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ADAPTATION OF THE TRAFFIC SIGNAL CONTROL DESIGN METHOD TO A HAMBURGER ROUNDABOUT

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Abstract

Introduction: Currently, hamburger roundabouts with traffic signal control have limited application in the road networks of large cities. During analysis of scientific and technical literature, we established that it does not contain any systematic information on the possibility of their application or methods to determine their parameters. **Purpose of the study:** We aimed to adapt Webster's method of traffic signal design to hamburger roundabouts with traffic signal control, considering the specifics of traffic management. **Methods**: In the course of the study, we used methods of traffic analysis and simulation in the field-proven Aimsun software, recommended for use by scientific and technical literature on traffic management. We also assessed the efficiency of the adapted method by using the simulation results and comparing average transport delays at intersections considering the standard and adapted methods. **Results:** It was established that the adapted method of traffic signal cycle design reduces the average transport delay by 28% on average.

Keywords

Traffic, hamburger roundabout, transport delay, traffic signal cycle.

Introduction

There are several methods of traffic signal cycle and phases design, proposed by P. Koonce (2008), V. M. Polukarpov (Zyryanova and Filimonova, 2017), V. A. Vladimirov (Zyryanova and Filimonova, 2017), A. A. Vlasov (Vlasov et al. 2009), and F. Webster (1958). In Russian scientific and technical literature as well as practice, Webster's method became the most widespread (Rosavtodor, 2012, 2013).

Currently, hamburger roundabouts with traffic signal control have limited application in the road network of such cities as Fairfax (USA), Minsk (Belarus), Samara (Russia), and some others. Such a transport junction is intended to ensure traffic management by giving priority to those moving in the main direction, allowing them to go through the central island.

During analysis of regulations as well as scientific and technical literature (Central Research and Design Institute for Urban Development of the National Committee for Civil Engineering and Architecture, 1980; Garant, 2020; Kaligin et al. 2019; Ministry of Motor Roads of the RSFSR, 2004; Redington, 1995; Rosavtodor, 2012, 2016; Tollazzi, 2015; Tollazzi and Renčelj, 2014; Tollazzi et al., 2011, 2016; US Department of Transportation, Federal Highway Administration, 2010), we established that they do not contain any systematic information on the possibility of hamburger roundabouts' application or methods to determine their parameters, transport delays, etc. The Guidelines for Road Marking (Ministry of Motor Roads of the RSFSR, 2004) recommend using a two-phase traffic signal cycle, and the Guidelines for the Development and Implementation of Traffic Management Measures "Improving the Efficiency of Using Roundabouts" (Garant, 2020) recommend using the basic theory of traffic signal control management in relation to roundabouts. According to Tolazzi (2015), the diameter of the island in a hamburger roundabout with traffic signal control shall be 60 m or more. The Guidelines for the Design of Roundabouts During the Construction and Reconstruction of Motor Roads (Rosavtodor, 2016) recommend using roundabouts with a complex (non-standard) layout (e.g., roundabouts with a straight-through section, including hamburger roundabouts) at intersections where five or more streets come together at an estimated traffic intensity of 15,000–50,000 of normalized units per day. The circular area in the middle shall have 1–3 lanes.

The number of lanes at the entrance/exit to/from a roundabout shall be from 1/1 to 3/3. The estimated speed at such a junction shall be 10–20 km/h. In these Guidelines, transport junctions without traffic lights are considered. The Guidelines for Road Marking (Ministry of Motor Roads of the RSFSR, 2004) recommend using traffic lights at signalized roundabouts and signalized roundabouts with a straight-through section. In the case of signalized roundabouts, traffic flows approaching the intersection pass it at a green light (as in the case of standard intersections), and left-turning traffic flows move simultaneously with those moving straight ahead. In the case of signalized roundabouts with a straight-through section, prevailing traffic flows in one or two streets, moving straight ahead, move along the shortest path (diameter), and in the points of intersection with the roundabout, traffic lights are installed. The Guidelines provide examples of sign posting, traffic lights arrangement, and road marking.

