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PERFORMANCE ANALYSIS OF ONE-LEVEL SIGNALIZED URBAN INTERSECTIONS WITH EXCLUSIVE PEDESTRIAN PHASES AND DIAGONAL CROSSINGS

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Abstract. The exclusive pedestrian (hereinafter P) phase with a diagonal crossing is routinely introduced to improve P safety at high-volume intersections. The article analyses and evaluates the feasibility of the exclusive P phase and diagonal crossing at single-level smaller intersections, identifying the advantages and disadvantages of the exclusive P phase and diagonal crossing from the point of view of time losses. In the experimental part, traffic flow modelling is carried out. The traffic flow simulations show that an exclusive P phase is most beneficial in terms of time losses at an intersection with 2+2 lane

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intersecting streets and ≥ 900 P/hour with ≥ 1600 vehicles/hour (hereinafter V). In addition, an exclusive P phase can be implemented at the small intersections analysed in this paper, where the volume of V is low or medium, regardless of the number of P at the intersection.

Keywords: efficiency assessment, geometric model of intersection, intersection control, pedestrian scramble, pedestrian priority, time losses, traffic flow modelling.

Introduction

Pedestrians (hereinafter P) are the most vulnerable group of road users, and ensuring their safety in the street network is one of the main challenges of the urban transport system. In theory, P should be safe when crossing at a P crossing, but the complex structure of the city's street network makes this difficult. P traffic at traffic light-controlled intersections is usually accompanied by parallel traffic of vehicles (hereinafter V) and V making right and left turns. This means conflicts between P and V making turning manoeuvres often arise at this type of intersection. This is one of the most frequent conflicts at intersections. To improve the level of P service and safety, an exclusive P phase with a diagonal crossing is being introduced at a traffic-light controlled intersection with high P traffic due to the presence of attractions in the surrounding area. The exclusive P phase stops V traffic in all directions at the intersection and theoretically eliminates conflicts between P and V, which can increase P safety, while the diagonal crossing can reduce travel time and walking distance for P who want to cross the intersection diagonally. It is often hypothesised that an exclusive P phase with a diagonal crossing can only be introduced when very high P flows are present at a big intersection. In Lithuania, as in some other foreign countries, exclusive P phases in the traffic light control cycle are introduced, but the diagonal P crossing at an intersection is not clearly regulated, so it is appropriate to determine whether there are such V and P flows where it is beneficial, from the viewpoint of time losses, to introduce a diagonal crossing at an intersection.

In this context, co-authors have set the main objective of the work to determine, with traffic flow micro-modelling, at which V and P threshold flows it is appropriate to introduce an exclusive P phase with a diagonal crossing at the intersection, considering the time-saving approach. This work analyses standardised and simplified time-saving solutions for traffic light-controlled intersections with an exclusive P phase and diagonal crossing, and the sufficiently important and positive traffic safety aspect of diagonal crossings and an exclusive P phase has been analysed in previous articles (Vaziri, 1998; Bechtel et al., 2003; Kattan et al., 2009; McKernan, 2016; Juozevičiūtė & Grigonis, 2022). Modelling traffic flows at intersections is often carried out using software applications that, once the models are properly calibrated, can provide suggestions for the evaluation of transport infrastructure alternatives (Eom & Kim, 2020; Qadri et al., 2020; Vaiana et al., 2013; Gallelli et al., 2017; Gallelli et al., 2021; Gallelli & Vaiana, 2019).

After the implementation of an exclusive P phase with diagonal crossing at intersections, it is important to understand how the time cost changes and which technical parameters of the intersection loading determine time cost. Historically, the exclusive P phase with a diagonal crossing became common in Denver, Colorado around 1951, due to Mr H. Barnes (Federal Highway Administration, 2017). The P phase with a diagonal crossing was given the name “Barnes dance” when a city hall reporter wrote the crossings “made people so happy that they are dancing on the streets.” However, due to low usage of diagonal crossings (The Denver Channel, 2011) (less than 10% of P were crossing in such a way) and increased willingness to balance the system for P, cars, transit, and bicycles (The Denver Post, 2011), Denver eliminated diagonal crossings at intersections in 2011. The city maintains “all-walk” signal operations but will not allow people to cross diagonally.

Previous research has also analysed whether a properly designed exclusive P phase with a diagonal crossing reduces the average distance P walk at an intersection and whether P can cross such an intersection with minimal delay compared to a controlled intersection without the possibility of crossing the intersection diagonally. Such research was carried out by Marsh in 1982 (Marsh, 1982), using a computer-based traffic flow simulation programme at New Zealand intersections. Research found that, at an intersection with an exclusive P phase and a diagonal crossing, the average P has to walk a shorter distance of 5% to 7%. Other researchers confirmed a similar result (Bechtel et al., 2004), who found that an exclusive P phase with a diagonal crosswalk reduced P walking distance by an average of 13%, resulting in a non-increase in average P delays. For P who wanted to cross perpendicularly, the delay increased in some cases (depending on the point in the light cycle when the P approached the intersection), while for P crossing diagonally, the delay decreased.

In Toronto, Canada, following an intersection management change in 2008, experts (Bissessar & Tonder, n.d.) found that the implementation of an exclusive P phase with a diagonal crosswalk changed the level of service of the V from B to D during the peak hour (delay per V before – 15.6 s, after the installation – 37.6 s). This means V delays increased by 141%. However, this type of control was chosen since the average number of P crossing this intersection in Toronto was 50 000 per

24 h, while the number of V was much lower, at 36 000 V per 24 h. Two exclusive P phases with a diagonal crossing were also introduced in Calgary, Canada. The same experts carried out tests and found that the level of service at both intersections changed from B to C during the peak period (at intersection 1, the delay per V before was 17.8 s, after 31.2 s, at intersection 2, the delay per V before was 12.8 s, after 27.3 s).

A study using traffic flow modelling software was carried out to evaluate the effectiveness of an exclusive P phase with a diagonal crosswalk in the central business district of Melbourne, Australia (Nash & Smith, 2010). This was found to slightly reduce P delay but to increase V delay by several times. Another study presented results that were more extensive. In 2014, researchers Tu and Sano (Tu & Sano, 2014) found in a simulation study that, for high P volumes, an exclusive P phase with a diagonal crosswalk could improve the capacity of an intersection by as much as 36% considering that, not only V, but also P were included in the time-saving calculations. Thus, if the number of P at an intersection is more than 4800 in 1 peak hour, it is useful to provide a diagonal crossing at all traffic flows. In addition, it was found that, with 1200 V and 2000 P, it would be beneficial to introduce an exclusive P phase in terms of time savings. The researchers concluded that the lower the V flow and the higher the P flow, the more advantageous it would be to introduce an exclusive P phase with a diagonal crossing in terms of time savings. The researchers also found that, in a modelled intersection where P traffic was combined with V traffic, the LOS (Level of service) of the intersection was directly related to the number of P and number of V turning, i.e., the level of service of the intersection could change from C to F as a result of the increased P traffic, and this change was exponential. With the introduction of an exclusive P phase at the intersection with the diagonal crossing, the level of service of the V remained at D, regardless of the variation in P volumes.

Scientists point out that it is important to assess the impact on the intersection permeability before changing the control of an intersection (Mahmud & Magalotti, 2018). These scientists used a simulation programme to simulate an intersection with an exclusive P phase and a diagonal crossing, using standard intersection control (P phase activated with parallel-moving V) and selecting the optimum traffic light cycle and phase times. In this study, the total theoretical delay for road users was reduced by more than 50%.

