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A simulation based comparative analysis of interconnected signalized intersections and roundabouts from the aspect of permeability

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Abstract

The utilization of the tools provided by digitalization became increasingly important for the micro-level modelling of road traffic, since it typically takes the form of a highly dynamic system. In the publication, the PTV Vissim traffic simulation software is used for the modelling of such a system, a traffic junction formed by two interconnected signalized intersections. The first goal of the analysis was to reveal how the optimization of the signal program in a specific way affects the operation of the entire system in terms of throughput during peak periods. After that, the possibility of modelling the same traffic junction with roundabouts was also explored. Finally, the results for the total traffic throughput of the system during the peak periods were compared in case of the different model variants. The resulting comparison present the permeability variation in a well-structured way and could also provide a useful example for the field.

Keywords: traffic simulation, traffic throughput, signalized intersection, roundabout

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1. Introduction

The publication presents a coordinated investigation of two intersections that have a significant impact on the daily traffic of the citizens of the University of Miskolc, which also served as one of the starting reasons for the research work. The main goal of the study was to examine the optimization possibilities of the system formed by the two interconnected signalized intersections and the connected road sections, with the inclusion of the analysis of a conceptual roundabout-based solution. With the comparison of the different model variants, a final aim of the research was to rank the different approaches from a permeability perspective in terms of total traffic throughput, which could provide a useful example for the field for the examination and analysis of similar problems. The study was based on the creation of detailed traffic simulations for the different model variants. The application of various traffic simulation software has became especially widespread in the latter period for such problems, which is also illustrated by the related literature. For example, in their paper entitled "Trends in real-

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time traffic simulation", Pell, Meingast and Schauer compared 17 traffic simulation environments according to several aspects, including the Vissim software, the latter of which is used in the current study (Pell, Meingast and Schauer, 2017). In the paper titled "Simulation of traffic systems - an overview", Pursula gives a comprehensive description of the important role that simulation environments and tools have played in the last 40 years (Pursula, 1999). Kotusevski and Hawick also reviewed multiple traffic simulation software (Kotusevski and Hawick, 2009). In their paper, Saidallah, Fergougui and Elalaoui presented a comparative study of urban road traffic simulators (Saidallah, Fergougui and Elalaoui, 2016). Kamrani, Abadi and Golroudbary made a traffic simulation with the ARENA software for the analysis and optimization of two adjacent unsignalized T-junctions during rush hours (Kamrani, Abadi and Golroudbary (2014). Besides, Skapinyecz and Erdei also explored the application possibilities of modern traffic simulation environments in education and research through the example of the Vissim software (Skapinyecz and Erdei, 2021).

The following figure presents the layout of the analysed intersections, supplemented with the identification of the incoming and outgoing routes:

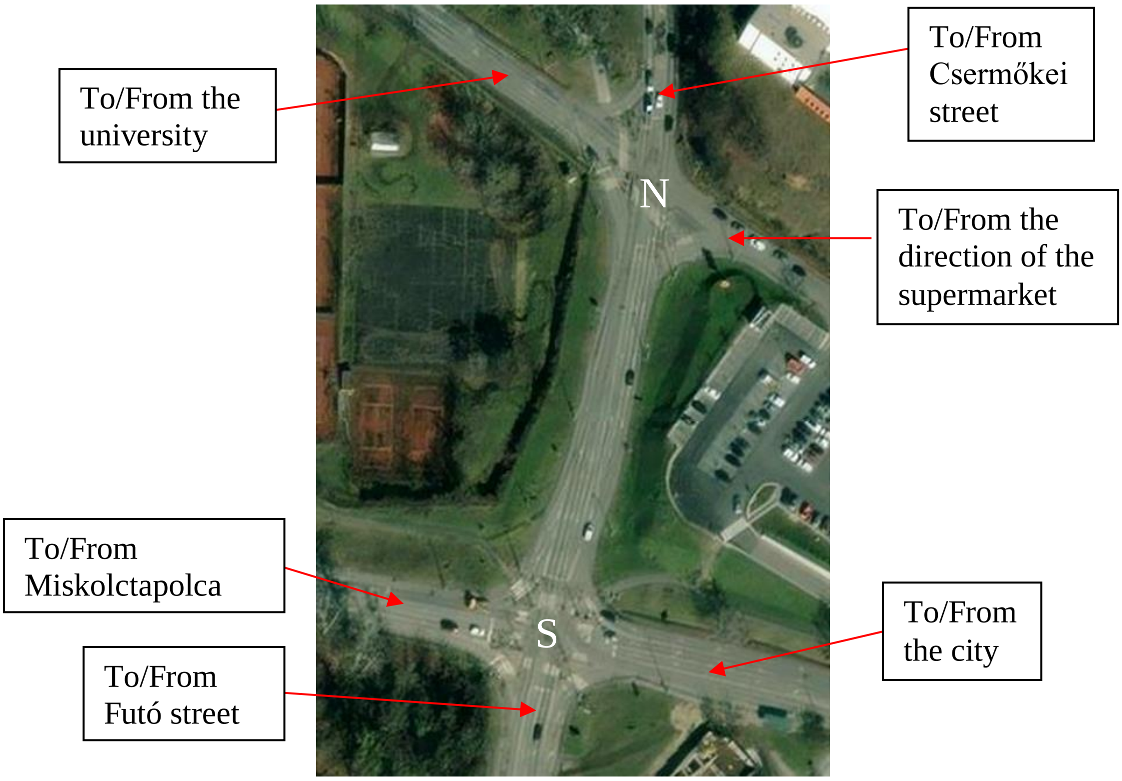

Figure 1: The two analysed intersections (S: southern, N: northern)

As it was mentioned, the simulations were carried out with the use of PTV Group's Vissim traffic simulation software (Academic version). A significant emphasis was placed on making the models as realistic as possible, which included a thorough traffic counting during the peak periods, however it is still important to emphasize that the results are only meant for scientific purposes, as any implementation would require a complete traffic engineering analysis based on completely precise data (besides, the industrial version of the software would also be required in that case as well). The entire research can be found in the first author's bachelor's thesis in Hungarian (Kollár, 2022).