The following recommendations for the use of traffic signal control at roundabouts are given:

- high vehicle traffic intensity;
- heterogeneous traffic flows;
- the share of left-turning vehicles in the prevailing direction is more than 0.25–0.3;
- high pedestrian traffic intensity.

Purpose of the study

We aimed to adapt Webster's method of traffic signal design to hamburger roundabouts with traffic signal control.

Study

Fig. 1 shows a hamburger roundabout with traffic signal control in Fairfax (USA). Fig. 2 shows traffic management facilities.

Komarov et al. (2021) and other researchers (Rosavtodor, 2016) studied the influence of transport as well as organizational and planning factors on the efficiency of traffic management (with transport delays as the main criterion) at

Figure 1. Hamburger roundabout with traffic signal control in Fairfax (USA)

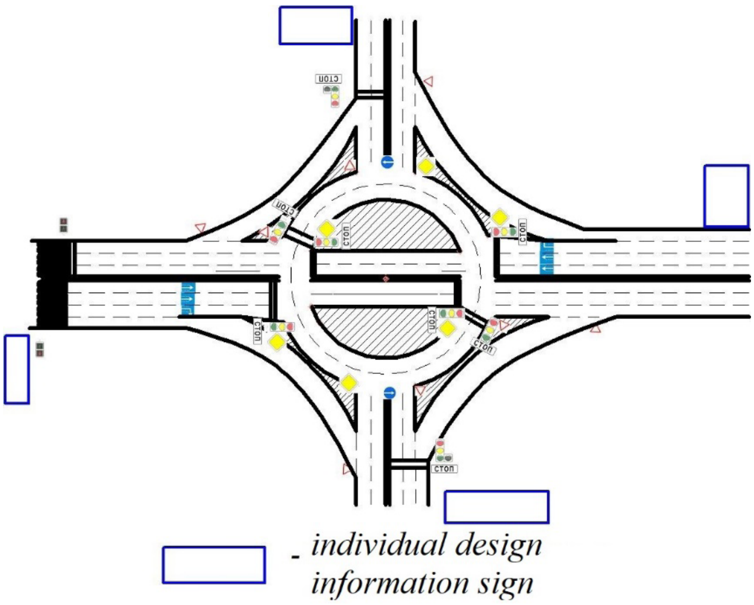

Figure 2. Traffic management facilities at the roundabout

hamburger roundabouts with traffic signal control. It was established that, as for the main direction, the estimated and experimental data (transport delays) agree with each other at the saturation degree $\chi \le 1$ (in this case, transport delays will be less than 38 s), and as for the minor direction, the data agree with each other at the saturation degree $\chi \le 0.72$ (in this case, transport delays will be less than 30 s).

To develop recommendations for traffic signal control at a transport junction, it is necessary to solve the following system of inequalities:

$$\begin{cases} \chi_{main} \le 1 \\ \chi_{minor} \le 0.72 \end{cases}. \quad (1)$$

The saturation degree can be determined by the following equation (Rosavtodor, 2012, 2013):

$$\chi = \frac{N_i * T_{cycle}}{M_i * t_{green}}, \quad (2)$$

where N_i — traffac intensityon the main road in the straight direction (normalized units/hour);
M_i— saturation flow for the main road (normalized units/hour);
T_{cycle}— duration of the traffic signal cycle (s);
t_{green} — duration of the green interval (s).

Since a two-phase traffic signal cycle is used at the junction (Garant, 2020; Komarov et al. 2021; Ministry of Motor Roads of the RSFSR, 2004; Rosavtodor, 2016), then:

$$T_{cycle} = t_{g\_main} + t_{g\_minor} + t_{change}, \quad (3)$$

where t_{g_main} — duration of the green interval for the main direction, s;
t_{g_minor}— duration of the green interval for the minor direction and the circular area, s;
t_{change}— duration of the change intervals that can be determined by the corresponding recommendations (Rosavtodor, 2012, 2013).