A comparative study on intersection management was performed in 2018 by researchers (Zhang & Su, 2018). The simulations were carried out at large four-leg intersections with intersecting streets with lane counts ranging from 3+3, 5+5, 7+7 to 10+10, and with traffic light working cycle lengths ranging from 120 s to 180 s. By simulating the intersection, the scientists found that, when P traffic was combined with parallel V, P and V delays were lower when the volume of vehicular and P traffic fell within these ranges:

- V ≤ 2160, P ≤ 740;
- 1728 ≤ V ≤ 3600, 972 ≤ P ≤ 2700;
- 2880 ≤ V ≤ 7200, 1296 ≤ P ≤ 3600.

The research results showed that an exclusive P phase with a diagonal crossing was beneficial in terms of time delay at intersections where the traffic volume of the road users fell within these ranges:

- V ≤ 2160, P ≤ 740;
- 1728 ≤ V ≤ 3600, P ≥ 2700;
- 2880 ≤ V ≤ 7200, P ≥ 3600.

The simulation results show traffic flows are, to a large extent, the decisive factor in the choice of intersection management. Intersection control, where P traffic is combined with parallel V, is useful when P and V volumes are relatively low. The exclusive P phase with diagonal crossing reduces delays for road users moving in high-traffic flows. The scientists concluded that it was important to consider the total delay of all road users (both V and P) when modelling an intersection and selecting the appropriate control. However, this study had limitations that prevented the results from being applied to smaller intersections. First, the intersections studied were very large (between 3 and 10 traffic lanes), which was typical of large cities with populations in the millions. Second, the modelling of the intersections did not assess the effect of increasing and decreasing the flow of turning V on the delay.

Thus, a number of studies confirm that an exclusive P phase with a diagonal crosswalk installed at an intersection either increases V delay or indicates that there is a potential for optimizing the performance of the intersection (Bissessar & Tonder, n.d.; Nash & Smith, 2010; Mahmud & Magalotti, 2018). This shows how important it is to simulate intersection changes with modelling software before making changes to intersection management. Research by scientists (Tu & Sano, 2014; Zhang & Su, 2018) has shown that an exclusive P phase with a diagonal crossing at certain P and V flows reduces overall delay for road users. An exclusive P phase with a diagonal crosswalk at intersections is effective when high P volumes are observed (Bechtel et al., 2004; Mahmud & Magalotti, 2018; Zhang & Su, 2018).

Vaziri (1998) compared accident statistics at six intersections using 20 years of accident data after a study performed in Beverly Hills, California. Based on the data collected ten years before and 10 years after the introduction of an exclusive P phase with diagonal crossing, he developed a list of recommendations to help assess whether an intersection should be equipped with an exclusive P phase with diagonal crossing, but stressed that these were not indisputable criteria and further research would be needed when considering changes to an intersection. List of recommendations by the researcher:

- The total number of P at the intersection should be high (ideally ≥ 1000 P per hour) at least four hours per day;
- The number of V at an intersection should be low and stable for most of the day with a high percentage of V performing the turning manoeuvre. It is important that the peak period of V traffic coincides with the peak P intensity, as the extended V phases and the increased P waiting time will not provoke P to cross the intersection during an unauthorised signal due to the high volume of V traffic. The recommended V intensity of the intersection should be ≤ 2000 V/hour;
- It is recommended that the level of service (according to HCM, 2010) of the selected intersections is at least C;
- To determine the length of the P phase flashing the green signal and the red signal before activating the V phase, the time needed to cross the intersection diagonally at normal speed must be calculated. As a result, less time is needed for the exclusive P phase at a smaller intersection, which reduces V delay. It is recommended that the diagonal crossing should be no longer than 12 m for minor streets and between 12 and 20 m for major streets;
- It is recommended to select intersections carefully to introduce an exclusive P phase with a diagonal crossing, especially when the intersection is not a one-way street;
- The selected intersections must be well-lit to ensure that the diagonal P crossing is clearly visible in the dark;
- Additional P traffic lights and other information measures are desirable at intersections to provide clear traffic management.

The Department of Planning, Transport, and Infrastructure of South Australia (Government of South Australia, Department of Planning, Transport and Infrastructure, 2019; Nash & Smith, 2010) has drawn up a document for the installation and operation of an exclusive P phase with a diagonal crossing, which aims to improve P safety and guarantee reasonable flexibility in the phasing of the traffic lights at the intersection to ensure proper traffic management at the intersection. Locations, where exclusive P phases with diagonal P crossings may be introduced, should comply with the following requirements:

- P flows must be high. High flow – at least 10 P per traffic light cycle. For example, if P are evenly distributed at an intersection and the traffic light cycle length is 120 s, the minimum P flow at the intersection should be around 300 P/hour;

- At least 10% of P, for at least 4 h a day, need to cross the intersection diagonally (determined by means of observations, surveys and monitoring of P movement);
- Both V and P delays are generally increased with the introduction of a diagonal P crossing, compared to standard intersection management, where P move with V flows. This is likely to lead to greater frustration and a stronger tendency for unauthorised P crossing at a prohibited signal, so V flows need to be high enough to discourage P from crossing unsafely at the intersection;
- If these requirements are only met at certain times of the day or days of the week, consideration may be given to the introduction of part-time diagonal crossing or the introduction of an active P phase. The P phase is not included in the traffic light cycle until a P calls for it by pressing the call button;
- Public transport should not suffer additional delays with a diagonal P crossing, which requires the consent of the public transport company;
- An exclusive P phase with a diagonal crossing should not be implemented where there are more than 4 intersection entrances, streets intersect at an angle of 70–90 degrees, there is a diagonal crossing of more than 36 m, there are two intersections, side by side, connected by a continuous control, there are intersections of fast-moving streets, or there are major streets;
- Diagonal crossings are recommended where there is heavy use of the city's shops and/or tourist areas.

After reviewing a number of studies and the recommendations/requirements for exclusive P phases and a diagonal crossing in individual countries, it is clear the recommendations depend on the characteristics of the site: the permissible length of the diagonal crossing, the percentage of P crossing while using the diagonal crossing, the geometry of the intersection, and the varying perception of what constitutes a "high P volume" from one place to another. Thus, the niche of this study is small traffic-light-controlled intersections with an exclusive P phase and a diagonal crossing. The aim of the traffic flow micro-modelling is to determine at which V and P threshold flows it is appropriate to introduce an exclusive P phase with a diagonal crossing at the intersection, considering the time-saving approach.

1. Building and evaluating the model

Traffic congestion is a daily problem in major cities and major roads in many countries. The road and street network system is complex due to the interaction between P and V, so to present a new solution to a network problem, it needs to be tested, evaluated, and exemplified in a model before it is implemented in a real situation. Simulation tools, including but not limited to PTV VISSIM, AIMSUN, PARAMICS, and others, are utilized to visualize, validate, and analyse newly proposed solutions, facilitating the development of optimal traffic networks and their control strategies. Studies have been carried out to determine which modelling software has advantages in different aspects (Ullah et al., 2021; Sun et al., 2013; Saidallah et al., 2016). PTV VISSIM micro-modelling software was employed in this work with predefined settings as it is widely used to model all kind of geometrically existing crossings (including roundabouts) with vast amount of traffic and other parameters to be defined and refined, for multimodality option, usage of Widemann car following model, etc.

This study does have clear limitations rooted in specific assumptions. These limitations encompass several areas, including the predetermined intersection management options, fixed cycle lengths with minimal phase numbers, the simplification of geometric intersection models, uniform assumptions regarding V and P volumes, and a predefined distribution of V turning manoeuvres. These simplifications are a result of the research aim for feasibility and comprehensibility. However, it is important to recognise that extending these assumptions would open the door to a broader spectrum of alternatives. For instance, increasing the number of phases to accommodate various turning V movements and enhance traffic safety is a plausible approach, but it would invariably make the optimization of the traffic light cycle a more complex and integral component of the task. However, in this case, the same V and P flows and manoeuvres are assumed in all directions, resulting in completely reduced relevance of the V delay optimization with a minimal number of V phases. The study calculated the travel time for V and it used the default VISSIM parameters for the V structure.

