The main directions for optimizing traffic flows to increase their throughput

Yaroslav Shamlitsky\textsuperscript{1*}, Anatoly Popov\textsuperscript{1}, Evgeny Morozov\textsuperscript{1}, and Alexandr Devyatkov\textsuperscript{1}

\textsuperscript{1}Reshetnev Siberian State University of Science and Technology 31, prospect “Krasnoyarsky rabochy “, Krasnoyarsk, 660037, Russia

Abstract. This paper analyzes various problems of mathematical modeling of traffic flows that are relevant for optimizing and reducing the congestion of road networks in large cities and metropolitan areas. Various types of relationships between traffic lights on a controlled section of the road have been studied, formulas have been proposed for calculating the optimal joint mode of operation and minimizing the formation of traffic jams in front of the intersection. A model for calculating the optimal traffic flow on a section of the road network and its implementation at the program level are proposed. Key words: traffic flow, road network, traffic flow optimization, traffic network congestion, traffic light phase adjustment, optimal speed calculation.

1 Introduction

The road industry is one of the most important sectors of the economy of any industrialized country. No wonder roads are called the “circulatory system” of any state. They play a huge socio-economic role in the life of modern society. In the Russian Federation, due to the vast spatial extent of the territory, transport costs are significantly higher than the world average. Highways are very capital-intensive, but at the same time very cost-effective structures.

The high congestion of the transport network is a consequence of the late rebuilding of drivers, as well as the constant duration of the traffic light phases and the inability of road users to adapt to them. Drivers making a late maneuver force other road users to slow down, resulting in a so-called moving traffic jam. Traffic lights that work the same regardless of the time of day or day of the week also lead to traffic jams, since flows at different times can have completely different intensity and even direction. So on weekday mornings, drivers go to work, to the place of study, located mainly in the central part of the city, and in the evening, on the contrary, they return to the district, “sleeping” areas.

The low level of development of the Russian road network is a significant deterrent to the growth of a market economy, in which road transport plays a dominant role. Unfortunately, the construction of roads is not going fast enough, and the city's road transport networks cannot cope with the ever-increasing load on them. Often, the construction of roads is limited by not only the financial framework and construction capabilities, but by the architecture of

* Corresponding author: yar.publ@gmail.com
the city. The latter makes it impossible to build new or expand existing roads in densely built-up or historical areas of the city.

Therefore, the relevance of the development and software implementation of algorithms that can analyze the existing road transport network of the city and determine the optimal traffic routes from various points of view is high.

2 Materials and methods

The high congestion of the transport network is a consequence of the late rebuilding of drivers, as well as the constant duration of the traffic light phases and the inability of road users to adapt to them. Drivers making a late maneuver force other road users to slow down, resulting in a so-called moving traffic jam. Traffic lights that work the same regardless of the time of day or day of the week also lead to traffic jams, since flows at different times can have completely different intensity and even direction. So on weekday mornings, drivers go to work, to the place of study, located mainly in the central part of the city, and in the evening, on the contrary, they return to the district, “sleeping” areas. To solve these problems, consider some models that solve the existing traffic flow problems.

2.1 Traffic light model with a change in the duration of the phases of work

Consider a crossroads model in a small town. Denote crossroads as Crossroad, we will single out 4 main directions. By purpose, we divide the districts as follows [1-2]:

- A – business districts (offices, firms, shops);
- B – public institutions (schools, clinics);
- C – recreational areas (parks, holiday villages, food outlets);
- D – recreational areas (parks, holiday villages, food outlets);

Consider the different days of the week and time of day, as well as their corresponding priority areas:

- weekdays - morning - A and B; weekdays - evening - C and D;
- weekends - morning - C and D; weekends - evening - D.

Note that the predominant traffic directions change quite often, and this should be taken into account when traffic lights operate in these directions.

Suppose there is a traffic light with three color signals: green, yellow and red. Denote by $t_g$, $t_y$ and $t_r$ the duration of observation of each color, respectively. According to the norms, the operating time of some traffic light phases is fixed, for example, the duration of the yellow signal phase should be equal to three seconds.

