sec/km
Density	7.69	6.67	6.91	6.27	veh/km
Flow	4095	4126	4107	4124	veh/h
Queue	29.85	21.17	20.88	16.28	veh
Speed	34.25	38.98	37.59	38.8	km/h
Total number of stops	8322.87	6069.72	7404.37	6401.28	#
Travel time	117.76	103.86	102.99	102.13	sec/km

Fuel consumption	355.53	300.6	338.06	293.98	liter
CO_2	874077.52	775912.65	843316.7	768464.08	gram
PM	340.52	274.26	210.73	174.77	gram

A general conclusion from the data presented in the table is that the best solutions are achieved when using the software product TRANSYT. Here, however, it is important for the study to be noticed that the differences in the numerical results of the other two experiments using bilevel optimization are very close to the results achieved with TRANSYT.

This observation leads to two significant conclusions:

- First, the bilevel optimization problem yields plausible results that are comparable to a software package that has been on the market for years and that, as mentioned, is used to evaluate different traffic management strategies.
- Second, because the results may be affected by the change in the input data, it is possible that for certain input data the dual hierarchical optimization turns out to achieve better values of the traffic indicators than are achieved with the software package TRANSYT. However, this conclusion is rather a hypothesis for future research in the field of using bilevel optimization for the purpose of improving traffic in urban environments.

The speed of reaching a solution when using MATLAB and TRANSYT should also be mentioned. When using MATLAB, the solution of the problem is achieved several times faster than it is necessary for TRANSYT to do the optimization of the road network.

Figure 4.1 presents the traffic flow data for the four simulations. As can be seen, the lowest flow is in the experiment with base case scenario - 4095 cars / hour. Surprisingly, with this indicator, the flow of the experiment with green split optimization is the highest - 4126 cars / hour, although with a slight advantage over the optimization with TRANSYT.

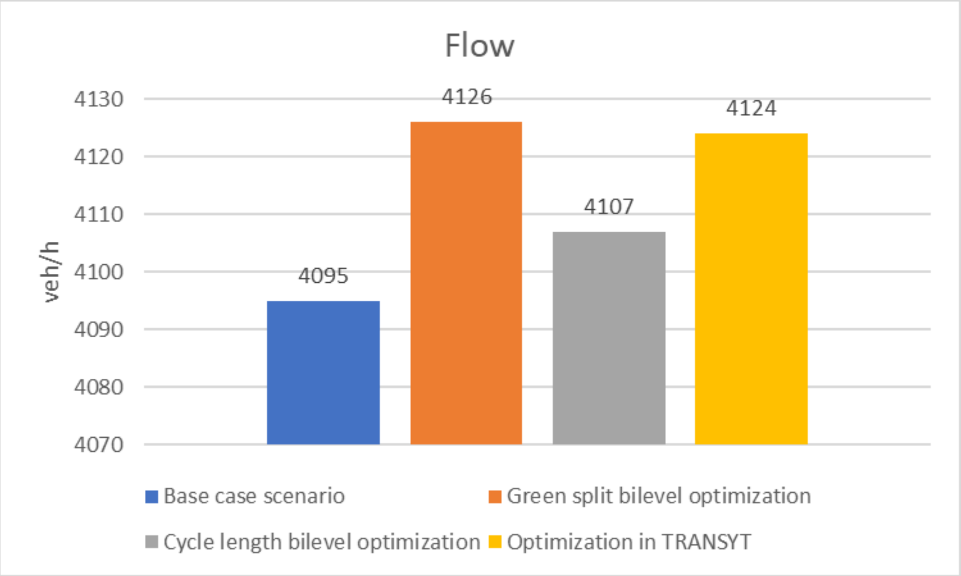


Fig. 4.1. Comparison of flow in four simulations

The speed shown in Figure 4.5 is the lowest for the base case experiment, and for the second time the bilevel optimization of the green split (38.98 km / h) is slightly ahead of TRANSYT (38.8 km / h). Exact values for each experiment are shown in Figure 4.5.