2. General characteristics of signalized intersections and roundabouts

Signalized intersections and roundabouts are two of the most widely applied forms of traffic junctions. As such, their general characteristics have been extensively described and studied in the related literature for many decades. According to the book Traffic Engineering by Roess et al., the use of traffic signals can substantially reduce the number and nature of intersection conflicts as no other form of control can, due to the capability of assigning right-of-way to specific movements (Roess et al, 2004). The same source lists the advantages of traffic signal control as the following (Roess et al, 2004):

- facilitating the orderly movement of traffic,
- increasing the traffic-handling capacity of the intersection if proper physical layouts and control measures are used and if the signal timing is reviewed and updated on a regular basis (every two years) to ensure that it satisfies the current traffic demands,
- reducing the frequency and severity of certain types of crashes, especially right-angle collisions,
- traffic signals are coordinated to provide for continuous or nearly continuous movement at a definite speed along a given route under favorable conditions,
- traffic signals are used to interrupt heavy traffic at intervals to permit other traffic, vehicular or pedestrian, to cross.

On the other hand, the book also identifies disadvantages related to traffic signal control in case the traffic signals are improperly designed, or their placement is not justified, which are the following (Roess et al, 2004):

- excessive delay,
- excessive disobedience of the signal indications,
- increased use of less adequate routes as road users attempt to avoid the traffic control signal,
- significant increase in the frequency of collisions (especially rear-end collisions).

As it can be seen from the previous, while signalized intersections provide unique capabilities in terms of traffic control, their performance is highly dependent on the proper design and placement of traffic signals. In contrast, the modern roundabout, first developed in the United Kingdom in the 1960’s (Robinson et al., 2000), eliminates the need for using traffic signals entirely by requiring the entering traffic to give-way to the circulating traffic. This also has the added effect of slowing down the traffic, thus increasing safety, while at the same time the vehicle flow is still continuously maintained. As a result, the use of roundabouts can decrease the possibility of collisions while at the same time can still facilitate a large traffic volume. The concrete safety advantages of modern roundabouts are the following according to a report of the U.S. Department of Transportation (Robinson et al., 2000):

- they have fewer conflict points in comparison to conventional intersections,
- low absolute speed associated with roundabouts allow drivers more time to react to potential conflicts,
- as most road users travel at similar speeds through the roundabout, their relative speeds are lower, which reduces the severity of potential crashes,
- pedestrians only need to cross one direction of traffic at a time at each approach as they traverse roundabouts.

However, roundabouts also have their own disadvantages, the most important of which is that their operation and safety performance are particularly sensitive to geometric design elements (Robinson et al., 2000). Besides, even though these types of intersections have been widely implemented in the recent decades especially across Europe mainly due to their safety advantages, they can still be somewhat novel for motorists during the initial use period, while local field conditions could also limit the possibilities for their implementation. One of the important characteristics of roundabouts that also has to be taken into account when they are utilized in a roadway system in conjunction with other types of intersections is that their performance is affected by their proximity to the latter and vice versa (Robinson et al., 2000). For example, when a roundabout comes right after a signalized intersection, the vehicles entering into the former will from closely spaced platoons, which will increase the roundabouts overall efficiency. On the other hand, as another example, the traffic leaving the roundabout is usually more random compared to other types of intersection control, which can also affect the performance of other unsignalized intersections or driveways downstream if the latter are too close to the former (Robinson et al., 2000).

Of course, there are a multitude of different aspects that could be examined when comparing signalized intersections and roundabouts. Many of these have been also studied in the literature, besides of the aspects of safety and traffic volumes. For example, Meneguzzer et al. compared the exhaust emissions at a roundabout implemented in place of a signalized intersection before and after the conversion, by utilizing a Portable Emission Measurement System (PEMS) installed on a test car (Meneguzzer et al., 2017). One of their findings was that in the case of CO_2 emissions, the roundabout produced less values in almost all tested conditions, but the differences were not always statistically significant (separately, they analysed the emission rates for NO_x and CO as well). Multiple studies also examined the noise levels both at signalized intersections and in roundabouts. Li et al. used a dynamic traffic noise simulation method based on microscopic traffic simulation to examine this problem (Li et al. 2017). They analysed the noise levels both in the entrance and exit lanes (and in the ring lane as well in case of the roundabout) at various traffic levels, and one of their findings was that the exit lane has the highest traffic noise intensity in case of both intersection type. Estévez-Mauriz and Forssén also applied a microscopic simulation approach to examine this problem area (Estévez-Mauriz and Forssén, 2018), while Khajehvand et al. used a drone-based approach to directly analyze traffic noise levels at roundabouts, and at signalized T-intersections and cross intersections (Khajehvand et al., 2021). Finally, multi-aspect studies were also implemented, for example Hydén and Várhelyi examined the effects of the large scale use of roundabouts through a case study from the aspects of safety, time consumption and the environment (Hydén and Várhelyi, 2000). As it was mentioned, the current study focuses on the traffic throughput analysis of an interconnected system based on microscopic traffic simulation, which is going to be presented in the followings.

3. Description of the initial model

2.1 Data collection

The first step in building the model was the recording of the traffic data for the intersections. As it is supported by the relevant literature, we can distinguish two time intervals during the day where the intensity of passing traffic increases significantly. For example, in their paper Macioszek and Kurek dealt with the examination of many intersections during the Covid epidemic and in almost every case they recovered the curve characterized by two peak periods (Macioszek and Kurek, 2021). In a 2016 publication, Bartuška, Ladislav, Vladislav Biba, and Kampf, examining the 24-hour distribution of traffic, also identified two peak periods where the amount of incoming traffic increases significantly (Bartuška et al., 2016). In 2004, Weijermars, W. A. M., and Eric C. van Berkum investigated the change in daily traffic distribution during the week (Weijermars and van Berkum, 2004). The research of Hanan et al. presented in a 2017 paper also supports the authenticity of the curve defining the two peak periods (Hanan et al., 2017).

