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A signal timing assignment proposal for urban multi lane staged controlled signalised roundabouts

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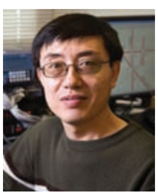

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Preliminary note

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A signal timing assignment proposal for urban multi lane signalised roundabouts

The relationship between the left-turning traffic volume and the storage area at signalised roundabouts is investigated, and a calculation procedure for signal timing is proposed in this paper. The parameters associated with the developing stages of a new expression/model are also defined. Four different signal timing scenarios are considered. The results show that the proposed formula can be used for the design of signalised roundabouts.

Key words:

traffic, intersection, signalised roundabouts, simulation, VISSIM

Prethodno priopćenje

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Prijedlog vremenskog usklađenja semafora na gradskim višetračnim semaforiziranim kružnim raskrižjima

U radu se ocjenjuje odnos između količine vozila koja skreću lijevo i prostora za čekanje na semaforiziranim kružnim raskrižjima, te se predlaže postupak za izračun vremenskog ciklusa promjene svjetala na semaforima. Definiraju se i parametri vezani za razne korake razvoja novog izraza/modela. Korištena su četiri različita scenarija promjene svjetala. Rezultati pokazuju da se predloženi izraz može koristiti za projektiranje semaforiziranih kružnih raskrižja.

Ključne riječi:

promet, raskrižje, semaforizirana kružna raskrižja, simulacija, VISSIM

Vorherige Mitteilung

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Vorgeschlagene zeitliche Angleichung der Ampeln an städtischen mehrspurigen Kreisverkehren mit Ampeln

In der Abhandlung wird das Verhältnis zwischen der Menge der linksabbiegenden Fahrzeuge und des Warteraums an Kreisverkehren mit Ampeln beurteilt, und es wird ein Verfahren zur Berechnung des Zeitzykluses der Ampelumschaltung vorgeschlagen. Definiert werden auch die Parameter in Bezug auf verschiedene Entwicklungsschritte des neuen Modells. Verwendet wurden vier unterschiedliche Szenarien der Ampelumschaltung. Die Ergebnisse zeigen, dass der vorgeschlagene Entwurf für die Projektierung von Kreisverkehren mit Ampeln verwendet werden kann.

Schlüsselwörter:

Verkehr, Kreuzung, Kreisverkehr mit Ampel, Simulation, VISSIM

1. Introduction

The continuous growth of the world's population, along with an increasing number of vehicles, is at the origin of many challenges for the present day society. Losses caused by traffic accidents, traffic congestion and environmental impacts are just a few of these problems. Various types of intersection control methods have been considered for many years in the scope of efforts aimed at minimising negative effects of traffic congestion problems. Roundabouts are one of the intersection types that are aimed at improving the situation. In a number of countries, including China, United Kingdom, France, Sweden, Australia, the Netherlands, and Turkey, some roundabouts have signal control, especially in cases of dense vehicle and pedestrian traffic. This type of intersection is a combination of signalised intersections and roundabouts. Generally, they are used in cases of an increase in traffic flow demand or to curb violation of traffic rules by drivers. In the second case, because of traffic violations by drivers, the capacity of the intersection may decrease dramatically, and excessive delays may occur. Vehicle delays can be decreased and traffic safety can be improved by the use of signalised roundabouts [1]. Another main reason for the use of signalised roundabouts is related to driver behaviour at roundabouts without signals. In some developing countries, drivers are not accustomed to roundabouts and tend to violate the traffic rules. Thus, signal control has been integrated to reduce the number of traffic accidents and to increase intersection capacity.

Although the number of signalised roundabouts has been increasing worldwide over the past two decades, traffic researchers still have many questions and uncertainties related to the operation and design of signalised roundabouts. The effects on intersection capacity and level of service (LOS) of signalised roundabouts are discussed in relevant literature. The improvement of capacity and LOS has been one of significant issues for signalised roundabouts. Further research is needed to address this issue by placing emphasis on environmental, economic, and social effects [2].

Even though many studies can be found related to signalised intersections and unsignalised roundabouts, the number of studies related to signalised roundabouts still remains quite limited [3-11]. Akcelik compared roundabouts and roundabout metering in his studies. As a result, he declared that in some cases the performance of roundabouts can be improved by roundabout metering [12, 13]. Natalizio [14] studied the necessity and effectiveness of roundabout metering. Brabender and Vereeck [15] pointed out that roundabouts are an important option for reducing traffic accidents. According to their study, the reduction of traffic accidents is closely related to speed limits at main roads and bypass roads. They concluded that signalised roundabouts are the safest type of intersection. Qian et al. [16] compared roundabout metering with signalised roundabouts, and they established that signalised roundabouts are an efficient means for eliminating or reducing traffic congestion problems at intersections with medium to high traffic flows. Maher [17] proposed a new signal timing optimization approach using a cross-entropy method. This solution contributed to a more efficient resolution of complex combinatorial optimization problems. Bai et al. [18] investigated the effects of the diameter of signalised roundabouts, and the effects of cycle time on vehicle delay. They used numerical calculations and experimental traffic engineering approaches in their study and revealed that an increased radius of central islands leads to an increase in an average delay time. Johnnie et al. [19] attempted to determine the LOS of roundabouts with and without signals. They concluded that the LOS can be improved by the application of signalised roundabouts in cases of high demand. Tracz and Chodur [20] examined advantages and disadvantages of different types of phase plans that are applied at signalised roundabouts. They chose signalised roundabouts, which have high traffic volumes at urban arterials, and they proposed a monograph for the design of central islands. They also concluded that roundabouts with signals ensure better performance in cases of high volume of left turn movements. Ma et al. [21] proposed to improve an optimization model by simultaneously considering lane-markings and signal timings at signalised roundabouts. They formulated the maximization of capacity as well as the minimization of cycle time and vehicle delay for optimization of signalised roundabouts. Gokce et al. [22] focused on the signal timing optimization issue for signalised roundabouts. In their study, they used the particle swarm optimization method, which is one of the metaheuristic algorithms, and they obtained encouraging results. Cheng et al. [23] proposed a new model for calculating capacity of signalised roundabouts. Gardziejczyk and Motylewicz [24] focused on the influence of intersection type on noise levels in the vicinity of signalised roundabouts. Hatami and Aghayan [25] compared performance of elliptical roundabouts with turbo and modern roundabouts considering traffic signal control. At the end of their study, they established that modern and elliptical roundabouts have highest capacities in unsignalised and signalised controls.