Let us shift to phase coefficients y_i (Rosavtodor, 2012, 2013; Webster, 1958) that can be determined by the following equation:

$$y_i = \frac{N_i}{M_i}. \quad (4)$$

Then we obtain the following system of inequalities:

$$\begin{cases} t_{g\_main} \ge T_{cycle} \times y_{main} \\ t_{g\_minor} \ge 1.39 \times T_{cycle} \times y_{minor} \\ T_{cycle} \ge \dfrac{t_{change}}{1-(1.39 \times y_{minor} + y_{main})} \end{cases}. \quad (5)$$

To ensure simultaneous fulfillment of all inequalities, let us replace all inequality signs with equal signs.

$$\begin{cases} t_{g\_main} = T_{cycle} \times y_{main} \\ t_{g\_minor} = 1.39 \times T_{cycle} \times y_{minor} \\ T_{cycle} = \dfrac{t_{change}}{1-(1.39 \times y_{minor} + y_{main})} \end{cases}. \quad (6)$$

When Eq. (6) is used, the resulting values of the traffic signal cycle duration and the duration of the intervals are quite small. In terms of essence, this equation is close to Webster's method (Rosavtodor, 2012, 2013; Webster 1958). Let us adapt Webster's method for the minor direction by using the resulting coefficient of 1.39. Then we obtain the following equations for traffic signal control:

$$\begin{cases} T_{cycle} = \dfrac{1.5 \times t_{change} + 5}{1-(1.39 \times y_{minor} + y_{main})} \\ t_{g\_main} = \dfrac{(T_{cycle} - t_{change}) \times y_{main}}{1.39 \times y_{minor} + y_{main}} \\ t_{g\_minor} = \dfrac{1.39 \times (T_{cycle} - t_{change}) \times y_{minor}}{1.39 \times y_{minor} + y_{main}} \end{cases}. \quad (7)$$

The efficiency of traffic management in Russia is assessed by the criterion described in Federal Law No. 443-FZ dated December 29, 2017 "On Traffic Management in the Russian Federation and on Amending Relevant Legislative Acts of the Russian Federation" (Silchenkov et al. 2020) as the ratio of time losses (delays) in vehicle and/or pedestrian traffic before and after the implementation of traffic management measures given that traffic safety is ensured.

Then, using the upgraded traffic model in the Aimsun software (Rosavtodor, 2016), we assessed the efficiency of the adapted method in comparison with the standard one as relative changes in the average transport delays. The upgrade of the traffic model implied changes in the number of lanes so that to ensure that the junction is symmetrical.

In the course of the study, the following assumptions were made:

- traffic flows include passenger cars only;
- the diameter of the island is 60 m;
- the approaches to the junction in the main direction are characterized by the same intensity (the same is true for the minor direction);
- in the main direction, the traffic flow moves only straight ahead since the influence of the left-turning flow on transport delays is insignificant (Komarov et al. 2021);
- the approaches to the junction in the minor direction are characterized by the following: 50% of vehicles move straight ahead, and

50% of vehicles turn left;
- the lane width is 3.75 m;
- the longitudinal slopes are 0‰;
- the distribution of the traffic flows in the software is set in a random manner (without user's participation);
- and so on.

Procedure:
- the following phase coefficients were taken: for the main direction, $0.2 \leq y_{main} \leq 0.8$; for the minor direction, $0.2 \leq y_{minor} \leq 0.5$;
- saturation flows were determined for the approaches to the junction by the corresponding recommendations (Garant, 2021; Kremenets et al. 2005; Redington, 1995; Rosavtodor, 2012); intensities for each pair of y_{main} and y_{minor} were determined as well;
- traffic signal control cycles were determined by the standard and adapted methods;
- the traffic flow intensity values and data on the traffic signal control cycles were introduced in the traffic model; transport delays were determined for each approach; the average transport delay at the intersection was determined;
- for each pair of y_{main} and y_{minor}, 10 simulations were performed, and the average transport delay was determined;
- for some pairs of y_{main} and y_{minor}, it was impossible to determine the average transport delay since vehicles could not move due to high traffic intensity values. These pairs of y_{main} and y_{minor} are not presented in comparative Table 1.

Table 1 shows the results of the study.