In accordance with the literature, two intervals were selected for the measurement of peak traffic, one in the morning and one in the afternoon, from 7:30 to 8:00 and from 16:30 to 18:00 respectively. However, before the traffic counting could begin, first the actual traffic light programs have to be determined for both intersections. As the programs were not directly available for the authors, these have to be manually recorded with the aid of a timer. First the period time of the signal light system of the given intersections were determined, then the cycle times of all the signal lights. Based on the measurement, it became clear that the period time of the southern intersection is shorter than that of the junction leading to the university (the northern intersection). In the followings, it was necessary to determine the order in which the measured phase times alternate in both intersections. As an example, the following Table 1 shows the measured green times of the traffic lights determined for the northern intersection:

Table 1: Measured green signal periods of the northern intersection

Route	*Green periods [s]*
turning left from Csermőkei street	10
continuing straight ahead from the direction of Csermőkei street	47
turning right from Csermőkei street	-
turning left from the university	25
turning right from the university	-
continuing straight ahead from the direction of the university	25
turning left from the direction of the southern intersection	62
continuing straight ahead from the direction of the southern intersection	120
turning right from the direction of the southern intersection	-
turning left from the direction of the supermarket	25
turning right from the direction of the supermarket	25
continuing straight ahead from the direction of the supermarket	25
Full cycle time [s]	180

The most time-consuming part of the data collection was the traffic counting, as altogether it took multiple days over the course of several weeks. It was necessary to go to the site in the mornings and in the afternoons in order to accurately record the number of vehicles arriving from different directions. It should be pointed out that the investigation also covered the proportion of vehicles moving from the given directions towards the various decision options. The measurements were taken in all possible directions for 10-10 minutes, and then from the obtained values it was possible to infer the data for the indicated directions, projected for one hour. This was necessary because the data was also recorded on an hourly basis in the Vissim software.

Based on the results of the traffic counting, it is clear that in the morning hours almost twice as many vehicles arrive from the city as in the afternoon hours, and a significant majority of them continue in the direction of the university. In addition, it can also be noticed that most vehicles arrive from the same two directions during the examined times of the day, with the difference that the amount of traffic arriving from the city in the morning and from Futó street in the afternoon is more significant. There is also a difference in the number of vehicles coming from Miskolctapolca, which is higher in the early hours than in the afternoon. Analyzing the other directions, we can establish the fact that the amount of incoming traffic is almost the same in the two investigated time intervals. As an example, the following table 2 shows the traffic data measured in the morning, broken down according to each direction:

Table 2: The traffic data measured in the morning

Direction	*passenger vehicle [No. /10 min]*	*small truck [No./10 min]*	*large truck [No./10 min]*	*bus [No./10 min]*	*total [No./10 min]*	*est. hourly number*	*Ratio*
city – dir. of the supermarket					135	810	0,000
city – Csermőkei street	17	1					0,133
city – university	50						0,370
city – Miskolctapolca	30	7		2			0,289
city – Futó street	26	2					0,207
Futó street – dir. of the superm.	1				98	588	0,010
Futó street – Csermőkei street	40	4	4				0,490
Futó street – university	23	2					0,255
Futó street – city	11	1					0,122
Futó street – Miskolctapolca	9	3					0,122
Miskolctapolca – dir. of the s.	0				82	492	0,000
Miskolctapolca – Csermőkei st.	6						0,073
Miskolctapolca – university	1						0,012
Miskolctapolca – Futó street	21	2					0,280
Miskolctapolca – city	47	5					0,634
university – dir. of the superm.	3				38	228	0,079
university – city	8			4			0,316
university – Futó street	6	1					0,184
university – Miskolctapolca	1						0,026
university – Csermőkei street	15						0,395
Csermőkei street – dir. of the s.	3				72	432	0,042
Csermőkei street – city	8						0,111
Csermőkei street – Futó street	40	5	5	1			0,708
Csermőkei st. – Miskolctapolca	5		1				0,083
Csermőkei street – university	3			1			0,056
dir. of the superm. – university	7				23	138	0,304
dir. of the superm. – city	1						0,043
dir. of the s. – Miskolctapolca	5						0,217
dir. of the superm. – Futó street	4						0,174
dir. of the s. – Csermőkei street	5	1					0,261

3.2 Structure of the initial model

The modeling of the intersections naturally began with the construction of the roads in the simulation environment. After that, an hourly traffic volume was specified for each introductory road section, as well as the directions of travel and the distribution ratios between them. The latter were specified for both the morning and the afternoon traffic data, so effectively this in itself meant the setting of two basic versions of the model.

In the following steps, the signal light units were built, as well as other elements were added that helped to better depict reality within the model. Such elements are, for example, the pavement markings on the road and the various signs appearing on the posts. For the sake of completeness, pedestrian traffic routes have also been marked. Six areas have been specified from which passers-by can start and different decision options have been assigned along which they can continue their journey. The parameters of the latter were estimated based on measurement experience. The columns supporting the traffic light units and the pedestrian crossings were placed in an effort to be as realistic as possible.