This implies some restrictions imposed on the operation time of traffic light phases [3-4]:

1. $t_y = 3$ seconds.
2. $t_{ry} < 2$ seconds.
3. $t_g > \min \{t_A, t_B, t_C, t_D, t_E\}$, where the right side lists the values of the duration of the time intervals sufficient for the passage through the traffic light of at least one vehicle of a certain category that is allowed to pass through this intersection.

These restrictions allow you to avoid situations when the time of the traffic signal is not enough to overcome the intersection.

It is required to find a numerical value that displays the ratio of the durations of the enabling and prohibiting signals. Since the duration of the yellow signal cannot be varied, we will consider only the ratio of the green and red signals, which we denote as $k$.

Let the density of the traffic flow approaching the traffic light be $\rho$, then, according to macroscopic models, we can calculate the speed of propagation of information about the braking of vehicles:
\[
\frac{Q(\rho_{\text{max}}) - Q(\rho)}{\rho_{\text{max}} - \rho} = \frac{q}{\rho_{\text{max}} - \rho'},
\]

where \(\rho_{\text{max}}\) — the maximum possible density of vehicles on a given section of the road and \(q\) - the value of the flow of vehicles.

Then you can calculate the number of vehicles that will accumulate during the burning of the prohibiting traffic light:

\[
(p_{\text{max}} - \rho) \frac{q}{\rho_{\text{max}} - \rho} t_r = qt_r.
\]

In order for this number of cars not to increase over time, it is necessary that the time of turning on the green signal of the traffic light is enough to pass through the intersection of all the accumulated cars, which can be set by this inequality:

\[
(q_g - q)t_g \geq qt_r \Rightarrow k = \frac{q}{q_g - q'}
\]

which determines the value of the optimal ratio of green and red signals.

Thus, by adjusting the value of \(k\), it is possible to set different durations of the phases of the traffic light, thereby accelerating the passage of traffic flows at different times of the day, depending on the priority of the direction. The solution of this problem gives a partial answer to the question of changing the duration of the phases of the traffic light, but does not take into account the rebuilding at the entrance to the traffic light, which ultimately affects the important density factor.

Therefore, for competent optimization of a particular intersection, one should first calculate the change in the densities of pathovehicles that occur during the rebuilding, and only then use this ratio.

It can be summarized that in order to solve the problem of adjusting the phases of a traffic light and the dependence of the traffic density on the current time, it is necessary to collect data on the priority of directions for each intersection, then conduct a simulation of the movement, taking into account possible rebuilding, select the value of the parameter \(k\), which minimizes the increase in the density of congestion in front of the intersection , and make these changes in the duration of the phases of the traffic light, taking into account the obtained optimal values.

### 2.2 Calculation of the optimal speed to the next intersection

Unfortunately, the model of traffic light settings considered in the previous section has its drawbacks. It is suitable only for studying the case of motion along a main road where vehicles can pass at the maximum speed limit without any delay. An example of such a section of the path can be shown graphically, as shown in Figure 1:

![Fig. 1. Driving on the main road.](image)

However, in practice, there are often situations with crossing roads of the same traffic priority, as in Figure 2. In this case, it will no longer be possible to create an advantage in
movement in one direction without creating difficulties when traveling in a perpendicular direction [5-6].

Fig. 2. Driving on a main road and an intersection with the same traffic priorities.

However, there is an opportunity to improve traffic when approaching a traffic light with the same priorities: if drivers are warned in advance about the time the traffic light turns green at the next intersection, then it will be possible to set the optimal model for their movement. Currently, according to sociological surveys, 41% of drivers, starting from an intersection, seek to gain maximum speed, while they still have to stand at the next traffic light.

This movement is incorrect due to the following factors:

- Road safety. Driving at high speed within the city is dangerous both for other road users and for pedestrians [7], especially in bad weather conditions, which follows from the description of the Tanaka macroscopic model.
- Creation of an artificial traffic jam. Driving at the right speed would allow you to arrive at the next intersection without braking at the traffic lights, which creates an artificial traffic jam associated with the dissemination of information about the leading cars ahead or braking, according to the microscopic leader-following model.
- Increased costs. Rapid acceleration and braking leads to excessive fuel consumption and rapid wear of car parts, which corresponds to an increase in the car owner's cost of maintaining a vehicle.