In this part of the study, three intersection management options were modelled:

1. Concurrent P phasing (CPP) – P at the intersection are unprotected, walking alongside parallel V traffic;
2. Exclusive P Phase (EPP) – P are protected in the exclusive phase but can only cross the intersection perpendicularly;
3. Exclusive P phase with diagonal crossing – P are protected in the exclusive phase and can cross the intersection in all directions, including the diagonal crossing.

Based on the above-mentioned research (Zhang & Su, 2018; Vaziri, 1998; Government of South Australia, Department of Planning, Transport and Infrastructure, 2019; United States Department of

Transportation, Federal Highway Administration, n.d.; Tang et al., 2020), the control cycle time of traffic lights should be positioned around 120 s to avoid P violations. Apparently, 120 s is the time a person can wait without feeling tension, making them want to cross an intersection at a prohibitive signal. The duration of the exclusive P phase shall be calculated in such a way that a P entering the intersection at the flashing green signal can cross the intersection in the permitted directions at the normal speed of 1.2 m/s. During CPP control of an intersection, the duration of the P phase coincides with the duration of the V phase.

Three geometric models of intersections were modelled:

1. A four-leg intersection where the intersecting streets have two traffic lanes: one lane in each direction (lane width 3 m, total lane width is 6 m);
2. A four-leg intersection where the intersecting streets have two traffic lanes: two lanes in each direction (3 m lane width, total lane width is 12 m);
3. A four-leg intersection where the intersecting streets have five traffic lanes: three lanes for entering the intersection and two lanes for exiting (lane width 3 m, total lane width is 15 m).

The modelled intersections vary in load as the number of V and P volume changes: from 300 to 900 P per hour and from 800 to 2400, 3200, or 4800 V per hour (the number of V modelled depends on the size of the intersection).

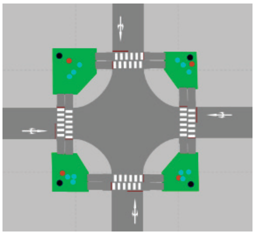
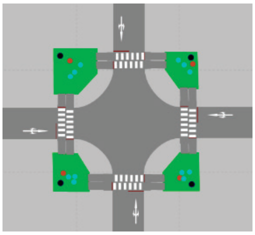
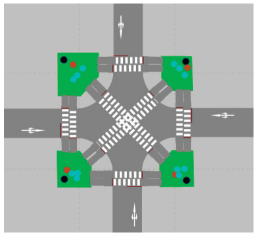
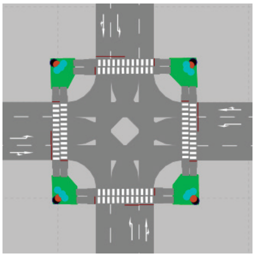
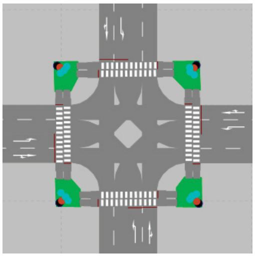
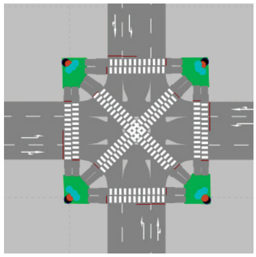
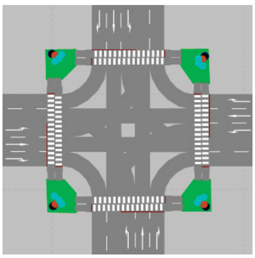
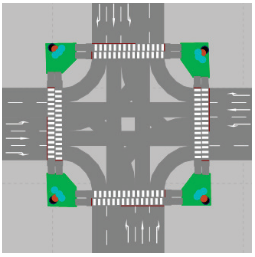
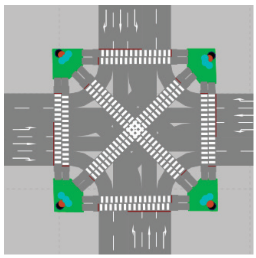
There are different V turning manoeuvres at intersections – they can proceed left, straight, and right. The distribution of V flows is 25% left, 25% right, and 50% straight. It is assumed that the demand for P movement at intersections is the same in all directions. The main intersection modelling descriptive data are shown in Table 1.

The following is a description of the development of the first intersection geometrical model that simulates P and V traffic on a four-leg and 1+1 lane intersection under three different intersection control options and a description of the flow (origin-destination) combinations. The same procedure is applied to the second (2+2) and third (3+2) geometric models of the intersection.

When developing a traffic model, the V and P origin-destination matrixes were developed, which indicated the directions of V and P movement from one zone to another (Figure 1).

Three combinations of the V origin-destination matrices were created, considering the different V intensities, and three combinations of the P origin-destination matrices were created, taking into account P intensities. The combinations of the V origin-destination matrices are shown in Table 2. The combinations of the P origin-destination matrices are shown in Table 3.

Table 1. Description of the theoretical intersection control options and geometric models

Control options / Geometric models and flow combinations	Option I 2 or 4 phases, unprotected P (2 directions to walk)	Option II 3 or 5 phases, P are protected (4 directions to walk)	Option III 3 or 5 phases, P are protected (6 directions to walk)
1+1 traffic lanes; 300–900 P; 800–2400 V			
2+2 traffic lanes; 30–900 P; 800–3200 V			
3+2 lanes; 300–900 P; 800–4800 V			

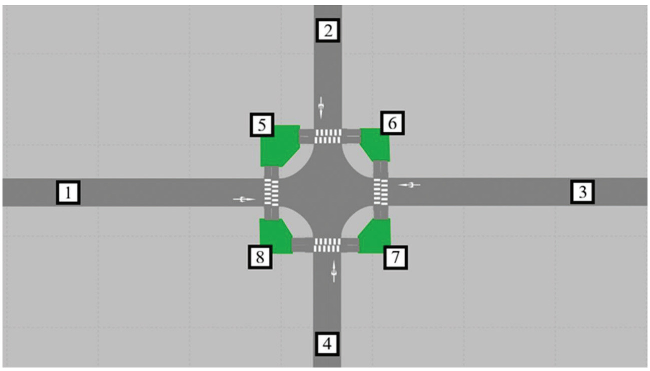


Figure 1. V (1–4) and P (5–8) zones

In Option I, the traffic light cycle consists of 2 principle phases (Figure 2), with the P phase being activated with the V parallel movement and turning. In this option, P at the intersection are not protected from conflicts with the V, and P movement during the phase is possible in two directions.