As can be seen from the above studies, the number of studies relating to performance and optimum operation of signalised roundabouts is far from adequate. The relation between turning flows and storage area has not been properly examined in detail in the literature. Although signalised roundabouts have been used in many countries, the signal timing procedure is not properly defined. A particular aim of this study is to address these shortcomings.

2. Problem definition and objectives

The problem considered in this research is related to urban multi-lane signalised roundabouts that have staged control by signalization. Staged control means that there are two stops of the traffic flows: one of them is located on the approach and the other one is located on the central island. Two particular issues to address are the design of the storage area to be sufficient for left turning traffic volumes and signal timing procedures. If signal timings are inadequately designed for accommodating left turning volumes, the storage area in the central island may be blocked by the left turning traffic and the conflicting flows (such as the through flow from the other direction) may not be able to move until the left turning flow is cleared or the signal has transitioned to the next phase, which causes some additional vehicle delays. In this research, a control system design approach is taken into consideration and a new signal timing calculation approach is developed.

The main objectives of this study are to propose a signal timing procedure for urban multi-lane staged control signalised roundabouts and to reduce vehicle delays. To accomplish these objectives, the following tasks were carried out:

- development of a signal timing procedure using urban multi-lane signalised roundabouts in Turkey
- development of a signal timing optimization model considering the storage area of the central island
- four scenarios were designed and 200 different cases were analyzed
- the VISSIM software was used for model validation of the proposed formula and the scenarios were tested [26]
- the obtained results were compared.

