OPTIMIZATION OF WORK OF TRAFFIC SIGNALS IN ORDER TO REDUCE THE LENGTH OF THE WAITING QUEUE AND DELAYS IN ISOLATED INTERSECTION: A CASE STUDY

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ABSTRACT

Saturated flows at intersections with traffic lights represent the restrictive traffic situation, whereas in preliminary always used as a basis for selecting an optimal plan at the traffic light phase. Unsuitable coordination of the work in the traffic lights reduces the capacity of the traffic intersections, increasing delays and generally increase the travel time. From this stems the need for the application of new methods for improving the work of traffic light signals. In most of the cases, traffic light signals working on the principle of fixed time. In this paper is used optimization method to determine the duration of the signal timing plan at traffic lights and distribution of green times through phased in order to minimize delays and number of vehicles in the traffic lane. For the same input data, the results obtained with optimization are compared with the results obtained with Webster's classical model. It is proved that, with optimization of traffic light signals, without intervention in changing the geometry of the intersection, reduced delays and waiting queue.

KEYWORDS: optimization, the traffic light cycle, phase, delays, waiting queue, level of service.

1. INTRODUCTION

From aspect of traffic control, traffic intersections represent the most critical places on the road network. The movement of vehicles through intersections should be regulated in order to reduce the conflict points. Setting and application of light signals is one of the most effective ways to regulate priority passing through the intersection. The problems faced by traffic engineers, is to make
the distribution of green times within the light cycle. Primarily, the implementation of the work of the traffic light signals depends on two fundamental criteria.

According to the hierarchy, these two criteria are: strategic criteria (which give the answers in the question, whether the light signals were introduced into the function) and operational criteria (which give the answers in the question what should be minimized, respectively maximized in the intersection).

The operational criteria of traffic light signals that are mostly used today are: criteria for minimizing the delays, respectively linear combinations of delays, criteria to minimize travel times, criteria to minimize overall travel times- network costs, criteria to maximize the capacity, criteria to minimize the waiting queue within the allowed limits, criteria to minimize overall delays for road users.

In order to concretizing the criteria that were mentioned above, within this paper are reviewed the functional indicators the existing situation at the crossroads “Skënderbeu” and “Zahir Pajaziti” in Podujevë and are analyzed the possibilities for improvement.

The form of this intersection which is highly frequented is "T"-intersection, and is located in the urban part of the city. Also, traffic flow is controlled by traffic light signals and the system of regulation with fixed time.

Based on the intersection geometry and traffic flow at the entrance of the intersection, for characteristic days and times, is concluded that the phase adjustment in this intersection, not adequately meet the needs of traffic participants. Vehicle and pedestrian flow is given in Table 1.

After analyzing the traffic flow size, within this paper is attempting to improve the indicators of the junction, through optimization.

In Fig. 1. is given the current situation of the “T” intersection, while phase adjustment is shown in Fig. 2.
2. SATURATED FLOW THROUGH THE GENERAL METHOD

To calculate the saturated flow size is using the expression (1),

\[ S_i = Q_{op} \cdot N \cdot f_1 \cdot f_2 \cdot f_3 \cdot f_4 \ (vph) \],

where are:
- \( Q_{op} \) - operational flow,
- \( N \) - number of lanes in the same order,
- \( f_1 \) - pedestrian impact factor,
- \( f_2 \) - impact factor of conflicting flow,
- \( f_3 \) - impact factor of flow structure,
- \( f_4 \) - impact factor of the size of the city

After calculation the saturated flows with general method, is assigned capacity utilization coefficient at the entrance of the intersection, which are considered the busiest lanes that have greater capacity utilization coefficient.

The obtained results are presented in Table 2.