Table 2. Combinations of V origin-destination matrices with 200/400/600/800/1000/1200 V/hour entering the intersection per zone

Zones	1	2	3	4	Sum
1	0	50/100/150/ 200/250/300	100/200/300/ 400/500/600	50/100/150/ 200/250/300	200/400/600/ 800/1000/1200
2	50/100/150/ 200/250/300	0	50/100/150/ 200/250/300	100/200/300/ 400/500/600	200/400/600/ 800/1000/1200
3	100/200/300/ 400/500/600	50/100/150/ 200/250/300	0	50/100/150/ 200/250/300	200/400/600/ 800/1000/1200
4	50/100/150/ 200/250/300	100/200/300/ 400/500/600	50/100/150/ 200/250/300	0	200/400/600/ 800/1000/1200
Sum	200/400/600/ 800/1000/1200	200/400/600/ 800/1000/1200	200/400/600/ 800/1000/1200	200/400/600/ 800/1000/1200	800/1600/2400/ 3200/4000/4800

Table 3. Combinations of the P origin-destination matrices with 75/150/225 P/hour generated per zone

Zones	5	6	7	8	Sum
5	0	25/50/75	25/50/75	25/50/75	75/150/225
6	25/50/75	0	25/50/75	25/50/75	75/150/225
7	25/50/75	25/50/75	0	25/50/75	75/150/225
8	25/50/75	25/50/75	25/50/75	0	75/150/225
Sum	75/150/225	75/150/225	75/150/225	75/150/225	300/600/900

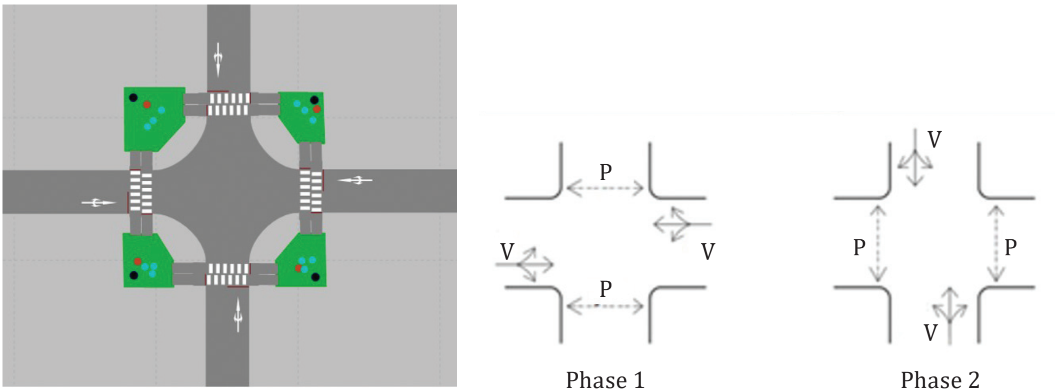


Figure 2. Principal phases of the traffic light cycle of Option I

The duration of the traffic light control cycle (120 s) for Option I of the intersection is divided into two phases. Phase V consists of traffic light 1–5 signal sequence and the phase P consists of traffic light 2, 3 and 5 signal sequence:

1. The red + yellow light signal is on for 1 s before the green light signal is activated;
2. The green light signal is on for 52 s for V and 51 s for P;
3. Flashing green light signal for V is on for 4 s; for P it is on for 3 s;
4. Yellow light signal is on for 1 s before the red light signal is activated;
5. Red light signal, before the movement of other road users in the second phase, is on for V for 2 s and for P for 5 s.

The PTV VISSIM software was used to create a traffic light work cycle (Figure 3).

In Option II, the traffic light cycle consists of three principle phases (Figure 4), with the P phase being activated separately from the V moving in particular directions. In this option, P at the intersection are exclusively protected from conflicts with the V, and P movement during the phase is possible in four directions.

The duration of the traffic light control cycle (120 s) for Option II of the intersection is divided into three phases. Phase V consists of traffic light 1–5 signal sequence and the phase P consists of traffic light 2, 3, and 5 signal sequence:

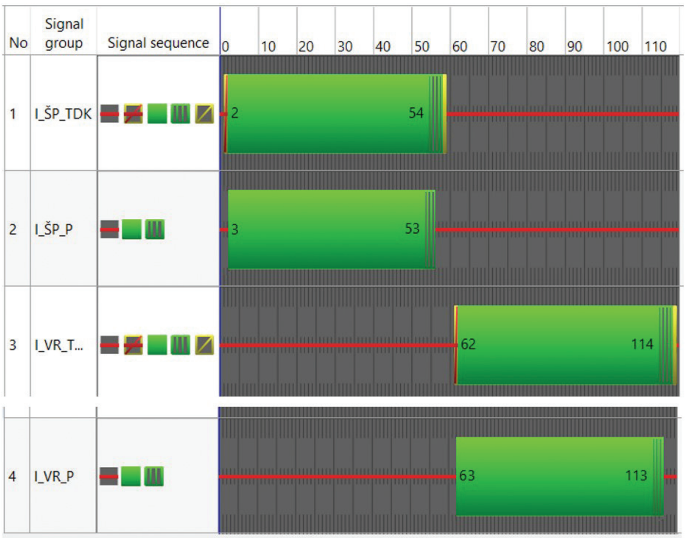


Figure 3. Traffic light cycle for Option I of the intersection (V phases No. 1 and No. 3, P phases No. 2 and No. 4)

1. The red + yellow light signal is on for 1 s before the green light signal is activated;
2. The green light signal is on for 45 s for V and 5 s for P;
3. Flashing green light signal for V is on for 4 s and for P for 3 s;
4. Yellow light signal is on for 1 s before the red light signal is activated;
5. Red light signal, before the movement of other road users in the second phase, is on for V for 2 s and for P for 5 s.

The PTV VISSIM software was used to create a traffic light work cycle (see Figure 5).

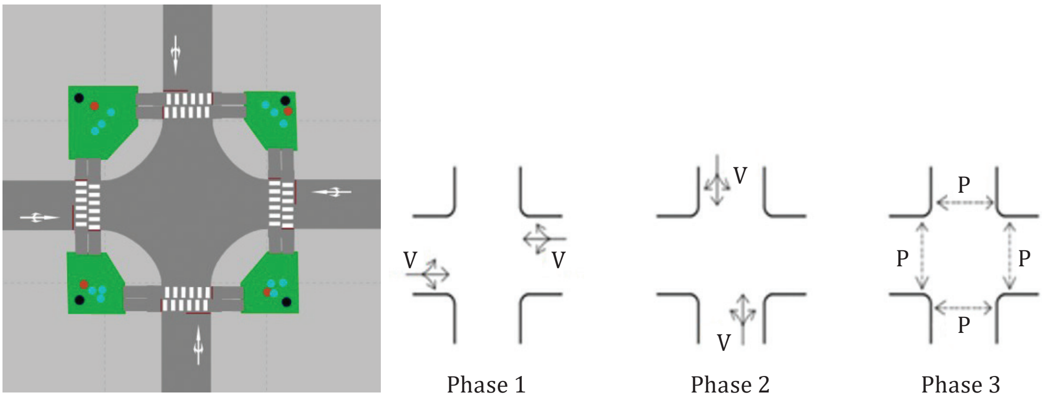


Figure 4. Principal phases of the traffic light cycle of Option II

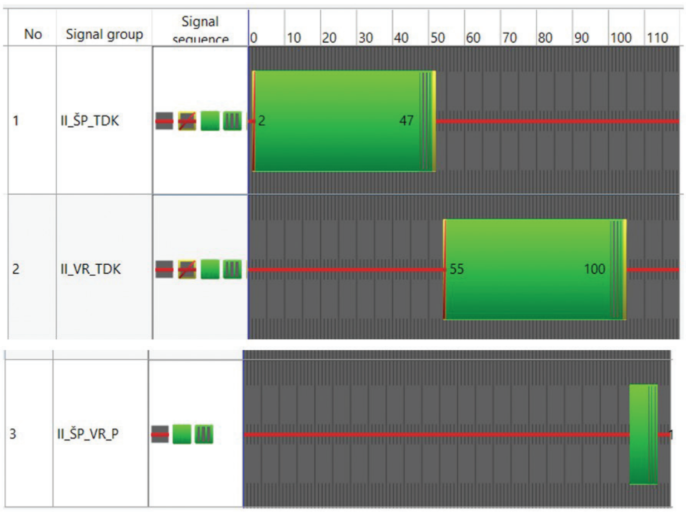


Figure 5. Traffic light cycle for Option II of the intersection (V phases No. 1 and No. 2, P phase No. 3)

In Option III, the traffic lights cycle consists of three principle phases (Figure 6), with the exclusive phase P activated separately from the V moving. In this option, P at the intersection are protected from conflicts with the V, and P movement during the exclusive phase P is possible in all directions.