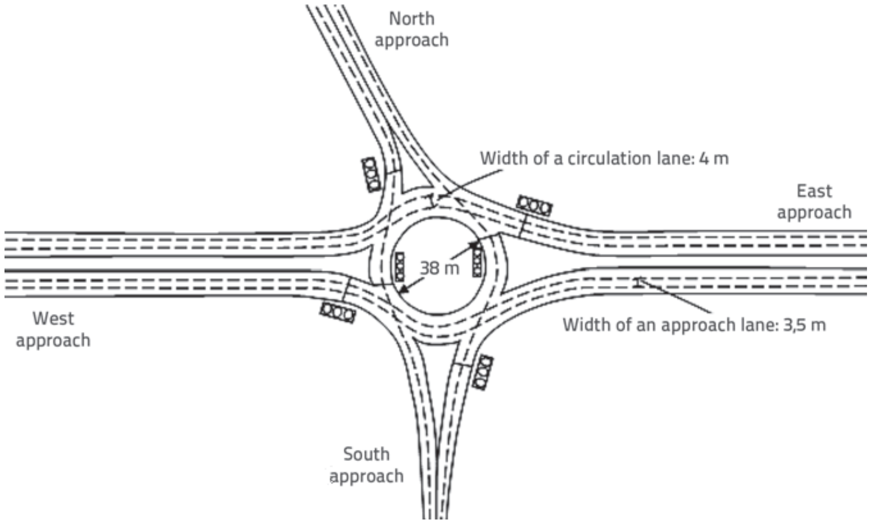

Figure 1. Intersection geometry considered in the study

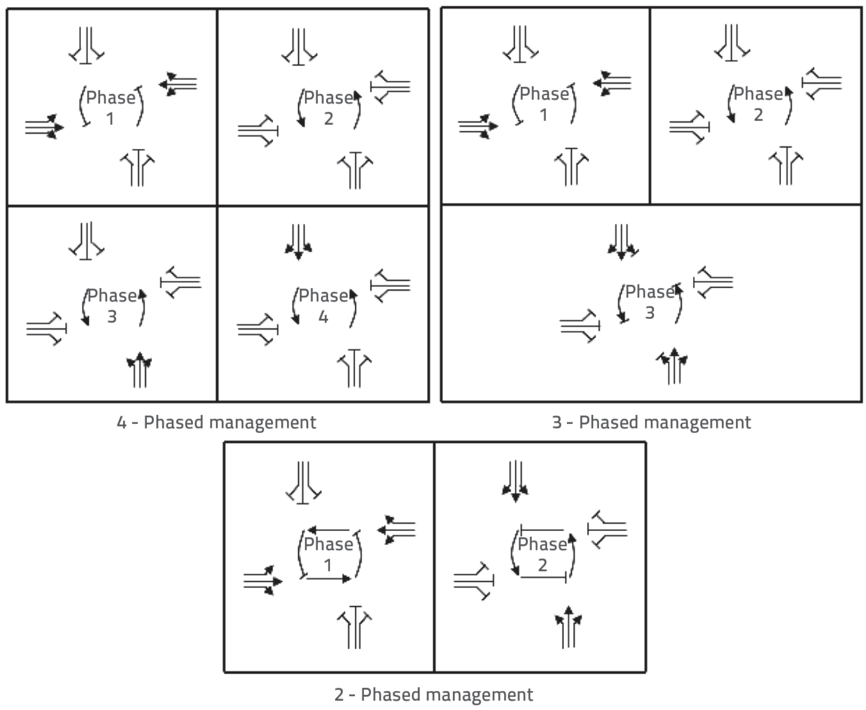

Figure 2. Sample phase plans used for signalised roundabouts

3. Signalised roundabouts

Signalised roundabouts include traffic signals implemented on all arms of the intersection and around the main circle. It is an integration of signalised intersections and roundabouts. Generally, it is used in case of an increase in traffic flow demand, or violation of traffic rules by drivers. In the second case, because of violation of traffic rules by drivers, the intersection capacity may decrease dramatically and excessive delays may occur. In many cases, especially during peak hours, the roundabout may also be congested. Besides violation of traffic rules, left turning volumes and traffic composition (heavy vehicle rate) also have an adverse effect on the capacity of signalised roundabouts. To overcome these deficiencies, a proper signal timing design approach should be defined. This study suggests an analytical approach to signal timing calculation at urban multi-lane signalised roundabouts. A special type of application considered in this study is shown in Figure 1.

Traffic flows at signalised roundabouts are generally controlled by two, three or four-phased plans. Figure 2 depicts sample phase plans used for signalised roundabouts. The phase plans have a considerable effect on the performance of signal control systems. They may be determined by field observations and some specific analyses. Left turning flows, pedestrians, and traffic composition (heavy vehicle rates) are some important parameters that should be considered in phase plan selection. Any negligence of these parameters may lead to unexpected performance results. Thus, design engineers need certain information or a guide to develop more sustainable solutions for roundabouts with signals. For improving understandability of sample phase plans, movements of traffic flows for 4-phase management are also presented as a sample in Figure 3.

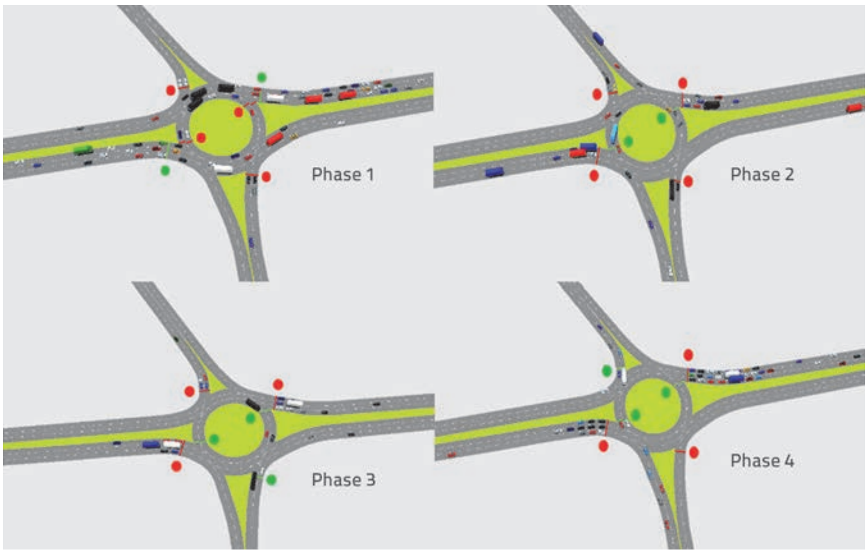

Figure 3. Movements of traffic flows for four-phase management

3.1. Parameters

Certain parameters should be taken into consideration at the design and operation stages of signalised roundabouts. These parameters are:
- geometric condition
- design elements
- traffic volume
- left turning rate
- storage area of central island for left turning vehicles
- signal timing for all vehicles.

At the design stage, if the parameters stated are not regarded in detail by field observations, a designer has to make some assumptions about the values. In this case, the values assumed may not be compatible with those obtained from the field, which can result in an improper design. On the other hand, no software is currently available to help design signalised roundabouts. Therefore, there is a need for a guide or a calculation procedure for signalised roundabouts. The above parameters are examined and discussed as follows.

3.1.1. Geometric condition

Geometric conditions of a roundabout have a considerable effect on design. Geometric elements or components such as the turning radius, lane width, radius of central island, etc., should meet the required standards. The design of intersection may have some faults when non-standardized elements are used. On the other hand, the intersection capacity may be reduced because of these design faults.

3.1.2. Storage area of central island for left turning vehicles

The storage area of the central island for left turning vehicles should have some specifications in order to serve the traffic flows with minimum effects. The number of circulation lanes and the dimensions of the circulation lanes are the main elements to consider. The designer should consider these elements and collect the required data from the field, such as the dimensions of the space for left turning traffic flows.

3.1.3. Traffic volume of left turning vehicles

Besides geometric conditions and storage area dimensions, left turning traffic volumes have some considerable effects on the design of signalised roundabouts. The number of vehicles and traffic composition should be observed for a proper design.
The signal timing for circulating flows should be determined based on traffic volumes, with a particular emphasis on heavy vehicle traffic. On the other hand, traffic volume variations should also be observed in both peak and off-peak periods, and the trends of this variation should be recorded. Otherwise, signal timing assigned may not be sufficient for traffic volumes, and some vehicles may have additional delays. This improper signal timing design may also result in traffic jams.
The rate of heavy vehicles for left-turn traffic volumes should be considered with great care. The intersection may be congested if the rate of heavy vehicles is higher than expected. On the other hand, the departure headways of vehicles may be affected from this composition [27, 28]. The observations and estimations of heavy vehicles should be conducted already at the design stage.