<table>
<thead>
<tr>
<th></th>
<th>Phase I</th>
<th>Phase II</th>
<th>Phase III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lane</td>
<td>1.1</td>
<td>2.1</td>
<td>3.1</td>
</tr>
<tr>
<td>( Q_i )</td>
<td>480</td>
<td>300</td>
<td>200</td>
</tr>
<tr>
<td>( S_i )</td>
<td>1096</td>
<td>1908</td>
<td>1350</td>
</tr>
<tr>
<td>( Y_i = \frac{Q_i}{S_i} )</td>
<td>0.437</td>
<td>0.157</td>
<td>0.148</td>
</tr>
<tr>
<td>( Y_{imax} )</td>
<td>0.437</td>
<td>0.157</td>
<td>0.148</td>
</tr>
<tr>
<td>( Y_{im} )</td>
<td>0.437</td>
<td>0.157</td>
<td>0.148</td>
</tr>
<tr>
<td>( Y )</td>
<td>( Y_{im} + Y_{2max} + Y_{3max} = 0.742 )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Where are:
- \( Q_i \) – flow intensity for direction,
- \( S_i \) – saturated flow size,
- \( Y_i = \frac{Q_i}{S_i} \) – capacity utilization coefficient for each lane,
- \( Y_{imax} \) – capacity utilization coefficient at entrance for phase,
- \( Y \) – capacity utilization coefficient at the entrance intersection.

3. DETERMINATION OF THE PROTECTION TIME AND CREATION OF RELEVANT MATRIX

The general expression for calculation of protection time, takes into consideration extreme cases of vehicle movements of the both flows, which conflict must be prevented: flow \( i \)” which lose right of passage with completion of its phase, and flow \( j \)” which obtains that right in the current phase of signaling plan:

\[ \Delta t_{i-j} = \frac{l_i}{V_i} - \frac{l_j}{V_j} + 1 \ [s] \]
Where are:
- \( l_i \) – distance from the vehicle of phase “\( i \)” up to the conflicting points,
- \( V_i = 30 \text{ [kph]} \) – speed of last vehicle who legally passes the intersection in phase “\( i \)”
- \( l_j \) – distance from the vehicle phase which wait the right to pass through the intersection of the phase “\( j \)” up to the conflict points,
- \( V_j = 60 \text{ [kph]} \) – speed of the vehicle in phase “\( j \)” which is assumed that the vehicle can arrive at conflicting point.

The third part of the calculation of the time protection is fixed second, which always added to the two others. This caused increasing of the protective time, aiming an additional security by which reach a compensation for some simplifications made during the calculation (the neglect the length of the vehicle, imprecise measurement of the length of road to the conflict point, etc.). Matrix of the protective times is given in Table 3.

<table>
<thead>
<tr>
<th>( \Delta t_{i-j} )</th>
<th>1.1</th>
<th>2.1</th>
<th>2.2</th>
<th>3.1</th>
<th>3.2</th>
<th>P1</th>
<th>P2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>×</td>
<td>×</td>
<td>2.73</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>2.1</td>
<td>×</td>
<td>×</td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>2.2</td>
<td>×</td>
<td>×</td>
<td></td>
<td>×</td>
<td>×</td>
<td>1.71</td>
<td>×</td>
</tr>
<tr>
<td>×</td>
<td>0.58</td>
<td>×</td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>3.2</td>
<td>×</td>
<td>0.94</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>P1</td>
<td>8.97</td>
<td>8.97</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
<tr>
<td>P2</td>
<td>×</td>
<td>×</td>
<td>9.08</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
</tr>
</tbody>
</table>

4. APPLICATION OF WEBSTER'S MODEL - FOR CALCULATING THE SIGNALING PLAN

As a starting point of the Webster's model for calculating the signaling plan, is used expression for vehicle delays at the entrance to the signaling intersection.

\[
C = \frac{1.5 \cdot L + 5}{1 - Y} \text{ [s]}
\]

(3)

The parameter \( L \) presents lost time respectively unused time within cycle, which is calculated by the expression:

\[
L = n \cdot d + \sum_{i=1}^{n} \Delta t_{i-j} \text{ [s]}
\]

(4)

Where are:
- \( n = 3 \) – the number of phases of the signaling plan,
- \( d = a + c = 3 \text{ (s)} \) – the sum of lost time at the beginning of the green interval (\( a \)) and the unused part of the yellow interval (\( c \)),
- \( \Delta t_{i-j} \) – the time between current protective phase “\( i \)” and the next phase “\( j \)”.
The parameter \( Y \) in the expression (3) represents the sum of the maximum values \( Y_j \) for each of the phases \( "i" \) of the cycle.

\[
Y = \sum_{i=1}^{n} Y_i, \quad \text{where} \quad Y_i = \max\{y_{j,i}\} = \left( \frac{Q_i}{S_j} \right)
\]

where is:

- \( Y_i \) – the ideal utilization degree of capacity in the intersection which represents the ratio of the size of the ideal flow \( Q_i \) and the saturated \( S_j \) of the traffic lane \( "j" \).