Following the mentioned steps, the places where two roads cross each other were designated, and then, in accordance with the rule of the road, their superior and subordinate relations were established. With the help of this, traffic can proceed without accidents even without the operation of the traffic lights. A so-called deceleration zone was designated for those right-turning options that are not controlled by traffic lights, which made the model even more lifelike. The following Figure 2 shows the network level representation of the initial model:

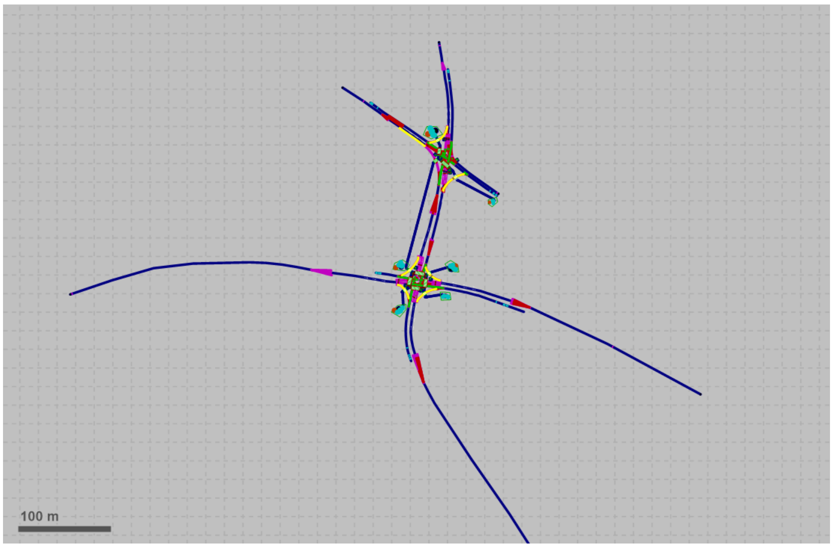

Figure 2: Network level representation of the initial model

After all the structural and formal elements were completed, the next step was to program the traffic lights of the two intersections. This was done with the help of the measured data and green times. In order for the traffic lights operating at the two intersections to be fully consistent, the two traffic light programs had to be coordinated. This problem was solved by choosing a main starting direction on the spot, which in this case was the lane going straight from Futó street towards Csermőkei street, and then it was determined how many seconds apart the two traffic lights turned green. The result was that the light at the Futó utca junction turned green 48 seconds later than the intersection leading to the university. According to the resulting data, this slippage was also adjusted in the model, and then its investigation and analysis could begin. The following Figure 3 shows the behavior of the model while running the simulation, in a 3-dimensional view:

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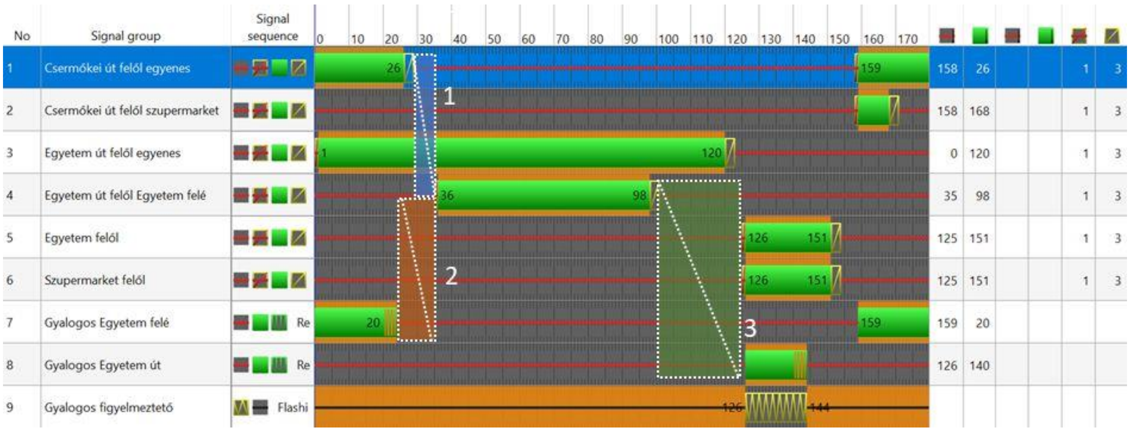
Figure 3: The operation of the model during the run of the simulation

4. Optimizing the signal program

While running the simulation, it was noticeable that the green time of the lane turning towards the university from the south is 22 seconds shorter than that of the lane going straight towards north, in accordance with the determined signal program for the northern intersection. This raised the possibility that the program could be optimized in order to increase the traffic throughput of the system, especially as the lane in question has one of the largest combined traffic volumes in the morning based on the traffic counting. However, certain constraints also had to be taken into account. First, as the northern and southern intersections are interconnected and this system is part of an even larger network of signalized intersections, therefore the cycle time had to be kept intact as otherwise the traffic throughput of the entire network could be negatively affected. Secondly, for the same reason the complete restructuring of the signal program neither was an option, as this could again negatively affect the functioning of the green waves in the wider network. Therefore, only individual changes could be considered. Overall, three modification options focusing on the green time of the lane turning towards the university from the south (4th row in the program) were identified, one of which was based on the observation already mentioned at the beginning. These options are highlighted and numbered in the following Figure 4. and will be described afterwards:



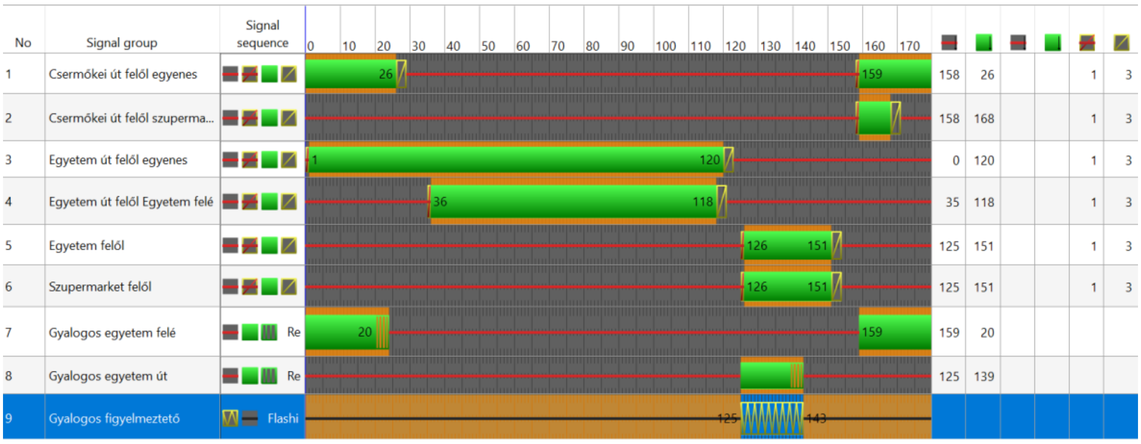
No	Signal group	Signal sequence	🟥	🟩	🟥	🟩	🟥	▨
1	Csermókei út felől egyenes	🟥 🟥 🟩 ▨	158	26			1	3
2	Csermókei út felől szupermarket	🟥 🟥 🟩 ▨	158	168			1	3
3	Egyetem út felől egyenes	🟥 🟥 🟩 ▨	0	120			1	3
4	Egyetem út felől Egyetem felé	🟥 🟥 🟩 ▨	35	98			1	3
5	Egyetem felől	🟥 🟥 🟩 ▨	125	151			1	3
6	Szupermarket felől	🟥 🟥 🟩 ▨	125	151			1	3
7	Gyalogos Egyetem felé	🟥 🟩 🟩 Re	159	20				
8	Gyalogos Egyetem út	🟥 🟩 🟩 Re	126	140				
9	Gyalogos figyelmeztető	▨ ▬ Flashi						

Figure 4: The original signal program of the northern intersection with the possible modification options

The option numbered as 1 and illustrated with a blue rectangle in Figure 4 was that the 4th signal could start earlier at T+29 seconds (where T is the start of the cycle), instead at T+36 seconds. However, the 7 second gap between the 1st and 4th signals is obviously needed to guarantee the necessary intermediate time between their green periods. This is crucial in order to allow the vehicles at the end of the 1st signal to safely leave the intersection. Therefore, as this 7 second gap had to be left intact, this option was obviously rejected.

Following from the previous, the option numbered as 2 and illustrated with a brown rectangle turned out to be even more problematic, as in this case, the 4th signal would have started even earlier at T+24 seconds, which would have required the significant shortening of the 1st signal as well in order to avoid overlap and maintain the necessary intermediate time. As the lane related to the 1st signal also facilitates a significant combined traffic volume based on the traffic counting (more than 50 vehicles in 10 minutes in the morning), this would have had a clearly negative effect. Moreover, the pedestrians coming from/going to the university also need a significant intermediate time after their green signal is ended (7th signal), which also ruled out this option.

Option number 3 was the one that was first identified, which was to increase the length of the 4th signal in the other direction, as it is 22 seconds shorter than that of the parallel lane going straight towards north (3rd signal). This option is illustrated in Figure 4 with a green rectangle and as it can be seen, in theory the length of the 4th signal could be increased by more than 20 seconds before it would reach the start of the following signal group (5th and 6th signals). However, the necessary intermediate time again had to be guaranteed, so the green period of the 4th signal was instead chosen to be increased only by 20 seconds, which is still significant (see Figure 5). Since there were no other immediate obstacles, this modification was accepted, assuming that it could increase the total number of vehicles passing through the combined system, since in the morning more than 70 vehicles in 10 minutes might go through the lane related to the 4th signal.



No	Signal group	Signal sequence	🟥	🟩	🟥	🟩	▨	▨
1	Csermőkei út felől egyenes		158	26			1	3
2	Csermőkei út felől szuperma...		158	168			1	3
3	Egyetem út felől egyenes		0	120			1	3
4	Egyetem út felől Egyetem felé		35	118			1	3
5	Egyetem felől		125	151			1	3
6	Szupermarket felől		125	151			1	3
7	Gyalogos egyetem felé	Re	159	20				
8	Gyalogos egyetem út	Re	125	139				
9	Gyalogos figyelmeztető	Flashi						

Figure 5: The optimized signal program of the northern intersection

In order to find out whether, in principle, it is indeed possible to carry out the selected modification (option 3), it was also required to define in the model the minimum necessary intermediate time between the two phases relevant from the perspective of the change (the green phase of the traffic turning towards the university from the south, and the green phase of the cross traffic realised between the university and the opposite branches of the junction) and compare the result with the signal program, as this is essential for the accident-free operation of the northern junction in the simulation.

At this point, however it is very important to highlight the fact that the analyses and its results can only be interpreted within the framework of the simulation model! Of course, the created model approximates reality as best as it is possible in the frame of the realised research, but the parameters and the results contained in it are nevertheless still only close approximations (the collected traffic data is as good as the result of any other traditionally conducted traffic counting with a similar scope, but the signal program also had to be determined manually, which naturally leaves open the possibility for slight measurement errors, while the completely precise layout of the intersections was also not available for the authors). Therefore, if we would no longer utilize the results solely in the software environment, then before introducing any changes, a full-scale traffic engineering analysis – together with conducting many other examinations, tests, data collections and an expanded traffic counting - would also be mandatory based on the completely precise layout and signal program of the intersections, for determining whether a similar solution could be realistically implemented in the real system in accordance with the existing regulations!

With accepting and taking into account the limitations described above, the intermediate time was first determined for the crossing of the lane turning from the direction the southern intersection towards the university by the lane coming from the university towards the opposite branch of the junction, purely as an approximate parameter that can only be used within the framework of the simulation. The two progress curves in question can be seen highlighted with white lines in the following Figure 6:

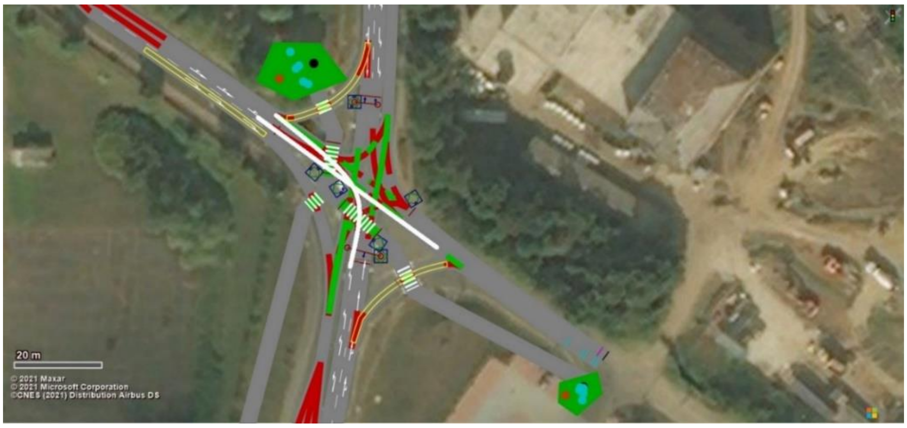


Figure 6: The progress curves and their crossing required for determining the first intermediate time interpreted in the model

The calculation of the intermediate time was based on the formula determined in the Hungarian e-UT 03.03.31 road technical regulation – the latter is viewable on the homepage of the Hungarian Public Roads and is published by the Hungarian Road and Rail Society. The format in which the general formula is applied in the current research can be found in one of the practical educational materials of the traffic engineering course at the Department of Transport Technology and Economics of the Budapest University of Technology and Economics, and it is the following:

$$t_k = t_{\acute{a}tm} + \frac{l_{ki}+l_{jm}}{v_{ki}} - \frac{l_{be}}{v_{be}} \tag{1}$$

Where:

t_k : is the intermediate time,

$t_{\acute{a}tm}$: safety time, which in all cases is 3 seconds

l_{ki}: clearance distance

l_{jm}: the length of a passenger vehicle, which is determined as 6 meters for all cases

v_{ki}: speed of the outgoing vehicle: if the road section is straight, then 10 m/s, if it is between 6-25 m arc radius, then $\sqrt{4 * R}$

l_{be}: approach distance

v_{be}: the speed of the approaching vehicle: if the road section is straight, then it is 13.9 m/s, when turning then it is 11.1 m/s

In the case of the two progress curves mentioned above, as a first step, the parameters of the lane turning into the university from the south were measured. The structure of this lane can basically be divided into two units, a straight section and a turning section. The other lane, coming from the university, consists of a single straight section. The meeting point of the two lanes can be observed in the previous Figure 6. Figure 7 below shows the measurement of the straight section and part of the turning section of the curving arc inside the model (it was only possible to measure the length of the entire arc in two steps, the first of which consist of these two measurements). It can be seen from the figure that the length of the straight section is 9.13 meters and the first half of the turning section is 7.67 meters.

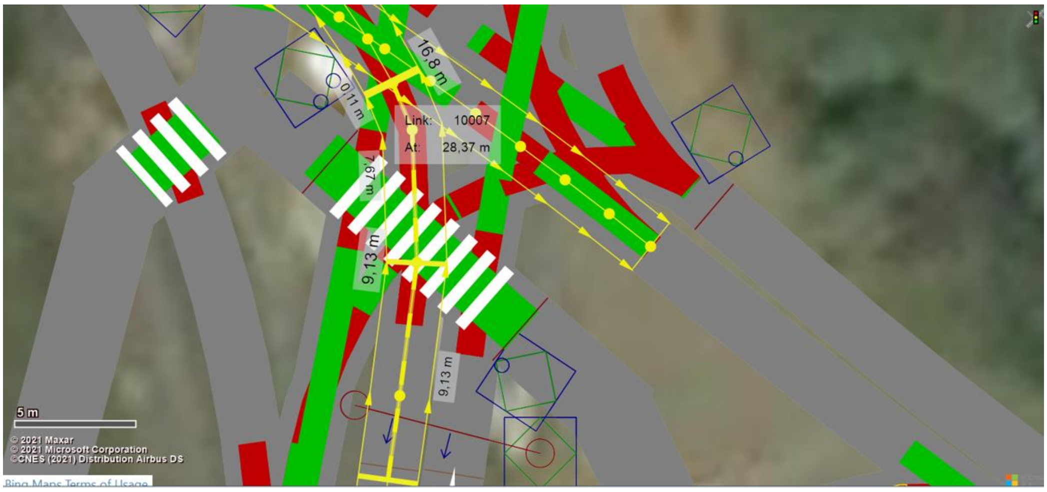


Figure 7: The first step of measuring the distances required to calculate the first intermediate time interpreted in the model

After the previous measurements, three more steps were necessary to record all the distance parameters needed to determine the first intermediate time. After the measurements, by properly substituting the measured data and the parameters from the regulation into formula (1), 5.113s was received for the first necessary intermediate time, which is clearly smaller than the 8-second intermediate time existing between the investigated phases in the modified signal program (the latter can be observed in Figure 5 by comparing the 4th and 5th rows of the optimized program).

Following the previous analysis, the necessary intermediate time was determined in the case of three more relations relevant to the examined phases (see Figure 8 below):

Figure 8: The relations for determining the other three intermediate times interpreted in the model

The result of the complete analysis was that all four of the determined necessary intermediate times were clearly less than 8 seconds, so from this point of view there was no obstacle to the application of the optimized program within the model.

Here again it has to be highlighted that the necessary distance data for calculating the intermediate times were measured inside the model using only approximate methods, therefore the results are also only close approximations which are solely relevant inside the framework of the simulation and not in any other context! For determining the completely precise intermediate times, a full-scale traffic engineering analysis would be needed based on precisely measured real distance data!