The duration of the traffic light control cycle (120 s) for Option III of the intersection is divided into three phases. Phase V consists of traffic light 1–5 signal sequence and the phase P consists of traffic light 2, 3, and 5 signal sequence:

1. The red + yellow light signal is on for 1 s before the green light signal is activated;

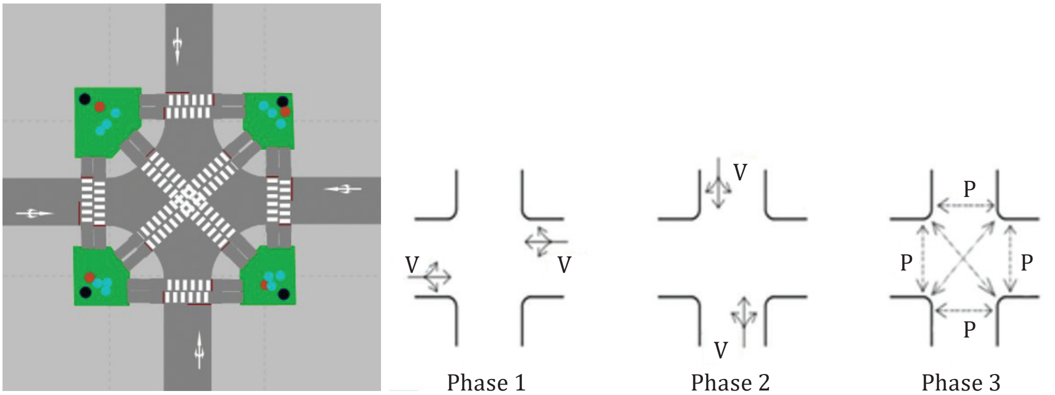


Figure 6. Principal phases of the traffic light cycle of Option III

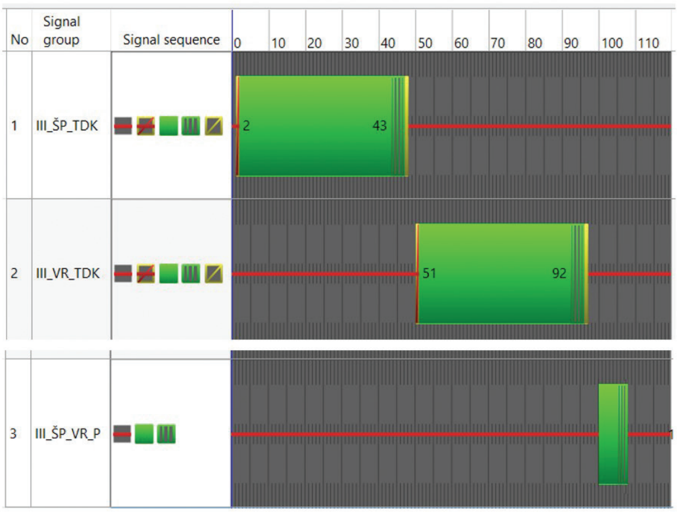


Figure 7. Traffic light cycle for Option III of the intersection (V phases No. 1 and No. 2, P phase No. 3)

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Vytautas Palevičius,
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Tomas Karpavičius,
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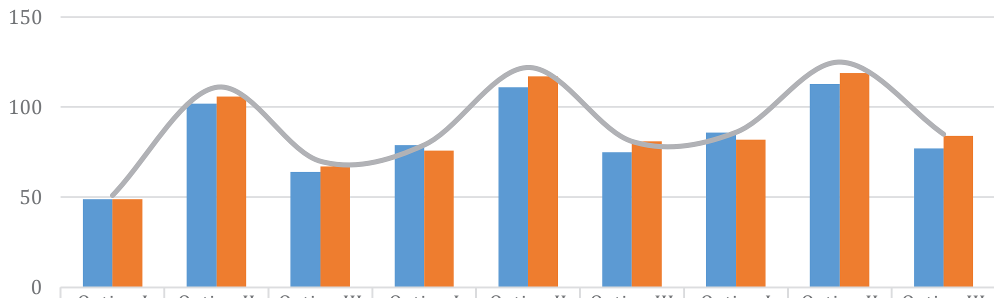
2. The green light signal is on for 41 s for V and 5 s for P;
3. Flashing green light signal for V is on for 4 s and for P for 3 s;
4. Yellow light signal is on for 1 s before the red light signal is activated;
5. Red light signal, before the movement of other road users in the second phase, is on for V for 2 s and for P for 13 s.

The PTV VISSIM software was used to create a traffic light work cycle (Figure 7).

2. Results of the research

By using PTV VISSIM software, three geometric models of the intersection were simulated with combinations of P and V flow volumes, and three different intersection management options were evaluated. The 117 simulation results were expressed in terms of the following criteria: average delay per car at the intersection; average speed of the V in km/h; average delay per car while not moving; total travel time of V; travel time of 1 V; total delay of V; number of the stops; total delay of V while not moving; number of V serviced; V left in the network; travel time of 1 P.

The capacity of a traffic light-controlled intersection and its level of service is indicated by the average V delay at the intersection, but to determine the quality at service of the intersection for all road users (traffic participants), it is important to evaluate P travel time.

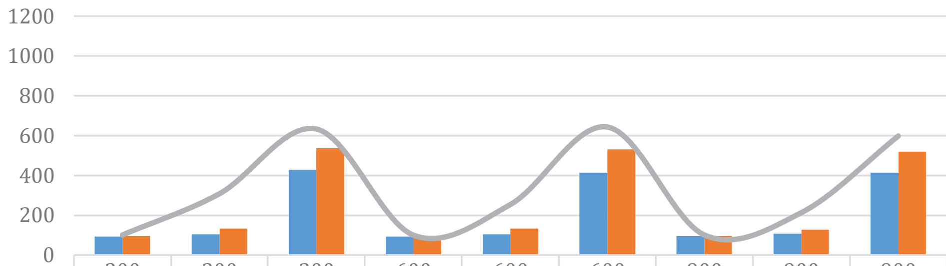


	1+1 lanes			2+2 lanes			3+2 lanes		
	Option I	Option II	Option III	Option I	Option II	Option III	Option I	Option II	Option III
300 P	49	102	64	79	111	75	86	113	77
600 P	49	106	67	76	117	81	82	119	84
900 P	51	111	70	79	122	81	86	125	85

Figure 8. Dependence of the average P travel time, s, on the geometric parameters of the intersection and on the control option of the intersection for selected combinations of P volumes