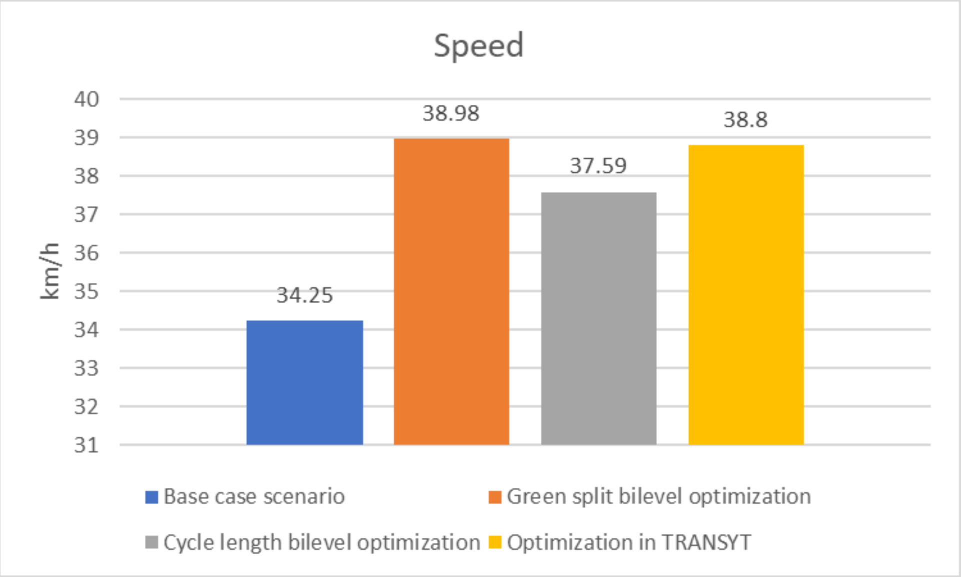


Fig. 4.5. Speed comparison in four simulations

The total number of stops is shown in Figure 4.6. He is the highest again for the first pillar of the figure. The third traffic indicator shows the best results for bilevel optimization of the green split (6069.72 number of stops) compared to TRANSYT (6401.28 number of stops).

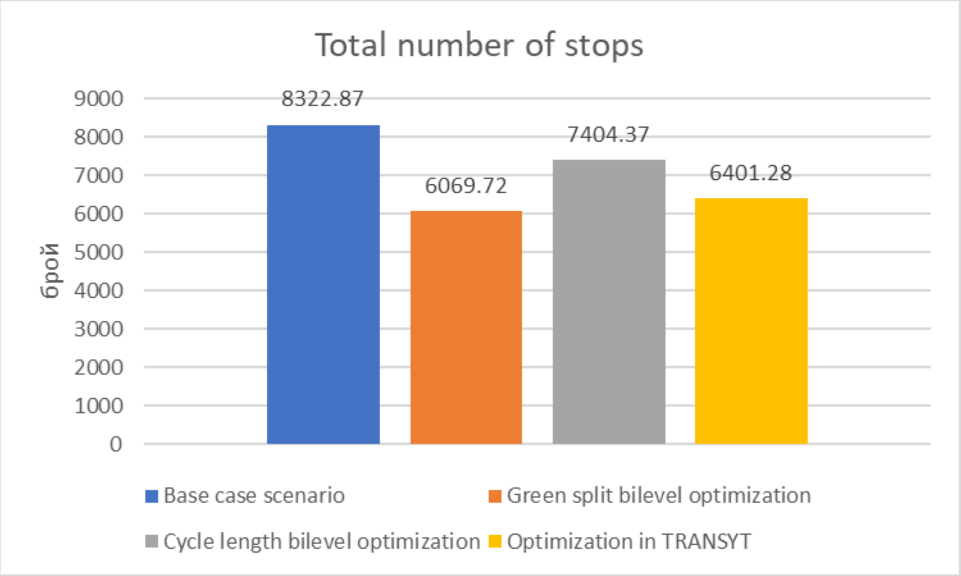


Fig. 4.6. Comparison of total number of stops in four simulations

Conclusion

In the fourth chapter a comparison of the results of the conducted simulations based on traffic indicators is made. This chapter is essential in terms of illustrating the benefits of bilevel optimization for urban traffic purposes. The bilevel optimization is placed in the context of a comparison with one of the oldest and most widespread software products, specifically developed for the optimization of a network of traffic-light-controlled intersections - TRANSYT.

The bilevel tasks defined and solved in this dissertation work gave close results with the results of TRANSYT, as one of the bilevel problems showed a slight advantage over TRANSYT in three indicators - flow, speed and number of stops. This gives grounds for further research in the field of using the bilevel optimization method for the purposes of optimization of urban road traffic.

CONCLUSION

Congestions are often a problem related to the growth of cities and the increase in the number of vehicles. This necessitates the search for solutions to deal with the problem of congestion and difficult traffic in large cities and in particular in Sofia.

An overview of some significant concepts and theoretical statements in the field of urban traffic is made. In this regard, the concepts related to traffic-light-signal regulation are clarified. Three traffic models are considered, one of which - store-and-forward model, is the basis for the formulation of a traffic model in the selected network of intersections. Mention is also made of traffic management strategies that have been developed and implemented worldwide.