3.1.4. Signal timing

The proper signal timing design has a great impact on performance of the intersection control system. Although there are many software programs for the simulation and design of intersections, signal timings of signalised roundabouts have not yet been specifically addressed by such software. On the other hand, some microsimulation software such as VISSIM and AIMSUN may be used for performance analysis only, i.e. the signal timing design is not included. Therefore, the signal timing design is a challenge for designers and it may be varied based on the designer's abilities and foresight. To overcome these deficiencies, a signal timing design approach for urban multi-lane signalised roundabouts is proposed, as described in the next section.

4. Signal timing method for urban multi-lane signalised roundabouts

The first signal timing methodology was introduced nearly 70 years ago by Webster (1950). Since then, a significant effort was made to develop more advanced methods (HCM, Akcelik, CCG, etc.). The use of signal control at roundabouts is a fairly new phenomenon. It is used in case of high traffic flows or violation of traffic rules by drivers. Although it is aimed at controlling traffic flows and preventing violations, the application is limited only to roundabouts that are controlled by a specific signal phasing case (i.e. non-storage case in the central island). The main research idea of this paper is to propose a new method for urban multi-lane signalised roundabouts that has storage area in central island and is controlled by one of the phase sequences shown in Figure 2. In Figure 4, the proposed approach for signal timing design is explained by a flow chart.

As shown in the flow chart, the signal timing is first determined without considering the roundabout option. Optimum green timings and cycle time (g_i, C_i) are determined in the second step. The cycle time and green time formulas defined in the HCM or by Akcelik may be used for this purpose. The third step includes determination of the number of cycles in an hour (n_c). After that, the storage area of a roundabout is determined by the number of rows formed by vehicles. The lost times of departing vehicles in the storage area (α) and departing headways (λ) are calculated in the fifth step. Then, the green time of the central island (ϕ) is calculated considering the calibration coefficient (ε) for signal timing. The new cycle time (C_n) is calculated in the seventh step regarding green time of the central island (ϕ). The calibration coefficient is checked and green time of the central island (ϕ) and new cycle time are re-calculated if needed. After that, the cycle time is checked. If it does not satisfy the designer calculation it will be repeated from Step 6. At the end, the degree of saturation values for traffic flows and the intersection are checked. The limit value is selected as 0.9 for the degree of saturation. It should be equal to or less than 0.9. If this step is satisfied, the design is finalized. Otherwise a new cycle time is assigned.

As explained in the step flow chart, one of the most important parameters is the green time of the central island. This formula is explained in the Eq. (1) [2, 29]:

$$\phi = \alpha + [(n-1) \cdot \lambda] + \varepsilon \qquad (1)$$

where:

- ϕ - green time of central island (sec)
- α - the lost times of departing vehicles in the storage area (sec)
- n - the number of lanes in storage area
- λ - departing headways of vehicles (sec)
- ε - calibration coefficient for signal timing α; the lost times of vehicles in queue may be determined by observations in the field

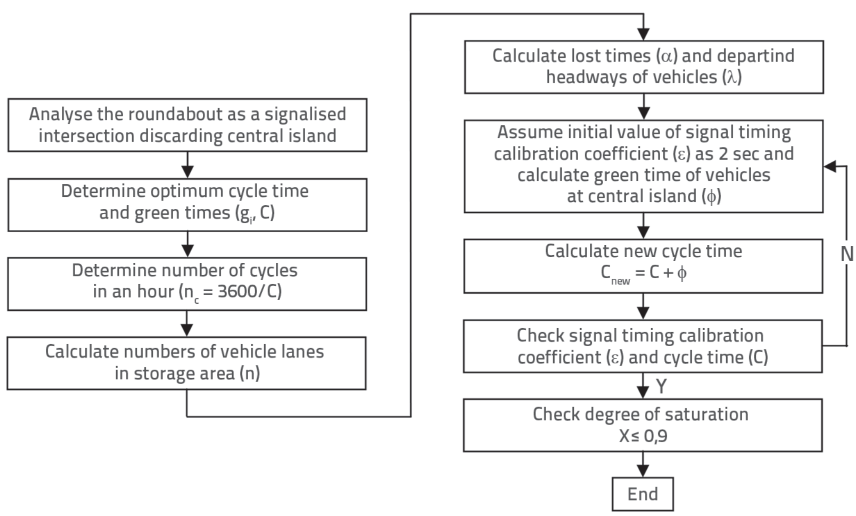

Figure 4. Steps of the proposed signal timing assignment procedure

n - the number of lanes in storage area has a strong relation to the left turning traffic volume, the number of lane in the storage area and the number of cycle in an hour parameters.

This can be determined using the Eq. (2) [2, 29]:

$$n = \frac{q_L}{(n_c \times n_{SL})} \qquad (2)$$

where:

- q_L - left turning traffic volume (veh/hour)
- n_c - the number of cycle in an hour (n_c= 3600/C)
- n_{SL} - the number of lane in the storage area.