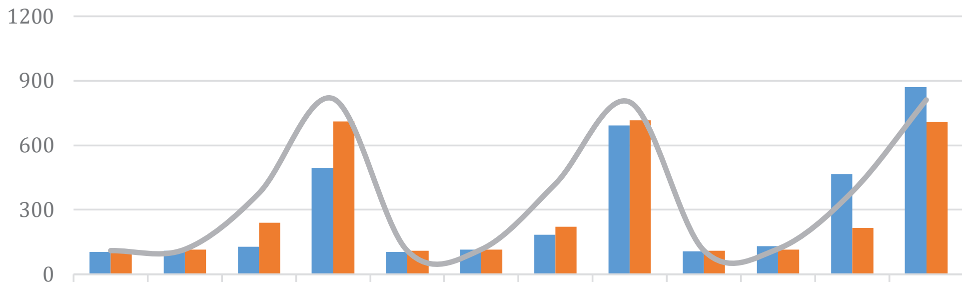
The modelling of the theoretical intersections has shown that, when streets with 1+1 traffic lanes intersect at an intersection, the lowest P travel time is when P traffic is combined with parallel moving of V, i.e., intersection control Option I (Figure 8). The intersection with 3+2 lanes is working well with control Option III as a result in the shortest trips. The exclusive phase P without diagonal crossing (Option II) results in almost a one-third longer P travel time compared to an intersection where the exclusive phase P is installed with a diagonal crossing.

a)



	300 ped./ 200 VE (800)	300 ped./ 400 VE (1600)	300 ped./ 600 VE (2400)	600 ped./ 200 VE (800)	600 ped./ 400 VE (1600)	600 ped./ 600 VE (2400)	900 ped./ 200 VE (800)	900 ped./ 400 VE (1600)	900 ped./ 600 VE (2400)
Option I	93	104	429	94	103	413	95	107	414
Option II	97	132	538	97	132	530	97	127	519
Option III	101	308	633	100	254	643	101	213	598

b)

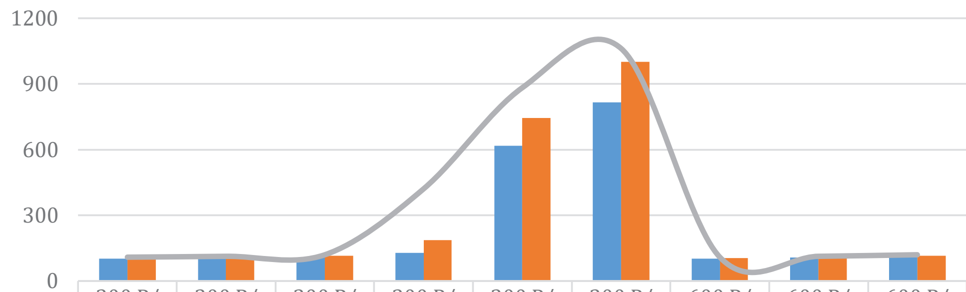


	300 P/ 200 V (800)	300 P/ 400 V (1600)	300 P/ 600 V (2400)	300 P/ 800 V (3200)	600 P/ 200 V (800)	600 P/ 400 V (1600)	600 P/ 600 V (2400)	600 P/ 800 V (3200)	900 P/ 200 V (800)	900 P/ 400 V (1600)	900 P/ 600 V (2400)	900 P/ 800 V (3200)
Option I	104	110	127	495	105	114	183	693	107	130	467	870
Option II	109	114	239	712	109	114	221	716	109	115	215	708
Option III	110	116	377	817	110	116	421	801	111	118	383	811

Figure 9. (a, b) Dependence of the travel time, s, of 1 V on the geometric parameters of the intersection and the intersection control option for selected combinations of traffic volumes

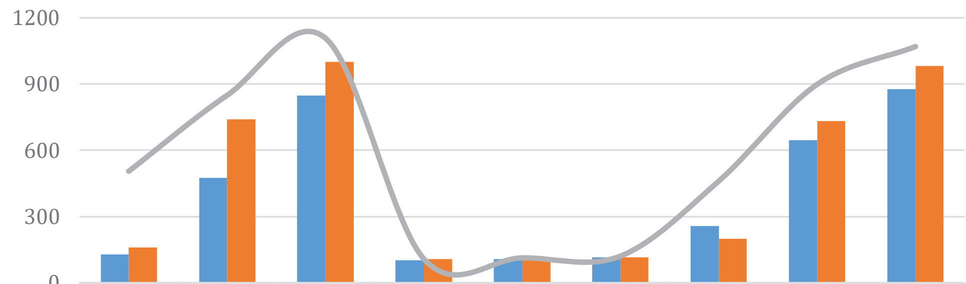
The results of the theoretical intersection simulations show that, in almost all cases, the V takes the least time to pass through intersection Option I, where V and P traffic run in parallel (Figure 9). However, the simulation results reveal that 2+2 geometrical model at ≥ 900 P/hour and V ≥ 1600 per hour results in the shortest V travel time. Option II eliminates P from the intersection during the movement phase of the V, allowing the V to move without interference. Control Option III is less favourable for V traffic, as the time of the exclusive phase P is longer compared to Option II, resulting in a higher average V travel time.

c)



	300 P/ 200 V (800)	300 P/ 400 V (1600)	300 P/ 600 V (2400)	300 P/ 800 V (3200)	300 P/ 1000 V (4000)	300 P/ 1200 V (4800)	600 P/ 200 V (800)	600 P/ 400 V (1600)	600 P/ 600 V (2400)
Option I	102	105	107	128	617	816	102	107	109
Option II	106	110	115	186	745	1000	106	110	115
Option III	109	113	120	421	883	1062	109	113	120

d)

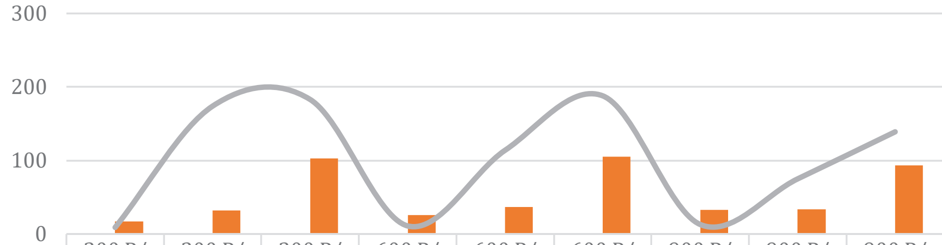


	600 P/ 800 V (3200)	600 P/ 1000 V (4000)	600 P/ 1200 V (4800)	900 P/ 200 V (800)	900 P/ 400 V (1600)	900 P/ 600 V (2400)	900 P/ 800 V (3200)	900 P/ 1000 V (4000)	900 P/ 1200 V (4800)
Option I	129	475	848	103	108	115	258	647	878
Option II	160	741	1000	107	110	115	199	733	983
Option III	505	849	1108	109	113	121	461	899	1070

Figure 9. (c, d) Dependence of the travel time, s, of 1 V on the geometric parameters of the intersection and the intersection control option for selected combinations of traffic volumes

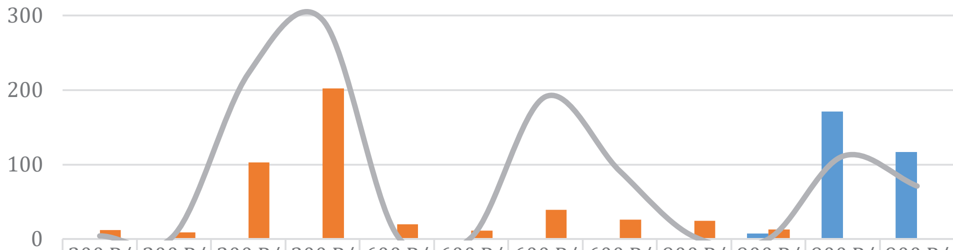
The level of service of an intersection for all road users (V and P) is further expressed in terms of time loss – time additionally spend when comparing different intersection control options (e.g., Option III–I), expressed in terms of the time difference (s) per road user (Figure 10). The simulation results show that, in almost all simulated cases, travel time per road user is lowest when the intersection is equipped with base intersection control: Option I – P are unprotected, V and P traffic are in parallel in the same phase. However, intersection control Option III, where streets with 2+2 lanes intersect, is best in terms of time loss when the intersection has a high P volume of ≥ 900 P/hour and a V volume

a)



