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SIMULATION OF TRAFFIC FLOWS ON THE BASIS OF FUZZY LOGIC
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Abstract:
The concept of congestion, as well as the issues of traffic flow modeling theory development are described. They developed a fuzzy output model for the management of traffic lights. This model is based on the basic parameters of traffic flow. The input and output linguistic variables that describe the traffic flow in a regular occurrence of traffic jams were formulated and the pool of rules was formulated, which leads to the conclusion about the relationship of traffic flow parameters and a traffic light cycle duration. The conclusions about the relevance and the feasibility of a developed fuzzy output model were made.

Due to the rapid growth of car ownership the developed model can also be used to design a new road network and reconstruct the existing one. It allows you to control traffic flows. The result is an increased bandwidth, a line reduction in front of the regulated intersections, the reduction of time spent on the road, fuel economy, and one more important factor - the improvement of ecological and economic indicators.

Keywords: vehicle, traffic jam, road network, traffic modeling, fuzzy modeling.

Introduction
Currently, due to the traffic volume increase and the impossibility of the road network (RN) the issue of the bandwidth increase is an urgent one. The growth of the vehicle fleet has both positive and negative factors.

The influence of such factors as traffic jams (Figure 1) with the loss of time on the road, the deterioration of people health, the negative impact on the environment, etc. Traffic jam is a traffic state close to a fixed or a fixed one moving at medium speed, significantly lower than the standard speed for this road segment [1].
Figure 1 - Traffic jam situation on the road network of the city of Belgorod.

This image shows a regular traffic jam situation in the morning rush hours. This situation occurs at one of road network crossroads in the city of Belgorod.

The existing problem in the theory of traffic flows was studied and considered by numerous researchers from different areas of expertise - physicists, mathematicians, transit people and economists. A considerable experience of the traffic process study was accumulated. Despite this, the transport process is poorly understood taking into account the following factors:

- The traffic flow is diverse and unstable, the obtaining of objective information about it is the most complex and resource-intensive part of the control system;

- The quality criteria for traffic control are contradictory ones: it is necessary to ensure the continuity of traffic while minimizing the losses from transport delays, imposing the restrictions on the speed and the direction of traffic [8,9];

- Road conditions are unpredictable both in terms of climatic parameter deviations and the stochastic changes of RN parameters despite its stability;

- The execution of resolutions concerning the traffic management is always inaccurate and taking into account the nature of the traffic process it leads to unpredictable effects [2, 3, 4, 10, 11, 12]. Of course, all these factors, discredit any attempts of analytical description concerning the regularities of traffic flows and require an active search for some alternative methods of research, including modeling.

The basics of mathematical modeling for traffic laws were described by the Russian scientist, Professor G.D. Dubelir in 1912.

Nowadays, there is a large number of works concerning the study and modeling of traffic flows. Such magazines as Transportation Research, Transportation Science, Mathematical Computer Simulation, Operation Research, Automatica, Physical Review E, Physical Reports are also study transport processes.

Thus, one may state that the field of research related to the modeling of transport streams can be regarded as a relevant and a modern one.
Methods

Many models have significant disadvantages along with numerous benefits, which allow not to take into an absolute account the main characteristics of a traffic flow, eventually providing an unfinished character in a traffic flow simulation [5, 13, 14, 17]. In this study, we will consider the theory of fuzzy sets. The basic ideas of this theory were proposed by the American mathematician Lotfi Zadeh more than 35 years ago. This theory allows to describe qualitative, imprecise concepts, as well as the knowledge about the world, to operate with the obtained values in order to get new information. The methods of information model development greatly expand the traditional scope of computer application and form an independent trend of scientific and applied research. This area is called fuzzy modeling [15]. Recently, fuzzy modeling is one of the most useful and promising areas of applied research in the field of management and decision-making. A fuzzy modeling is particularly important and useful when an uncertainty is present in the description of technical systems and business processes. This uncertainty impedes or excludes the use of precise quantitative techniques and approaches.

During the technical system control simulation allows to obtain more adequate results as compared with the results which are based on the use of conventional analytical models and control algorithms. Fuzzy techniques have a wide range of its application, covering different areas of knowledge each year.

Fuzzy logic is the basis for the implementation of fuzzy control methods. It describes the nature of people mind and the course of its speculation more naturally, than the traditional formal-logical systems. That is why the study and the use of mathematical tools for some fuzzy initial information provision allows you to develop the models which reflect the various aspects of uncertainty, constantly present in the reality around us most accurately [6].

The development and the application of a fuzzy output system includes a number of stages, the implementation of which is carried out by the means of the fuzzy logic main provisions [7].