The storage area and central island were not originally considered in the calculation of signal cycle time for a roundabout, t. It was re-calculated using Eq. (1) and Eq. (2). In this way, the new cycle time is increased and the number of cycles in an hour is decreased. Because of this, the number of lanes in the storage area is also increased and additional time for departing vehicles at storage area is needed. To satisfy this requirement, the calibration coefficient for signal timing of the central island is added to Eq. (1). $\in$ is initially assumed as 2 secs in the calculation procedure. It is checked after re-calculation by Eq. (3). If it satisfies an additional time for departing vehicles, the calculation continues with the next step. Otherwise, the calculation goes two steps back. The calculation procedure of this coefficient is given as follows [2, 29]:

$$\varepsilon = \left[\frac{q_L}{t_{Cadd} \times n_{SL}} \right] \times 2 \tag{3}$$

In this equation, t_{Cadd} represents additional timing and it may be calculated by Eq. [2, 29]:

$$t_{Cadd} = \left[\frac{3600}{(C_{new})} - \frac{3600}{(C)} \right] \tag{4}$$

Eq. (4) expresses the calculation of required cyclic additional timing for traffic flows at circulatory carriageway due to increase in cycle time. The timing calculated with Eq. (4) is used in Eq. (3) and calibration coefficient value is obtained. Then, this value is compared with initial value (2 sec). When this value is smaller than the initial value, the procedure continues with the next step. Otherwise, a new cycle time is calculated and the procedure continues iteratively. Eq. (3) and Eq. (4) are suggested for the calibration of calculation procedure.

The signal timing formula proposed is tested considering different cases. A validation of the formula is presented in the next section.

5. Validation

The validation of the proposed formula is conducted using data obtained from a real intersection (the Pekdemir intersection) in Denizli, Turkey. The Pekdemir intersection has two main roads in the east-west direction and two minor (secondary) roads in the north-south direction. The main roads include three lanes in each direction, while the minor roads have two lanes. The intersection is controlled by a four-phasing sequence as depicted in Figure 2.

Based on the field observations, the evening peak hour at the weekday, and the morning peak hour at the weekend are determined as the hours when traffic is the most crowded at Pekdemir intersection. Therefore, it was decided that traffic counts and observations must be made between 05:00 p.m. and 06:00 p.m. on Wednesday for the weekday count, and between 08:30 a.m. and 09:30 a.m. on Saturday for the weekend count. The Traffic Count and Survey Method in HCM is considered [30] to obtain the detailed traffic counts (the ratios of heavy and light vehicle, turning ratios, etc.). In the scope of the field observations, video cameras were placed at each intersection approaches and vehicle movements were recorded by these cameras at the above mentioned days and hours. At the next stage, recorded vehicle movements were analysed by traffic engineers in the office environment and the detailed approach based traffic counts were obtained for both peak hours. Total hourly traffic volumes amounted

Table 1. Base demand values used

Movement type	O-D directions	Low demand (base values)			High demand (base values)		
		Car [veh/hour]	**Heavy vehicle** [veh/hour]	**Total** [veh/hour]	**Car** [veh/hour]	**Heavy vehicle** [veh/hour]	**Total** [veh/hour]
Through	W-E	848	105	953	1015	101	1116
	E-W	994	86	1080	1293	82	1375
	N-S	182	20	202	231	10	241
	S-N	86	4	90	90	3	93
Right turn	W-E	11	0	11	20	0	20
	E-W	66	4	70	157	18	175
	N-S	49	0	49	45	2	47
	S-N	35	0	35	41	1	42
Left turn	W-E	86	21	107	101	25	126
	E-W	102	26	128	138	34	172
	N-S	22	6	28	26	6	32
	S-N	11	3	14	12	3	15
Total [veh/hour]		**2493**	**274**	**2767**	**3169**	**285**	**3454**

Table 2. Sample experimental cases

Sample No	Approach direction	Variation rate in traffic volume [%]	Left turning rate %]	Sample No	Approach direction	Variation rate in traffic volume [%]	Left turning rate [%]
1	E - W	50% decreased	10	29	E - W	N/A	50
	N - S	N/A	10		N - S	N/A	10
7	E - W	50% decreased	40	34	E - W	25% increased	20
	N - S	N/A	10		N - S	N/A	60
12	E - W	25% decreased	10	37	E - W	25% increased	40
	N - S	N/A	60		N - S	N/A	10
15	E - W	25% decreased	30	42	E - W	50 % increased	10
	N - S	N/A	10		N - S	N/A	60
19	E - W	25% decreased	50	47	E - W	50% increased	40
	N - S	N/A	10		N - S	N/A	10
24	E - W	N/A	20	50	E - W	50% increased	50
	N - S	N/A	60		N - S	N/A	60

to 2767 veh/hour and 3454 veh/hour for the peak hour at weekday and weekend, respectively. As can be seen in Table 1, the situation when the total traffic volume is lower than 3000 veh/hour was named as "Low Demand", whereas the situation when the total traffic volume is higher than 3000 vph was named as "High Demand".

As a result, two different base demand values were obtained. Using these base values, an experimental study was designed. Traffic volumes on the approaches and left turning rates were experimentally changed. By doing so, 50 different cases were formed. The sample experimental cases are presented in Table 2.

As can be seen in Table 1 and Table 2, the base values for the low and high demand conditions were experimentally changed. The traffic volumes in the E-W directions were decreased and increased in the range from 0 % to 50 %. The left turning flow rates were varied in the range from 10 % to 60 %.

5.1. Scenarios

For signal timing, four scenarios are taken into consideration using the above described data. The main aim of these scenarios is to find the best solution for the roundabout considered.

In the first scenario, all sample cases are analysed considering the existing signal timings presented in Table 4 and four-phased sequencing at Pekdemir intersection. At the end of the analyses, average vehicle delays, which are the measure of effectiveness for signalised and unsignalised intersections, are obtained from the VISSIM simulation program for each sample case.