	300 P/ 200 V (800)	300 P/ 400 V (1600)	300 P/ 600 V (2400)	600 P/ 200 V (800)	600 P/ 400 V (1600)	600 P/ 600 V (2400)	900 P/ 200 V (800)	900 P/ 400 V (1600)	900 P/ 600 V (2400)
Option I	0	0	0	0	0	0	0	0	0
Option II	17	32	103	26	37	105	33	34	93
Option III	9	174	183	11	114	188	13	75	139

b)



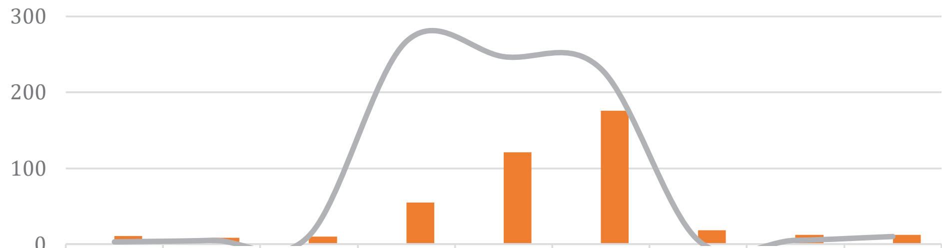
	300 P/ 200 V (800)	300 P/ 400 V (1600)	300 P/ 600 V (2400)	300 P/ 800 V (3200)	600 P/ 200 V (800)	600 P/ 400 V (1600)	600 P/ 600 V (2400)	600 P/ 800 V (3200)	900 P/ 200 V (800)	900 P/ 400 V (1600)	900 P/ 600 V (2400)	900 P/ 800 V (3200)
Option I	0	0	0	0	0	0	0	0	0	7	171	117
Option II	12	9	103	202	20	11	39	26	24	13	0	0
Option III	4	5	222	294	5	2	191	91	3	0	111	71

Figure 10. (a, b) Dependence of the time loss of the road user on the geometric parameters of the intersection and on the control option of the intersection for selected combinations of traffic volumes

of around 1600 V/hour. In addition, when analysing the results, the usefulness of control Options II and III in terms of time loss depends on the number of V at the intersection, i.e., when the number of V is low, it is more beneficial to implement intersection management Option III, which has an exclusive phase P with a diagonal crossing, but when the number of V increases, it is more beneficial in terms of time loss to implement intersection management Option II, which has an exclusive phase P without diagonal crossing.

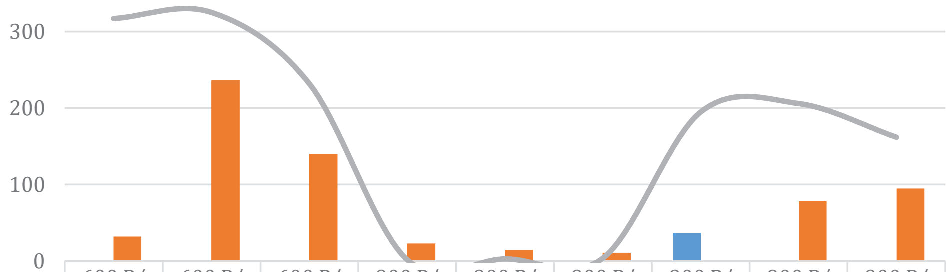
For the better representation of data in Figure 10 and to assess the extent of time losses in different geometric models of the intersection,

c)



	300 P/ 200 V (800)	300 P/ 400 V (1600)	300 P/ 600 V (2400)	300 P/ 800 V (3200)	300 P/ 1000 V (4000)	300 P/ 1200 V (4800)	600 P/ 200 V (800)	600 P/ 400 V (1600)	600 P/ 600 V (2400)
Option I	0	0	0	0	0	0	0	0	0
Option II	11	8	10	55	121	176	18	12	12
Option III	3	5	11	267	247	231	5	5	10

d)



	600 P/ 800 V (3200)	600 P/ 1000 V (4000)	600 P/ 1200 V (4800)	900 P/ 200 V (800)	900 P/ 400 V (1600)	900 P/ 600 V (2400)	900 P/ 800 V (3200)	900 P/ 1000 V (4000)	900 P/ 1200 V (4800)
Option I	0	0	0	0	0	0	37	0	0
Option II	32	236	140	23	15	11	0	78	95
Option III	317	325	232	2	3	4	195	206	162

Figure 10. (c, d) Dependence of the time loss of the road user on the geometric parameters of the intersection and on the control option of the intersection for selected combinations of traffic volumes

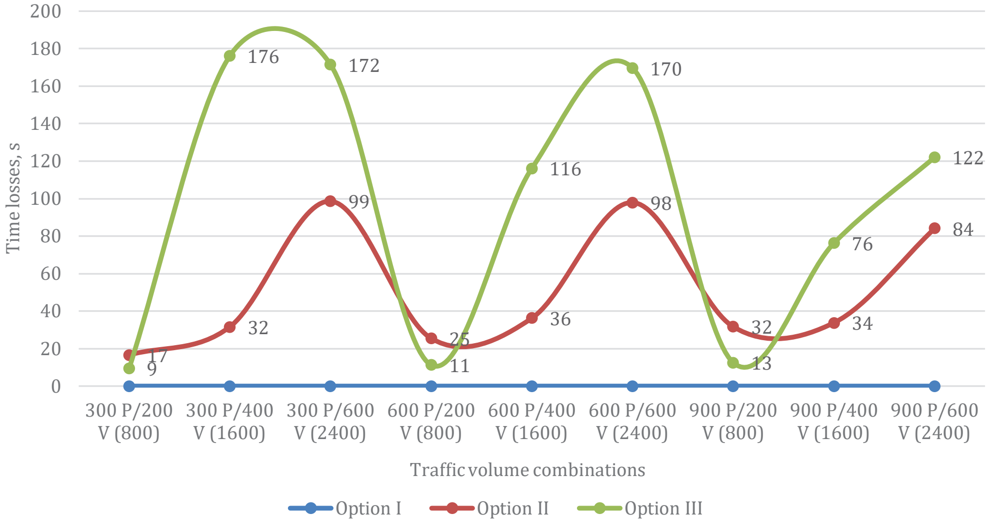


Figure 11. Dependence of the time losses experienced by 1 road user on the traffic volume combinations at different options of intersections with 1+1 lanes

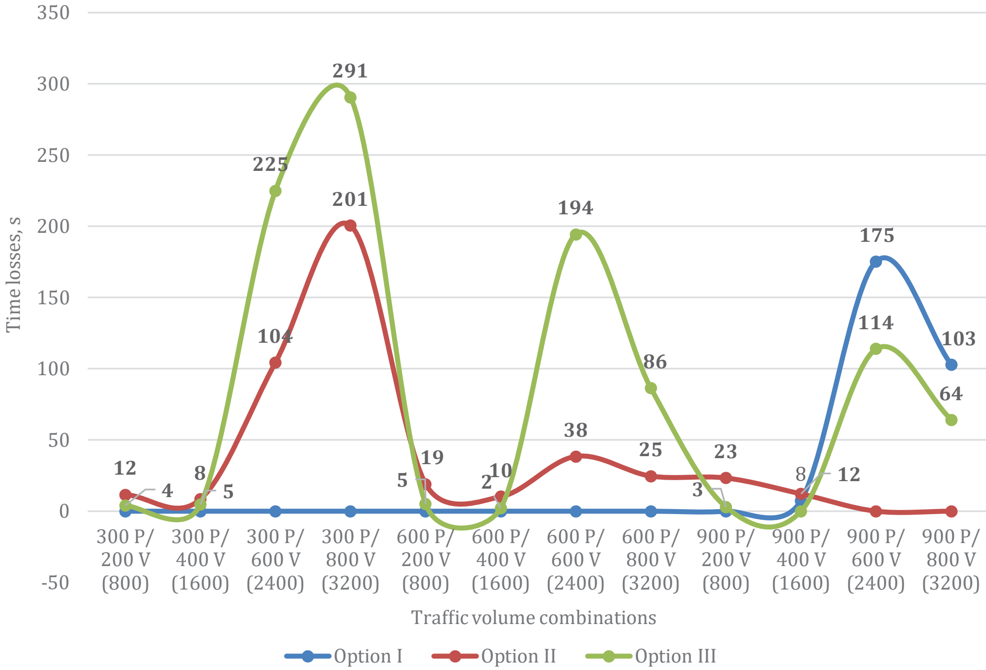


Figure 12. Dependence of the time losses experienced by 1 road user on the traffic volume combinations at different options of intersections with 2+2 lanes