The effect of using the optimized signal program was examined from several points of view. However, within the scope of this publication, it is not possible to provide a detailed description of all the tests, so only the most important result, the impact on the total traffic throughput of the entire system, will be presented. In order to determine the total traffic throughput, it was naturally necessary to measure the passing traffic in each incoming and outgoing lane in the simulation model. For this, measuring points called "Data Collection Points" were placed in the simulation environment for all lanes of both intersections. The following Figure 9 shows, as an example, how the points measuring the incoming traffic were placed at the southern intersection (for both intersections it was therefore necessary to place the points measuring the incoming and outgoing traffic separately):

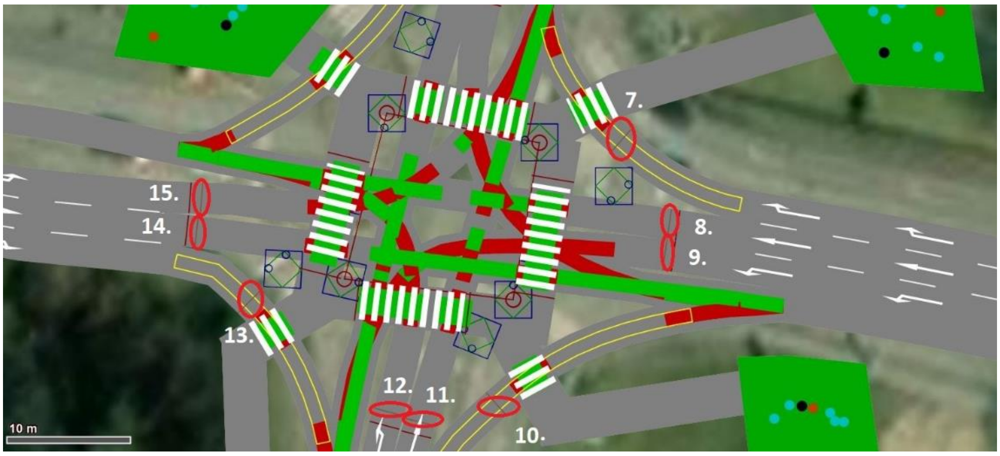


Figure 9: The location of the Data Collection points monitoring incoming traffic at the southern intersection

After placing the mentioned measurement points in all the lanes, it was possible to determine the total number of vehicles that drove in and out during the examined time interval for the entire system, which in this case was 15 minutes, for both the morning and the afternoon (See Table 3 below):

Table 3: Effect of the application of the optimized signal program on the entire system

	Morning			*Afternoon*		
	Initial	*Optimized*	*Difference*	*Initial*	*Optimized*	*Difference*
Number of incoming vehicles	490	500	10	426	428	2
Number of outgoing vehicles	454	482	28	409	417	8

5. Description of the roundabout-based model

Roundabouts are generally created at high-traffic or dangerous intersections. One of their advantage is that they can speed up the passage of traffic due to the almost continuously entering vehicle flow, even if this comes with a reduction in the speed of the vehicles. Because of this advantage, the possibility of replacing the traffic light intersections in the system in question with roundabouts was investigated. The main question of the analysis was that how a roundabout-based solution would compare to the existing system with the optimized signal program in terms of traffic throughput.

The basic parameters of the roundabouts in the new model were determined based on the Hungarian e-UT 03.03.11. road technical regulation and also on a lecture on the topic from the Department of Civil Engineering of the University of Pécs (Lindenbach, 2018). Starting out from the base parameters, in the framework of the model a type II normal roundabout was created at the location of the southern intersection, while a type I. normal roundabout (i.e. a roundabout located in a tightly built-up area) was implemented as a replacement for the intersection leading to the university (the northern intersection). Based on the regulation, it can be determined which types of vehicles must be examined separately for passing through roundabouts. For the type II., a separate roadworthiness test is required only for the vehicle transporter with a trailer, but for the type I., in addition to the previous one, it is necessary to carry out the mentioned test for both semi-trailer vehicles and articulated buses.

As in case of the optimization of the signal program, it must be highlighted here as well that the implemented roundabouts are only relevant inside the framework of the model. In fact, the parameters of the intersection leading to the university are not very favorable from the point of view of building a roundabout, so without a major landscaping and the creation of the appropriate environmental features, it is most likely not possible to create a roundabout of a type that would be suitable for passing the current traffic composition. During the simulation study, these factors were not taken into account, since the aim of the modelling was to compare the differences between the two systems, not to actually design a new road system, the latter of which is not possible without completely accurate data and a full-scale traffic engineering analysis. The next figure shows the design of the southern roundabout:

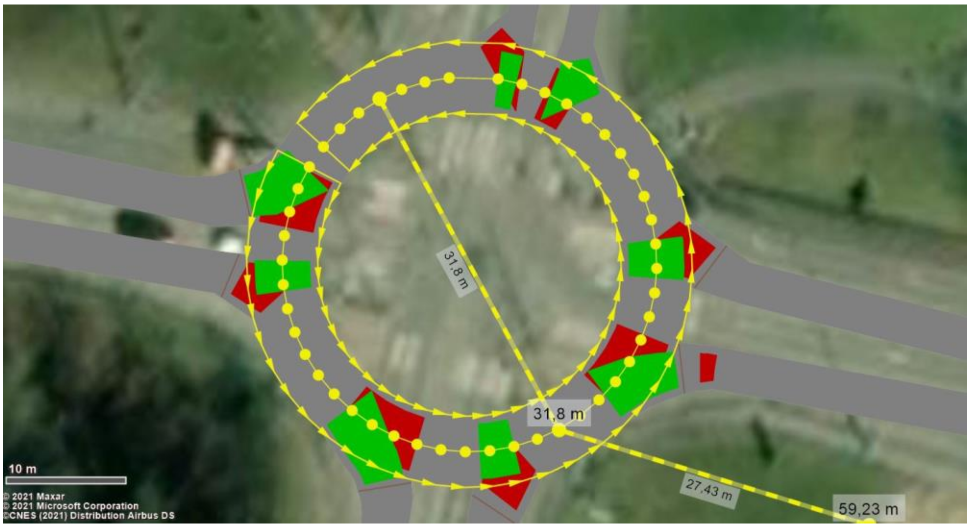


Figure 10: Design of the southern roundabout

As it was mentioned, the main parameters of the roundabout were based on the relevant regulation. The width of the road surface is 7 meters, and the inner diameter and the size of the passable ring were determined by subtracting half of the road surface from the diameter shown in Figure 10 and dividing the result by two. This is described by the following formula, where R_b denotes the inner radius:

$$R_b = \frac{31{,}8-7}{2} = 12{,}4 \text{ m.} \qquad (2)$$

The resulting inner radius value of 12.4 meters and the pavement width of 7 meters correspond to the parameters of a normal single-lane roundabout according to the regulations.