In the second scenario, sample cases in which the average vehicle delay is over the 120 sec/veh are taken into account. These cases are analysed considering same phase sequencing (four-phased management) at Pekdemir intersection with signal timings obtained by the proposed formula. Improved signal timings and average vehicle delay values for these sample cases are given in Table 4. In the third scenario, the focus is on the investigation of "vehicle storage" situation at signalised roundabouts. For this purpose, all sample cases are analysed again considering signalised roundabouts without vehicle storage. When all created sample cases are investigated carefully, it can be seen that traffic volumes for the North and South approaches are quite low (less than 350 veh/hour). Therefore, it is thought that the right of way for traffic flows at these two approaches may be provided at the same phase sequencing. In addition to this, the right of way for traffic flows at the West and East approaches are provided at distinct phase sequencing. In scenario 3, sample cases are analysed considering three phasing schemes and constant cycle time with 140 sec at Pekdemir intersection. Signal timings for each phase are distributed based on traffic volumes on the approaches using SIDRA Intersection [31]. Then, all sample cases are analysed considering the signal timings obtained from SIDRA Intersection in VISSIM. As a result, average vehicle delay for each sample are determined.

In the last (fourth) scenario, all sample cases are analysed considering three phasing schemes and an optimum cycle time. The optimum cycle time and signal timings for each phase are obtained from SIDRA Intersection based on traffic volumes at the approaches. Then, all sample cases are analysed considering the optimum cycle times and signal timings obtained from SIDRA Intersection in VISSIM. As a result, average vehicle delays are determined for each sample.

After implementation of these four scenarios, the number of sample cases in which the average vehicle delay is below 120

Table 3. Sample traffic volumes

Sample case	Number of storage area lanes (lane)	Total traffic volume [veh/hour]	East approach	West approach	North approach	South approach
			A.V.-L.T.V* [veh/hour]	A.V.-L.T.V* [veh/hour]	A.V.-L.T.V* [veh/hour]	A.V.-L.T.V* [veh/hour]
1	2	2180	959 - 383	803 - 321	279 - 28	139 - 14
2	2	3354	1598 - 320	1339 - 268	279 - 28	139 - 14
3	2	3354	1598 - 320	1339 - 268	279 - 167	139 - 83
4	2	3942	1917 - 192	1607 - 161	279 - 167	139 - 83
5	2	1962	861 - 431	631 - 316	320 - 32	150 - 15
6	2	2708	1292 - 387	947 - 284	320 - 32	150 - 15
7	2	2708	1292 - 387	947 - 284	320 - 192	150 - 90
8	2	4200	2153 - 215	1578 - 158	320 - 32	150 - 15
9	2	4946	2583 - 258	1893 - 189	320 - 32	150 - 15
10	2	2180	959 - 383	803 - 321	279 - 167	139 - 83
11	2	2180	959 - 479	803 - 402	279 - 28	139 - 14
12	2	2180	959 - 479	803 - 402	279 - 167	139 - 83
13	2	2767	1278 - 383	1071 - 321	279 - 28	139 - 14
14	2	2767	1278 - 383	1071 - 321	279 - 167	139 - 83
15	2	3942	1917 - 192	1607 - 161	279 - 28	139 - 14
16	2	1962	861 - 431	631 - 316	320 - 192	150 - 90
17	2	3454	1722 - 344	1262 - 252	320 - 32	150 - 15
18	2	3454	1722 - 344	1262 - 252	320 - 192	150 - 90
19	2	4200	2153 - 215	1578 - 158	320 - 192	150 - 90
20	3	2180	959 - 383	803 - 321	279 - 167	139 - 83
21	3	2767	1278 - 383	1071 - 321	279 - 28	139 - 14
22	3	3354	1598 - 320	1339 - 268	279 - 167	139 - 83
23	3	3942	1917 - 192	1607 - 161	279 - 167	139 - 83
24	3	1962	861 - 431	631 - 316	320 - 32	150 - 15
25	3	2708	1292 - 387	947 - 284	320 - 192	150 - 90
26	3	3454	1722 - 344	1262 - 252	320 - 192	150 - 90
27	3	4946	2583 - 258	1893 - 189	320 - 32	150 - 15
28	3	4946	2583 - 258	1893 - 189	320 - 192	150 - 90
29	3	2180	959 - 479	803 - 402	279 - 28	139 - 14
30	3	2767	1278 - 383	1071 - 321	279 - 167	139 - 83
31	3	2708	1292 - 387	947 - 284	320 - 32	150 - 15

***A.V.**: Approach Volume, **L.T.V.**: Left Turning Volume

sec/veh is determined for each scenario, separately for low and high demand conditions.

Besides these scenarios, the number of storage lanes is also considered in two cases as two lanes and three lanes for validation. Sample traffic volumes used in the simulation are given in Table 3. The results of Scenario I and Scenario II are compared for validation of the proposed formula. By doing so, a total of 200 different cases are taken into consideration. An experimental design approach is used in determining the cases considered for validation.

Table 3 shows sample traffic volumes including different left turning rates from each approach and the number of lanes in the central island. These values are designed considering the base values observed at the intersection and defined in Table 1 and Table 2. As can be seen in the table, east-west directions that have higher traffic volumes are the main roads. The left turning volumes from the E-W direction are critical for the intersection and because of improper signal timings and phase sequencing for left turning flows, the intersection experiences traffic congestion especially during peak periods of the day.