Durations of green intervals within the cycle are calculated according to the expression given below:

\[
g_j = \frac{Y_i}{Y} (C - L) \quad [s],
\]

### 5. OPTIMIZATION FOR CALCULATING OF WORK OF SIGNAL LIGHTING

Till now are developed many methods for solving optimization problems. The optimization problem in this paper is realized through linear programming, respectively through the Simplex algorithm.

The main goal has been to minimize: the number of vehicles on the queue, length of the waiting queue, delays (lost times), respectively optimal duration of cycle and distribution of green times in phases.

As the objective function is selected rows waiting model which is given by the following expression:

\[
\min N = \min \sum_{i=1}^{m} \left( \frac{q_i}{1 - Y_i} \right) \cdot (C - g_{j,i}) + m \cdot N_2
\]

where are:

- \( m \) – number of lanes in the intersection,
- \( j \in i \) – the green time in phase \( "j" \) which belongs to the group of lane \( "i" \),
- \( N_2 \) – increased waiting queues (optional) \( 2 \leq N_2 \leq 6 \).

The first part of expression has a linear form, while the second part with the increase of the waiting queues under the specified conditions may be replaced by a constant.

In the limits “under capacity” \( x_i \leq 0.85 \) increase of the waiting queues is up to 2 vehicles. For smaller value this is eliminated.

For values of “near capacity” \( x_i \leq 0.95 \) still can be accepted values 4-6 vehicles, while the state “over capacity” the number of vehicles in waiting queues grow rapidly.

Model of waiting queues can be approximated very well with the first part (linear function) under the condition that the degree of saturation of the lanes to be at "near capacity". For this case, because of the degree of saturation values are small, in the limit "under capacity" \( x_i \leq 0.85 \), then the second part of the expression (7) is neglected.

Limitations are given by the expressions (8), (9), (10), (11) and (12). Because of the “linearity” objective function must fulfill the conditions that for each lane group \( x_i \leq 0.85 \):

\[
\frac{q_i \cdot C}{g_{j,i} \cdot S_i} \leq x_i^{\max} = 0.85; \quad \text{where} \quad i = 1, \ldots, m
\]
\[ q_i \cdot C - 0.85 \cdot g_{ji} \cdot S_i \leq 0; \quad \text{where } i = 1, \ldots, m \]

In order of the traffic safety and certain restrictions of engineering it is necessary the duration of the cycle to held in defined limits:

\[ C_{\text{min}} \leq C \leq C_{\text{max}} \quad (9) \]

For engineering reasons is not recommended the duration of the cycle not less than \( C_{\text{min}} = 40 \) (s) and not more than \( C_{\text{max}} = 120 \) (s), while for safety reasons (up to 150 s in large intersection).

According to recommendations from the literature (signaling groups, green arrows, groups of pedestrians, public transport etc.) is necessary to ensure the minimum duration of the green light for each phase.

\[ g_j \geq g_j^{\text{min}}, \quad \text{where } j = 1, \ldots, m \quad (10) \]

Also, it is necessary to ensure that the amount of minimum green times of phases and lost times to be equal to the length of the cycle:

\[ C = \sum_{j=1}^{m} g_j + L \quad (11) \]

At the end should be fulfilling the condition that the duration of the cycle and duration of green lights in phases must be non-negative:

\[ C, g_j \geq 0 \quad (12) \]

By using the data obtained by the general method are achieved the results which are presented in the table 4.