Figures 11–13 were developed for different intersection control options. In the figures, the different coloured lines represent the time losses per road user for different intersection control options.

In all three figures, when the intersection has low V flows (up to 800 V/hour for a 1+1 traffic lane intersection; up to 1600 V/hour for a 2+2 traffic lane intersection; up to 2400 V/hour for a 3+2 lane intersection), regardless of P volumes, the difference in the time losses between the three intersection management options (especially I and III) is rather small. At intersections with such low V volumes, all three intersection management options are appropriate. If the certain priority is to be given to the P in specific urban area and V flows are low, the most appropriate is Option II control (exclusive P phase with diagonal crossing), as this control option has a lower time loss for P compared to Option II.

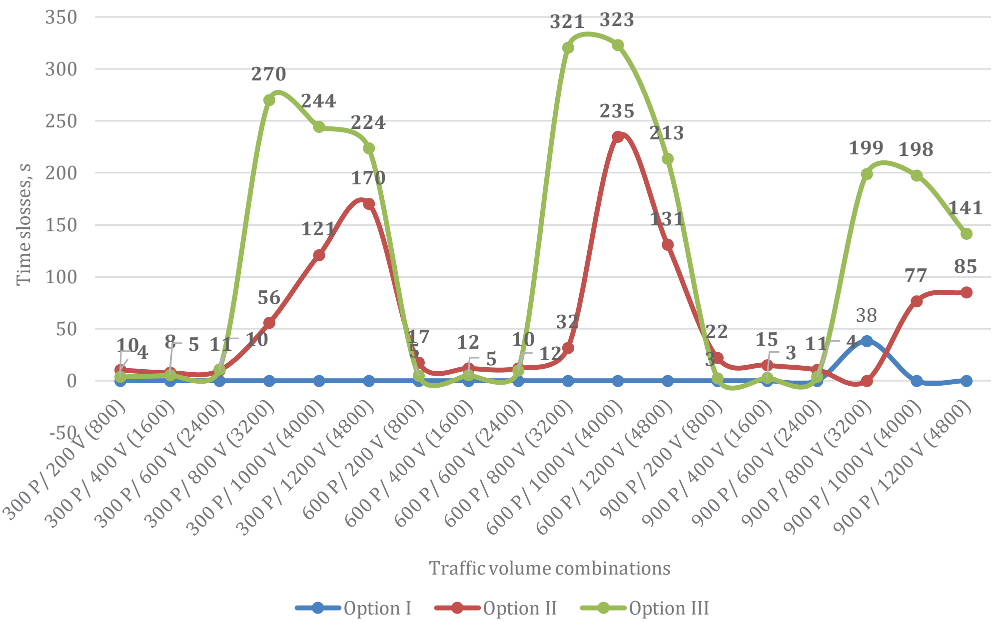


Figure 13. Dependence of the time losses experienced by 1 road user on the traffic volume combinations at different options of intersections with 3+2 lanes

Conclusions of the research

1. This theoretical research of one-level signalized urban intersections with exclusive phases P has clear limitations, as only part of possible alternatives were analysed. Possible limitations are related to assumed intersection management options, cycle length (s) with minimal number of phases, geometrical models of the intersections, number of V and P volume variation and distribution of V turning manoeuvres. Assumption on such criteria can certainly be expanded, including practical traffic light optimization. The research does not draw conclusions about the advantages or disadvantages of other modifications of traffic light one-level intersections, for example, with additional sections and phases.
2. The simulation of theoretical intersections has shown that, at streets with 1+1 traffic lanes intersecting at an intersection, P are most likely to cross the intersection faster when P traffic is in parallel with moving V (Option I). At an intersection where streets with 2+2 or 3+2 lanes intersect, P are most likely to cross the intersection faster when P traffic is in parallel with moving V (Option I) or during an exclusive P phase with a diagonal crossing (Option III). The most time consuming P movement is when there is an exclusive P phase without a diagonal crossing (Option II).
3. The results of the theoretical intersection simulations show that, in almost all cases, the least time consuming for V the intersection control Option I, where V and P traffic run in parallel. However, 2+2 lane geometrical model works well with control Option II at ≥ 900 P per hour range when the V travel time is shortest. Option III is less attractive for V as results in higher time travel than control Option I or II.
4. Simulation results show that, in almost all simulated cases, the losses per road user are lowest when the intersection is equipped with control Option I–P are unprotected, and V and P traffic are in parallel during same phase. However, the second intersection geometrical model, where streets with 2+2 lanes intersect, an exclusive phase P with a diagonal crosswalk is the most beneficial in terms of time losses when the intersection has a high number of P and V (≥900 P/hour and ≥≥2400 V/hour.
5. The intersections with exclusive P phases are often considered a specific remedy in certain urban areas due to positive traffic safety impact. The research has found, when comparing Options II and III with exclusive phases P, that the performance of road users in these options depends on the number of V, i.e., when the number of V is low, it is more beneficial to implement intersection management Option

III, which has an exclusive phase P with a diagonal crossing, but when the number of V increases, it is more beneficial in terms of time losses to implement intersection management Option II, which has an exclusive phase P without a diagonal crossing. This comparison does not include Option I of the control of junctions.

6. After completing the simulation of theoretical intersections, it has been determined that, when the intersection has to deal with low V flows (up to 800 V/hour for a 1+1 traffic lane intersection; up to 1600 V/hour for a 2+2 traffic lane intersection; up to 2400 V/hour for a 3+2 lane intersection), regardless of the P volumes, the difference in the time losses between the two intersection management Options I and III is relatively small. Therefore, by giving priority to P at intersections with relatively low V flows, the introduction of an exclusive P phase with diagonal crossings can be considered from the viewpoint of total time losses. Furthermore, when the intersection has to deal with high V flows (≥1600 V/hour for a 1+1 traffic lane intersection; ≥ 2400 V/hour for a 2+2 traffic lane intersection; ≥ 3200 V/hour for a 3+2 lane intersection), regardless of the P volumes, Option II might be considered. However, such consideration needs further analysis by integrating estimations of road safety and time losses.
7. Connected and Automated Vehicles (CAVs) are a rapidly evolving technology with the potential to significantly impact traffic flow and safety at signalized intersections. This study provides the basis for further research of the interaction between infrastructure, technology, and human behaviour in the transportation system. The implementation of CAV could have a significant impact on the performance of signalized intersections with exclusive phases P and diagonal crossings, and may require modifications to the design of these intersections. Additionally, the behaviour of CAVs at these types of intersections may need to be carefully studied to ensure safe and efficient interaction with P and other V.

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