The location of the intersection leading to the university contained many more challenges from the point of view of roundabout planning. Compared to the southern intersection, there is significantly less space available, as it is a relatively densely built-up area. Another difficulty is that the connecting road sections are not perpendicular to each other, so separate calculations would have to be used to confirm whether the connecting branches make the right angle with each other. In addition to all this, when creating a roundabout, it may cause a problem that the topography of the mentioned junction may not meet the regulations. From the point of view of the modelling, these questions were not taken into account in the frame of the current research, but as it was mentioned before, if such or a similar concept would be realistically examined outside the simulation environment, significant emphasis should be placed on the aforementioned tests. The design of the northern roundabout can be seen in the following Figure 11:

Figure 11: Design of the northern roundabout

The parameters of the roundabout planned for the northern intersection were determined in the same way as for the southern one. The width of the road surface here is 6 meters, and the inner radius is:

$$\frac{24{,}05-6}{2} = 9{,}025\ m. \tag{3}$$

When planning the roundabouts, it was also taken into account that a significant number of large vehicles appear at the converted intersections. This is also supported by the earlier presented traffic counting results broken down into the types of vehicles. Therefore, it is extremely important that the passage of these type of vehicle can proceed without disturbance even in the transformed junctions. That is why the role of the passable ring must be emphasized once again, which can help in such cases to pass without obstacles. As it was also mentioned before, outside the framework of the simulation, separate roadworthiness tests would be required for specific types of vehicles according to the category of each roundabout.

A difference in the new model is that, due to the two roundabouts, new options for moving forward have arisen, such as turning back. Although this was also included as a way forward, since in this case it was not possible to establish metrics for this, it was not assigned what proportion of the traffic turns back. A deceleration zone was added to the entrance lanes connecting to the roundabouts, and the passing speed in both roundabouts was set to 35 km/h. In addition, signs drawing attention to roundabouts have also been placed. Finally, the conflicting places where vehicles can collide were designated, and priority obligations were defined and adjusted.

After all the parameters had been set, the data collection inside the model could begin. Of course, the main question was primarily how the throughput of the nodes changed compared both to the initial system, and to the original system with the optimized signal program. In order to determine the throughput of the roundabout-based system, 6 Data Collection Points were placed at the intersections for both the incoming and outgoing lanes. The following Figure 12 shows the location of the measuring points for measuring the outgoing traffic:

Figure 12: Location of the measuring points for the measurement of the outgoing traffic

The results obtained and their comparison with the results from previous models will be presented in the following final paragraph.

6. Comparison of the different model variants from the aspect of traffic throughput and conclusions

In Table 4 below, the numbers of the incoming and the outgoing vehicles in both the morning and the afternoon periods are compared in case of all the three model variants:

Table 4: Comparison of the incoming and outgoing traffic in case of all the three model variants in the morning and in the afternoon

	Morning			*Afternoon*		
	Initial	*Optimized*	*Roundabout*	*Initial*	*Optimized*	*Roundabout*
Number of incoming vehicles	490	500	550	426	428	510
Number of outgoing vehicles	454	482	533	409	417	485

It is clear from the above table that, compared to the initial state, both the application of the optimized signal program and the introduction of the roundabouts could cause significant improvements in the throughput of the entire system. The decisive factor in is the number of the outgoing vehicles, since these are the ones that truly passed through the system. We can also observe that the number of vehicles "stuck" at a given time - i.e. those that entered the system while the simulation was running but could not leave it before its end - became less and less with the application of the modifications. There were 36 such vehicles in the initial model in the morning, which was reduced by half to 18 vehicles after the optimization of the signal program. Using the roundabout-based model, we can observe a further, albeit slight decrease, as in this case the number of vehicles remaining in the system in the morning period is 17. However, if we examine the relationship between the outgoing and incoming vehicles in relative terms, then it is clear that the roundabout-based solution proves to be the best, as 96.9 % of the incoming vehicles left the system in this case, while this ratio is 96.4 % in case of the optimized signal program and is only 92.7 % in the case of the initial model. Of course, in absolute terms it is evident from the table that the roundabout-based model lets through by far the highest number of vehicles.

Regarding the examinations for the afternoon period, the most spectacular improvement can also be seen at the introduction of the roundabouts, even more so than in the morning period, as the number of outgoing vehicles increased from 417 in the case of the optimized signal program to 485 in the case of the roundabout-based model. However, regarding the number of the “stuck” vehicles, the third model here proved to be a bit less optimal, with a “pass ratio” of only about 95.1 %. It is likely that this difference is in connection to the fact that the amount of traffic is somewhat lower in the afternoon period and as a result, the roundabout-based system functions less optimally. Still, it can be clearly seen from the table that the absolute traffic throughput capability of the examined system could be significantly increased with the introduction of the roundabouts in the afternoon as well, perhaps even more so than in the morning period.

Overall, the results of the research clearly show that from the perspective of traffic throughput, the roundabout-based solution proved to be the best option in the context of the examined problem. Of course, there are a variety of other aspects that should also be taken into account in case of any real proposal, but these were beyond the scope of the current research. Also, as it was mentioned before on multiple occasions, while the simulations were made to be as realistic as possible based on actual traffic counting data, the results can still only be interpreted as close approximations meant purely for scientific purposes, as any implementable modification proposal would require a full traffic engineering analysis based on completely accurate data, among other requirements. Still, the presented research and its results could serve as a useful example for the study of similar problems in the field of traffic simulation and analysis.

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