**Table 4.** Results obtained by a general method

<table>
<thead>
<tr>
<th>Lane</th>
<th>( q )</th>
<th>( S )</th>
<th>( Y )</th>
<th>( q/(1-Y) )</th>
<th>( x_{\text{max}} )</th>
<th>( x_{\text{max}} \cdot S )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>0.133</td>
<td>0.304</td>
<td>0.437</td>
<td>0.236</td>
<td>0.85</td>
<td>0.258</td>
</tr>
<tr>
<td>2.1</td>
<td>0.083</td>
<td>0.530</td>
<td>0.157</td>
<td>0.098</td>
<td>0.85</td>
<td>0.450</td>
</tr>
<tr>
<td>2.2</td>
<td>0.042</td>
<td>0.375</td>
<td>0.111</td>
<td>0.047</td>
<td>0.85</td>
<td>0.318</td>
</tr>
<tr>
<td>3.1</td>
<td>0.056</td>
<td>0.375</td>
<td>0.148</td>
<td>0.065</td>
<td>0.85</td>
<td>0.318</td>
</tr>
<tr>
<td>3.2</td>
<td>0.042</td>
<td>0.356</td>
<td>0.116</td>
<td>0.047</td>
<td>0.85</td>
<td>0.302</td>
</tr>
</tbody>
</table>

After applying the results obtained from table 4 and replacing in the expression (7) obtained mathematical program respectively the objective function take this form:

\[
\begin{align*}
\min N &= 0.236(C - g_1) + 0.098 \cdot (C - (g_1 + 6 + g_2)) + 0.046 \cdot (C - g_2) + 0.065 \cdot (C - (g_2 + g_3)) + 0.047 \cdot (C - g_3) \\
&\Rightarrow \min N = -0.913 - 0.334 \cdot x_1 - 0.209 \cdot x_2 - 0.112 \cdot x_3 + 0.492 \cdot x_4
\end{align*}
\]
But the specified limits have this form:
\[0.133 \cdot x_4 - 0.258 \cdot x_1 \leq 0\]
\[0.083 \cdot x_4 - 0.450 \cdot x_1 - 0.450 \cdot x_2 \leq 2.7\]
\[0.041 \cdot x_4 - 0.318 \cdot x_2 \leq 0\]
\[0.055 \cdot x_4 - 0.318 \cdot x_2 - 0.318 \cdot x_3 \leq 1.59\]
\[0.041 \cdot x_4 - 0.302 \cdot x_3 \leq 0\]
\[x_4 - x_3 - x_2 - x_1 = 16\]
\[x_1 \geq 15\]
\[x_2 \geq 6\]
\[x_3 \geq 15\]
\[C \geq 52\]
\[C \leq 120\]

With the application of mathematical appropriate form and the simplex method and applying replacement, solution of the optimal signal program is given as follows:

\[x_1 \equiv g_1 \equiv 45(s); \ x_2 \equiv g_2 \equiv 12(s); \ x_3 \equiv g_3 \equiv 15(s); \ x_4 \equiv C \equiv 88(s);\]

Therefore, in the following table are presented the results obtained for the cycle duration and distribution of green times in phases according the: Webster’s model and optimization.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Webster model</th>
<th>Optimization</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>g1 [s]</td>
<td>57</td>
<td>45</td>
<td>21.05%</td>
</tr>
<tr>
<td>g2 [s]</td>
<td>21</td>
<td>12</td>
<td>42.86%</td>
</tr>
<tr>
<td>g3 [s]</td>
<td>19</td>
<td>15</td>
<td>21.05%</td>
</tr>
<tr>
<td>C [s]</td>
<td>113</td>
<td>88</td>
<td>22.12%</td>
</tr>
<tr>
<td>L [s]</td>
<td>16</td>
<td>16</td>
<td>0.00%</td>
</tr>
</tbody>
</table>

A graphic presentation of accordion plans in both cases is given in Figure 3 and 4.

**Fig. 3.** Accordion plan of signals under the existing situation- without optimization
6. DETERMINATION NUMBER OF VEHICLE IN QUEUE AND LENGTH OF WAITING QUEUE

Number of vehicles in queues respectively lengths of queues in entrance of intersection are very important, due to the necessary length of traffic lanes and avoid blocking the normal of traffic. Greater length of the queue reaches at the end of the effective interval of the red light.

In this case the calculation is taken into account the expression (7) for determining the number of vehicles in waiting queues and the obtained results are presented in Table 6.