Table 1. Comparison of traffic signal cycle design methods

Phase coefficient, main road, y_{main}	Phase coefficient, minor road, y_{minor}	Adapted method: Duration, s				Standard method: Duration, s				Average delay, adapted method, s	Average delay, standard method, s	Relative difference, %
		Green interval, main road	Green interval, minor road	Duration of the change intervals	Traffic signal control cycle	Green interval, main road	Green interval, minor road	Duration of the change intervals	Traffic signal control cycle			
0.2	0.1	9	6	6	21	9	5	6	20	7.1	6.4	10.1
0.3	0.1	13	6	6	25	13	4	6	23	7.7	6.2	20.3
0.4	0.1	18	6	6	30	18	4	6	28	9.2	10.1	–10.4
0.5	0.1	26	7	6	39	24	5	6	35	11.5	19.1	–65.7
0.6	0.1	39	9	6	54	35	6	6	47	14.4	23	–59.2
0.7	0.1	68	13	6	87	56	8	6	70	21.8	38.3	–43.1
0.2	0.2	9	12	6	27	9	9	6	23	10.4	9.9	5
0.3	0.2	14	13	6	33	13	9	6	28	11.1	11.4	–2.8
0.4	0.2	22	15	6	43	19	10	6	35	13.8	16.4	–19.3
0.5	0.2	37	20	6	63	29	12	6	47	19.1	32.9	–72.4
0.2	0.3	10	21	6	37	9	13	6	28	13.1	20.5	–56.1
0.3	0.3	18	25	6	49	15	15	6	35	30.1	52.3	–73.6
0.2	0.4	14	38	6	57	10	19	6	35	7.7	7.4	3.8
											Average difference	–28

Results and discussion

As can be seen from Eq. (7), in the case of the adapted method, the duration of the green interval for the minor direction and the circular area increases. This is due to the existing recommendations for traffic management (namely, the use of two-phase traffic signal control).

The adapted method of traffic signal cycle design, applied to the traffic model built in the Aimsun software, reduces the average transport delay at the intersection by 28% on average, and in the most probable case when the sum of the phase coefficients for the main and minor roads is in the range of 0.5...0.7 — by up to 40%. At low traffic intensity values, when the sum of the phase coefficients is less than 0.4, it is preferable to use standard Webster's method of traffic signal control design.

This study can be useful in the development of recommendations for the use of a hamburger roundabout with traffic signal control and the update of recommendations for the use of roundabouts and traffic signal control design.

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АДАПТАЦИЯ МЕТОДИКИ РАСЧЕТА СВЕТОФОРНОГО ЦИКЛА ДЛЯ КРУГОВОГО ПЕРЕСЕЧЕНИЯ СО СВЕТОФОРНЫМ РЕГУЛИРОВАНИЕМ И ПРОРЕЗАННЫМ ЦЕНТРАЛЬНЫМ ОСТРОВКОМ

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Аннотация
Кольцевые пересечения со светофорным регулированием и прорезанным центральным островком нашли ограниченное применение на улично-дорожной сети крупных городов. В ходе анализа научно-технической литературы установлено отсутствие системной информации о возможности их применения, методик расчета параметров данного типа кольцевого пересечения. **Цель исследования:** Адаптировать существующую методику Ф. Вебстера расчета светофорной сигнализации для кругового пересечения со светофорным регулированием и прорезанным центральным островком с учетом особенностей организации дорожного движения. **Методы:** В исследовании использовались методы анализа, моделирования дорожного движения в программном комплексе Aimsun, неоднократно апробированный в этой области знаний и рекомендованный для применения в научно-технической литературе по организации дорожного движения. Оценка эффективности адаптированной методики проводилась по результатам моделирования сравнением средних транспортных задержек на пересечении при адаптированной и существующей методике. **Результаты:** Адаптированная методика расчета светофорного цикла дает снижение средней транспортной задержки в среднем на 28 %.

Ключевые слова
Дорожное движение, кольцевое пересечение со светофорным регулированием и прорезанным центральным островком, транспортная задержка, светофорный цикл.