The achievements in the field of defining and solving bilevel optimization problems in the field of optimization of urban traffic in a network of intersections are considered. A bilevel optimization problem is presented. The same formal statement in the context of car traffic in urban environment - control of traffic-light-regulated junctions.

The object of optimization - a network of four traffic-light-regulated intersections. The object is modeled in the Aimsun simulation environment. For the purposes of the experiments, a field study was conducted and data on the geometry of the road network and the traffic flow in the studied section were collected.

Attention was also paid to the impact of the optimization of the traffic on fuel consumption and indicators of air pollution. This relationship is expressed in the fact that the reduction of queues and congestion reduces both harmful emissions and fuel consumption. This reduction benefits society from a health perspective. Therefore, optimization of traffic in urban conditions is important not only for faster movement from one point of the city to another, but also for optimizing unwanted aspects of traffic such as air pollution.

Determining the duration of traffic light signals can be done using simulation models. The use of simulation software has the advantage that no real changes in traffic are required when trying out different traffic light settings. The settings are made in a simulation environment, in this dissertation the software used is Aimsun. The model and settings of traffic lights, as well as other parameters of infrastructure and traffic can undergo many changes within the computer simulation.

Another simulation software product is MATLAB, which is used for a numerical model of the object of simulation and optimization - a road network of four intersections along a main boulevard in Sofia.

The results of the solution of the bilevel problem are compared with the results of the software product TRANSYT, used worldwide for evaluation of traffic management strategies. The results show that one of the bilevel problems gives an advantage over TRANSYT in three traffic indicators. In summary, the comparisons lead to the conclusion that the solutions of the bilevel problems are closet to the solution of TRANSYT than to the results of simulation of base case scenario. Thus, with bilevel optimization, better traffic indicators are achieved than the simulation with base case scenario. The advantage of MATLAB over TRANSYT is the faster calculation, which is achieved. Bilevel optimization allows for more objective functions, control parameters and more constraints in the control space. In particular, bilevel optimization achieves greater throughput of the transport network from intersections, reduces queues at traffic lights and thus reduces congestion at traffic lights. The effects of better traffic indicators are also felt in fuel consumption and harmful emissions, which decrease with the improvement of traffic indicators.

CONTRIBUTIONS

The contributions of the dissertation are as follows:

1. A mathematical model of road network has been made - an urban road network, regulated with traffic light signaling, in order to optimize the network. The model allows to make analytical and numerical simulations to determine the optimal values of a system of traffic lights.

2. A new mathematical model is defined through two hierarchically related tasks for optimization of urban traffic, which allows to determine the optimal values of a larger number of control variables: cycle and duration of green light of a system of intersections.

3. The light signaling of traffic lights and the cycle duration have been optimized by applying the developed hierarchical model for optimization from point 2. The results of the numerical experiments show that the obtained solutions can be determined in real time, which allows to adapt the control of traffic light system according to the dynamics of transport traffic.

4. A simulation computer model of a network of intersections has been developed. The model allows to take into account additional conditions in traffic management, which cannot be formalized analytically, such as taking into account the presence of a tram line, permission to park in a system of transport intersections.

5. A comparison of the results obtained from the analytical optimization through the developed bilevel model and the simulation results of the computer model is made. It is shown that the bilevel model allows the application of real-time control due to the faster calculation of the optimal control interactions compared to the simulation results, which require significant implementation time.

Table Conclusion.1. Relationship between results, structure of the dissertation and publications.

Task	Contribution	Publication	Chapter
A mathematical model of the site has been compiled - an urban road network, regulated with light signaling, in order to optimize the simulated object	Scientifically applied	1, 2	3
A new mathematical model is defined through two hierarchically connected tasks for optimization of urban traffic.	Scientifically applied	1, 2	3
The light signaling of traffic lights and the duration of the cycle have been optimized by applying the developed hierarchical model for optimization from point 2.	Scientifically applied	1, 2	3
A computer model of the object of optimization by means of a simulation environment has been developed.	Applied	4, 5	3
Complicating the computer model of the	Applied	3	3

object. The model allows to take into account additional conditions in traffic management, which cannot be formalized analytically, such as taking into account the presence of a tram line, permission to park in a system of transport intersections.			
A comparison is made of the results obtained from the analytical optimization through the developed bilevel model and the simulation results of the computer model.	Scientifically applied	2	4

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DECLARATION OF ORIGINALITY

Hereby, I declare that I have composed the presented thesis independently on my own and without any other resources than the ones indicated.

All thoughts taken directly or indirectly from external sources are properly denoted as such.

This work has neither been previously submitted to another authority nor has it been published yet.

Signature:………………….
(Y. Boneva)