6. Analysis

6.1. Simulation studies and results

The equation (1) is validated through simulation. The SIDRA Intersection and the VISSIM microsimulation software packages are used for this purpose [26, 31]. As defined in the methodology section, a roundabout is first considered as a signalised intersection and the cycle time is calculated by the SIDRA Intersection software. Then, using the proposed formula, a new cycle time is determined and the performance of the formula is investigated using the VISSIM simulation. Present

Table 4. Comparison of sample cases for signal timings and average vehicle delay values

Sample cases	Existing signal timings [s]	Improved signal timings [s]				Cycle times [s]		Average vehicle delay [s/veh]		LOS	
		West – East Green timing [s]	Storage area green timing [s]	North Green Timing	South Green Timing	Existing	Improved	Existing	Improved	Existing	Improved
1	West – East Green Timing: 40 – 50, Storage Area Green Timing: 74 North Green Timing: 20, South Green Timing: 23	17 – 21	53	12	8	140	90	*	51.54	F	D
2		43 – 52	57	15	9	140	125	143.03	111.44	F	F
3		43 – 52	62	18	11	140	130	*	116.66	F	F
4		46 – 54	55	16	11	140	125	136.64	55.96	F	E
5		14 – 19	50	12	9	140	85	154.48	47.72	F	D
6		25 – 32	52	12	8	140	100	151.57	72.27	F	E
7		23 – 30	59	16	11	140	105	*	116.91	F	F
8		42 – 57	52	13	8	140	125	129.81	77.07	F	E
9		43 – 58	51	11	8	140	125	146.07	112.92	F	F
10		18 – 22	57	15	9	140	95	*	55.48	F	E
11		18 – 22	57	12	8	140	95	*	84.68	F	F
12		18 – 23	61	15	9	140	100	*	118.17	F	F
13		26 – 30	54	13	8	140	100	*	101.64	F	F
14		29 – 33	56	14	9	140	105	*	107.91	F	F
15		48 – 56	48	12	8	140	120	133.36	47.12	F	D
16		14 – 19	55	14	10	140	90	*	51.42	F	D
17		40 – 50	59	15	9	140	125	124.57	110.64	F	F
18		41 – 51	63	17	11	140	130	*	117.01	F	F
19		41 – 55	59	17	11	140	130	135.83	101.22	F	F
20		18 – 22	52	13	9	140	90	140.38	71.40	F	E
21		33 – 37	52	12	9	140	105	132.51	98.56	F	F
22		47 – 55	59	16	11	140	130	120.31	102.35	F	F
23		45 – 54	55	16	11	140	125	124.38	81.73	F	F
24		16 – 20	49	10	8	140	85	165.51	76.49	F	E
25		25 – 32	57	15	11	140	105	141.19	114.78	F	F
26		39 – 47	57	15	11	140	120	126.51	102.96	F	F
27		45 – 60	54	14	9	140	130	145.88	88.87	F	F
28		46 – 61	58	16	11	140	135	150.13	109.45	F	F
29		21 – 25	49	10	8	140	90	226.25	119.70	F	F
30		33 – 37	57	15	11	140	110	136.37	114.41	F	F
31		25 – 33	51	12	8	140	100	136.59	110.55	F	F

* Average vehicle delay > 250 sec/veh, All red time: 4+4=8 sec, Yellow time: 2+2=4 sec (at the start and end of the each phase)

signal timings and phase sequencing of the intersection are used for simulation. In addition to the present signal timing values, the new timing values calculated by the formula are also used. The average vehicle delay for the intersection is taken into account as the performance criteria during simulation runs. The earlier defined scenarios are tested in this way. Average vehicle delay values (sec/veh) and LOS for each case are compared using the present signal timing and proposed timing data. Sample comparison results are summarized in Table 4 and Figure 5, respectively. These results show comparisons between Scenario I and Scenario II.

As can be seen in Table 4 and Figure 5, the proposed formula gives more reasonable values than the present values. For instance, the green time for the central island is 74 secs for the existing conditions whereas the proposed formula yields different values ranging between 49 secs and 62 secs. Similar findings are also obtained for cycle times. The cycle times for existing conditions are observed as 140 secs while the proposed formula gives different and lower values than the existing ones. The signal timings obtained by the formula are generally lower than existing values and these make some savings in terms of average vehicle delays. Simulations show that about 36 % average delay reduction may be obtained by the proposed formula compared to the existing signal timings. The dramatic decrease in average delay time will result in significant fuel and emission savings, in addition to the benefits of lower waiting time. Figure 5 (c) shows comparisons of sample cases for the degree of saturation values for the central island of the roundabout. The findings are similar to those previously reported. The degree of saturation values for the proposed signal timings are mostly lower than those provided by the existing signal timings. This finding suggests that the efficiency of the intersection control system may be improved by the proposed signal timing formula.

The average delay values for the intersection are taken into account for comparison of the scenarios. The average delay values that are less than 120 sec/veh are considered as acceptable cases in the comparisons. Figure 6 shows some comparisons of the scenario cases. As shown in the figure, the second scenario provides about 40 % improvement in total compared to the first scenario, whereas this percentage is nearly 10 % in