In connection with these problems, it is recommended to warn drivers about the optimal driving mode until the next intersection. Modern technologies allow you to know the location of the car on the road section and even the lane using GPS navigation, and the time to reach the next intersection and pass it at the green traffic light is easily set using the phase reconfiguration model discussed earlier. At the same time, information about the optimal speed of movement can be reported using navigation programs.

To set the optimal movement, the acceleration of the vehicle to achieve the optimal speed, as well as the corresponding acceleration time and the distance traveled during this time, should be determined. Therefore, when calculating the acceleration of a car, one should take into account the totality of forces acting on it [8]:

\[ a_a = \frac{F_{wh} - F_{air} - F_k}{m}, \]  

(4)

In the above formula, the symbols used will set the following characteristics of the vehicle:
- \( a_a \) — car acceleration;
- \( F_{wh} \) — force from the moment \( M_{wh} \) on the wheel diameter \( D_{wh} \);
- \( F_{air} \) — air resistance force taking into account the aerodynamic drag coefficient of a car \( C_a \) with a frontal surface area \( S_a \) moving at a speed \( v_a \) at a certain air density \( \rho_{air} \);
- \( F_k \) — rolling resistance force for a given vehicle mass \( m \) and rolling resistance coefficient \( f_k \), where \( g \) is equal to the free fall acceleration.
Then, having found out the indicators of a particular car (the calculation was carried out for the Volkswagen Polo Sedan 1.6 / 81 (110) / 5-speed manual), it will be possible to determine various types of dependencies.

First, the dependence of acceleration and speed when the car is moving in various gears is determined, then the relationships of these quantities with time are specified, and, finally, the dependence between speed and distance, which is most convenient for practical use, is determined.

Now, having created a model of the movement of a vehicle, let's move on to considering various options for moving from a passed traffic light to the next one. To do this, we will conditionally divide them into several categories and try to single out the most optimal option for passing through the controlled area.

Let's designate the selected categories with the letters A, B, C and D and consider them in more detail, presenting the movement in each case on one chart (Figure 3):

**Fig. 3.** Dependence of speed and distance.

- A – driving at too high a speed is dangerous due to excessive acceleration and braking, and it will also lead to an early arrival at the intersection before the end of the red traffic light phase $t_r$ and downtime at the traffic light, followed by the spread of congestion with a constant increase in density $q^+;

- B – in this case, the vehicle is forced to stop moving when it reaches the traffic light and at the same moment continue it with acceleration, which will lead to excessive fuel consumption, increased likelihood of parts wear and a slight congestion;

- C – the car passes a traffic light without changing the set speed;

- D – insufficient vehicle speed will slow down the traffic following it.

Obviously, the best option among the proposed ones is case C. Now you need to programmatically calculate the optimal speed and inform the driver using navigation programs.

As a result of applying this algorithm, the value of the optimal speed on the considered section of the road will be calculated.

Next, we apply the proposed methods and algorithms for road sections in St. Petersburg, which are difficult to travel due to the inconsistency of traffic lights. Based on the algorithms of this work, a program will be compiled that performs calculations for the studied segments of the city's road network.
3 Results

As the first test section of the road, we will take the segment of St. Petersburg Avenue from the pedestrian traffic light near school No. 542 to the traffic light at the intersection with Factory Street.

Note the traffic lights on the test section, the number of lanes and adjacent road, we will draw up a visual diagram, based on which we will make a decision on the use of models. In total, there are 8 traffic lights on this section of the avenue, while the tested segment of the avenue is the main one in relation to the streets adjacent or crossing it. Mark the traffic lights on the map and calculate the distance between them. The results obtained are clearly shown in Figure 4:

![Map of traffic lights and distances](image)

**Fig. 4.** The location of traffic lights and the distance between them.

Then the total length of the road segment $S_{tot} = \sum_{i=1}^{n-1} S_{i,i+1} = \sum_{i=1}^{7} S_{i,i+1} = 2.265$ km. Data on the duration of the work phases measured in real time, as well as other values necessary for calculations, are presented in Table 1.