Table 6: The number of length and waiting of queues by lanes

<table>
<thead>
<tr>
<th>Lane</th>
<th>Number of vehicles N [veh]</th>
<th>Length of queues L [m]</th>
<th>Webster model</th>
<th>Optimization</th>
<th>Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>N [veh]</td>
<td>L [m]</td>
<td>N [aut]</td>
<td>L [m]</td>
<td>%</td>
</tr>
<tr>
<td>1.1</td>
<td>13.28</td>
<td>66.4</td>
<td>10.2</td>
<td>51</td>
<td>23.19 %</td>
</tr>
<tr>
<td>2.1</td>
<td>2.86</td>
<td>14.3</td>
<td>2.47</td>
<td>12.35</td>
<td>13.64 %</td>
</tr>
<tr>
<td>2.2</td>
<td>4.31</td>
<td>21.55</td>
<td>3.56</td>
<td>17.8</td>
<td>17.40 %</td>
</tr>
<tr>
<td>3.1</td>
<td>4.43</td>
<td>22.15</td>
<td>3.65</td>
<td>18.25</td>
<td>17.61 %</td>
</tr>
<tr>
<td>3.2</td>
<td>4.43</td>
<td>22.15</td>
<td>3.44</td>
<td>17.2</td>
<td>22.35 %</td>
</tr>
</tbody>
</table>

Graphic 1. Review number of vehicles waiting in the queue
While, for determining the length of waiting queues is used as the following expression:

\[ L = N \cdot (l + s) \]  

(13)

where are:

- \( L \) [m] – length of queue,
- \( l \) [m] – length of vehicles, approved 3.5 (m),
- \( s \) [m] – distance between vehicles in queue, approved 1.5 (m).

**Graphic 2.** Review of the waiting queues

7. **DETERMINATION DELAYS OF VEHICLES AND LEVEL OF SERVICE**

Exists many methods for determination delays of vehicles in the entry of isolated intersection with the lights signals. Greater implementation has HCM method and Webster model.

Delays depend on the capacity and degree of saturation, geometry of intersection, type of signaling plan, the characteristics of flow and environment. Average delays of vehicle for the corresponding lane calculated according to the following expression:

\[ d = d_1 \cdot PF + d_2 + d_3 \ [s] \]  

(14)

where are:

- \( d \) – total delays for vehicle (s/veh),
- \( d_1 \) – uniform delays (s/veh),
- \( PF \) – quality factor of the progression,
- \( d_2 \) – additional delays due to the random arrival of vehicles in intersection (s/veh),
- \( d_3 \) – initial delays (s/veh).

Size of uniform delays depends on the type of progression, respectively manner and type of vehicle arrival in the time of permitted signal (green signal).

Good progression of signals means when the percentage of vehicles arrives at the entrance of intersection in the same phase during the green interval.

Progression has impact only in the uniform delays and therefore be considered when calculating \( d_1 \).
Due to the nature of the paper for further calculation is used only expression for calculating the uniform delays \(d_1\), which is given below:

\[
d_1 = \frac{0.5 \cdot C \cdot \left( \frac{g}{C} \right)}{1 - \min (1, X) \cdot \frac{g}{C}} \quad [s/aut]
\]  

(15)

<table>
<thead>
<tr>
<th>Lane</th>
<th>Uniform delays - (d_1) [s/veh]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1</td>
<td>Webster model</td>
</tr>
<tr>
<td>2.1</td>
<td>Optimization</td>
</tr>
<tr>
<td>3.1</td>
<td>Optimization</td>
</tr>
<tr>
<td>3.2</td>
<td>Optimization</td>
</tr>
</tbody>
</table>

Table 7. Uniform delays and level of service

8. FINAL RESULTS

Based on the results presented above may be noted that the work program of light signals by optimization gives the best results compared to the Webster model (without optimization).

So, it gives better results for all efficiency indicators as: shorter duration of the cycle, better distribution of green times, smaller number of vehicles waiting in queues, smaller length of queues and reduces delays in the entry of intersection providing the good level of service.

9. CONCLUSION

From the engineering point of view the choice of the problem, respectively reduction of delays in most cases viewed as negligible. In reality does not affect the improvement of level of service (LOS) which is one of the fundamental parameters of efficiency indicators of light signals.

But in terms of evaluating the solution each reduction in delays has an impact on saving funds, fuels, reduction of environmental pollution etc.

The case in which it is applied optimization is a simple example, where the task in the future needs of the application to the complicated intersections and greater demand of traffic.
REFERENCES