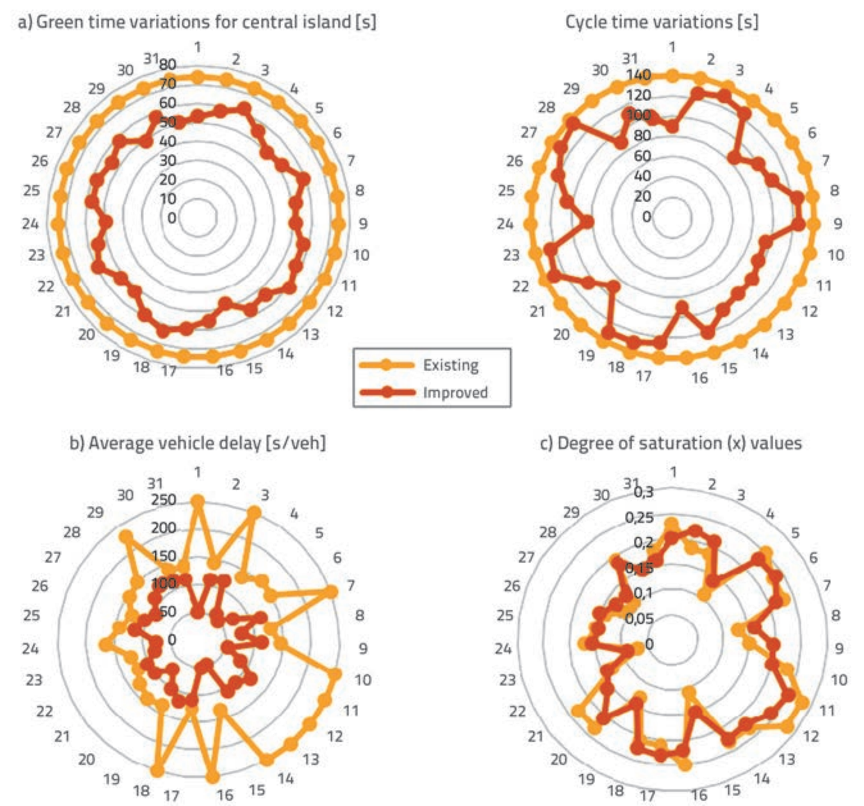

Figure 5. Comparisons of sample cases for: a) signal timings; b) average vehicle delay values; c) degree of saturation values for central island

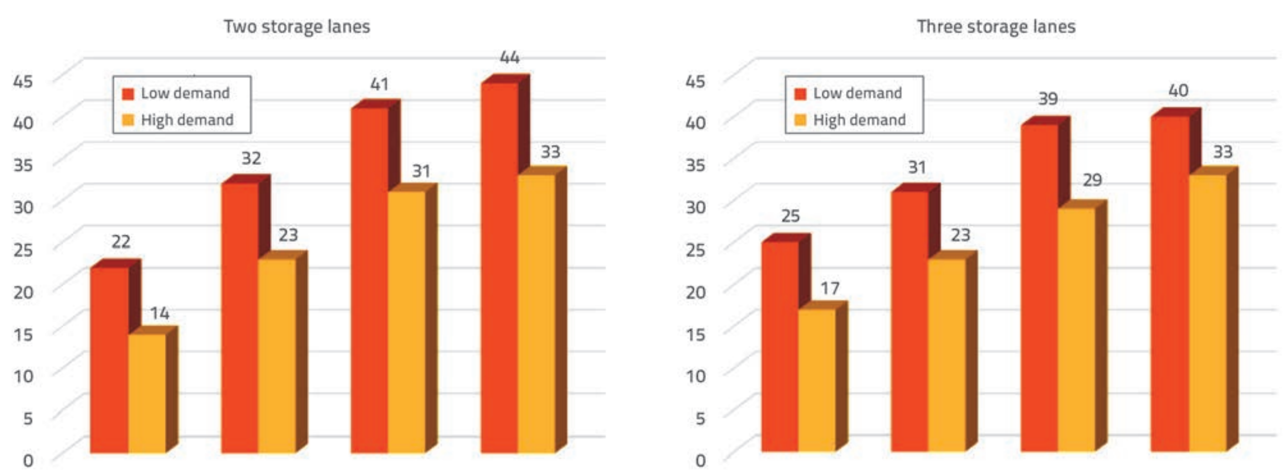

Figure 6 Comparison of the number of cases that have average delay values of less than 120 sec/veh

total for the comparisons with scenarios four and three. These comparisons support the motivation of this research. Based on these comparisons, it is recommended that the proposed formula be used for signal timing design purposes at urban multi-lane signalised roundabouts that have storage areas in the central island and are controlled by phase sequences similar to those defined in Figure 2.

7. Discussions and conclusions

A signal timing design proposal for urban multi-lane signalised roundabouts is presented in this research. Signalised roundabouts are used extensively in a number of countries, including Turkey. A formula is proposed for the design of signal timings. The central island of a roundabout and circulating traffic flows are taken into consideration in the proposed formula. It is aimed at reducing vehicle delays and making some improvements in the design procedure. Two hundred different cases are designed and simulated. Some findings can be summarised as follows:

- Traffic engineers need a guide for determination of signal timings (and cycle time) of signalised roundabouts. The proposed formula may be used for this aim and may help formulate better design solutions.
- The formula proposed deals with the circulating flows of roundabouts that are controlled by staged phase sequencing (i.e. storaged and circulated).
- Validation of the proposed formula provides some encouraging results. Two hundred different cases (traffic flow scenarios and phase combinations) were taken into account at the validation stage and about 75 % success rate was achieved.
- The results show that the design of the storage area of the central island is critical. The signal timings should be assigned considering the number of lanes in the storage area and circulating (left turning) traffic volumes.
- Another important finding is related to driver behaviours. Determination or estimation of average lost times and time headways of departing flows in the central island is crucial for an effective design and control.
- It was also established that traffic composition and especially a heavy vehicle proportion, have a significant effect on traffic flow. To represent this effect, it is taken into account in the proposed formula. The observations and simulations show that a higher rate of heavy vehicles may cause sharp increase in vehicle delays and traffic congestion.
- Simulations show that about 36 % average delay reduction may be obtained by the proposed formula compared to the existing signal timings.
- One of important findings of this research is related to the cycle time improvement. Results show that cycle times may be decreased at different rates ranging between 5 % and 50 %. Thus, the reserve capacity rates may be used effectively.
- The proposed signal timing formula yields significant improvements not only for average vehicle delays but also for levels of service.

For future works, the parameters regarded in the signal timing formula may be taken into account in detail and from different points of view. The cases considered in this work may be extended by including different traffic volumes and geometric conditions.

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