<table>
<thead>
<tr>
<th>№ traffic light</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t_r$</td>
<td>27</td>
<td>17</td>
<td>25</td>
<td>20</td>
<td>28</td>
<td>22</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td>$t_g$</td>
<td>48</td>
<td>33</td>
<td>50</td>
<td>30</td>
<td>47</td>
<td>53</td>
<td>47</td>
<td>46</td>
</tr>
<tr>
<td>$S_{i,i+1}$</td>
<td>300</td>
<td>330</td>
<td>278</td>
<td>314</td>
<td>341</td>
<td>472</td>
<td>340</td>
<td>-</td>
</tr>
<tr>
<td>$t_{\Delta i,i+1}$</td>
<td>22:47</td>
<td>17:42</td>
<td>20:45</td>
<td>12:37</td>
<td>22</td>
<td>31</td>
<td>22</td>
<td>-</td>
</tr>
</tbody>
</table>

It is worth noting that the density of vehicles on St. Petersburg Avenue significantly exceeds the density of cars on the streets crossing it at any time of the day, therefore, it becomes relevant to adjust the operating modes of traffic lights to ensure fast passage of the section in question. Based on the algorithm, a program was compiled in C# in the Microsoft Visual Studio 2010 development environment. The use of data from Table 1 showed that the
total downtime of one vehicle in the current operating mode varies from 53 to 129 seconds. At the same time, the total travel time of a given road section without taking into account the traffic light instructions will be only 136 seconds. Applying the algorithm, we obtain the following values of the difference between the cycles of neighboring traffic lights with synchronized phases of operation, where \( t_r = 24 \) and \( t_g = 51 \), presented in Table 2, at which cars pass the section without delays at intersections.

Thanks to the application of this algorithm, the travel time of the considered segment of St. Petersburg Avenue becomes 28.1\%-48.7\% less.

<table>
<thead>
<tr>
<th>№ traffic light</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>( t_{\Delta i,i+1} )</td>
<td>18</td>
<td>13</td>
<td>16</td>
<td>18</td>
<td>20</td>
<td>28</td>
<td>20</td>
<td>-</td>
</tr>
</tbody>
</table>

In the case when it is impossible to adjust the mode of operation of traffic lights, it will be possible to calculate the optimal speed of movement on each segment of the path, according to the algorithm for calculating the optimal speed of movement, until the next intersection. The results obtained are presented in Table 3, taking into account the maximum permitted speed within the city limits \( V_{\text{max}} = 60 \text{ km/h} \).

<table>
<thead>
<tr>
<th>№ traffic light</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
</tr>
</thead>
<tbody>
<tr>
<td>( V_{\text{opt}} )</td>
<td>49</td>
<td>44</td>
<td>47</td>
<td>39</td>
<td>38</td>
<td>50</td>
<td>52</td>
<td>50</td>
</tr>
</tbody>
</table>

At the same time, it is worth noting the following observation revealed during the operation of the algorithm: when driving this section at a speed exceeding the maximum allowed speed \( V_{\text{max}} \) by 20-30 km / h, you can manage to pass some intersections in the last seconds of the green signal of the traffic light or the yellow signal. Both drivers of private cars and drivers of route transport, which leads to an increase in the likelihood of road accidents, often use this observation.

### 4 Conclusion

As a result of the work, several new models were proposed that set the behavior of vehicles when passing an intersection with a traffic light installed on it. Based on the models, algorithms and calculation programs have been compiled and implemented, demonstrating on real data the benefits of using the considered methods and heuristics to improve the transport situation in large cities and megacities.

In this paper, only some examples of problems that arise when trying to optimize the movement of vehicles on traffic light-regulated sections of the road were considered. However, even taking into account these recommendations to improve the condition of the road network can make significant positive changes to the overall road situation in the metropolis.

### References

2. A. A. Bochkarev, Logistics and supply chain management 5 (40), 80 – 96 (2010)
5. O. A. Pozdnyakova, Railway transport 4, 56 (2012)
7. K. V. Abramov, Sociological research in the field of road safety as the most important tool for monitoring and planning public policy, All-Russian Center for the Study of Public Opinion, Moscow (2016)
8. V. M. Klennikov, E. V. Klennikov, Theory and design of the car (MADT, 1967)