1. Fuzzification: the development of a transition procedure from the clear values of the input variables to the fuzzy ones. The choice of the type and the mutual arrangement of belonging functions (BF) for input linguistic variables.
2. The development of rule pool structure: the development of harmonized sets of a regulator input-output relations.
3. Aggregation: the development of the procedure for truth condition degree determination in respect of each rule.
4. Activation: the development of determination procedure concerning the degree of conclusion truth for each of the rules.
5. Accumulation: the development of association procedure concerning conclusion truth degree along the entire base of rules.
6. Defuzzification: the development of transition procedure from a fuzzy value of an output variable to clear one.

Main part

After the examination of the selected RN part, which has traffic jam situations regularly, it was decided to consider the efficiency of the traffic light control in order to reveal the relationship between the intensity of vehicular traffic (VT) and the duration of the passing (green) traffic light signal [16].

In our studies, three input linguistic variables were taken for a fuzzy model of traffic light objects (TLO) control, which form the input vector \( \beta = [\beta_1, \beta_2, \beta_3] \), and one output linguistic variable \( \beta_4 \), where

- \( \beta_1 \) - the number of vehicles accumulating during a red signal;
- \( \beta_2 \) - the rate of vehicle number change accumulated during a red signal;
- \( \beta_3 \) - the coefficient of tire adhesion with the road surface;
- \( \beta_4 \) - the green signal duration.

In order to describe each variable FP are introduced, uniformly distributed over the entire range of changes.

For the first linguistic variable \( \beta_1 \), the values of which are determined from the statistical data:

- VS (Very Small) – [0; 0; 5; 22];
- S (Small) – [0; 22; 44];
- M (Medium) – [22; 44; 66];
- B (Big) – [44; 66; 88];
- VB (Very Big) – [66; 83; 88; 88].

Figure 2 shows FP for linguistic variable \( \beta_1 \) "The number vehicles accumulating during a red signal". They accumulated the data concerning the number of vehicles as the experiment result, which was conducted during the year.
We will divide the range of values for the linguistic variable $\beta_2$ «The rate of vehicle amount change accumulating during a red signal» into five areas, assigning a qualitative characteristic (term) to each of them:

- NB (Negative Big) [-24; -24; -19; -9];
- NS (Negative Small) [-19; -9; 0];
- Z (Zero) [-9; 0; 9];
- PS (Positive Small) [0; 9; 19];
- PB (Positive Big) [9; 19; 24; 24].

In order to obtain the form of fuzzy terms describing the linguistic variable $\beta_2$ «The rate of vehicle change accumulated during a red signal». Table 2, containing statistical values collected during the year on the basis of the experiment is developed according to the estimated data from the table 1. In our case, the value of time makes one minute. All the values taken by the rate of vehicle number change $\frac{dn}{dt}$, are divided into 11 intervals - this amount was selected on the basis of falling of at least one calculation point into each interval. Each of five lines, corresponding to each of the ranges, contains the number of calculated values in one of the intervals. Together they form the following matrix $(v_{ij})$, $i=1\div5$, $j=1\div11$.

The last line of the Table 2 listed the elements equal to $\nu_{2j} = \sum_{i=1}^{6} v_{ij}$. The choose a maximum element in this line $\nu_{\Sigma \max} = \max \nu_{2j}$. In the calculations $\nu_{\Sigma \max} = 38$.

<table>
<thead>
<tr>
<th>Linguistic term</th>
<th>The amount of values $\frac{dn}{dt}$, falling into the corresponding interval</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>1</td>
</tr>
<tr>
<td>NS</td>
<td>0</td>
</tr>
<tr>
<td>Z</td>
<td>0</td>
</tr>
<tr>
<td>PS</td>
<td>0</td>
</tr>
<tr>
<td>PB</td>
<td>0</td>
</tr>
<tr>
<td>$\nu_{\Sigma}$</td>
<td>1</td>
</tr>
</tbody>
</table>

Then all the elements $v_{ij}$ of the table (except for last line) are transformed according to the following formula:
In order to develop the FP of the linguistic variable the maximal elements of the converted Table 2 line are obtained.

**Table 2 – Converted statistical data to calculate the data of vehicle change number \( \frac{dn}{dt} \), accumulated during a red signal.**

<table>
<thead>
<tr>
<th>Linguistic term</th>
<th>(-24; -18)</th>
<th>(-18; -14)</th>
<th>(-14; -10)</th>
<th>(-10; -6)</th>
<th>(-6; -2)</th>
<th>(-2; 2)</th>
<th>(2; 6)</th>
<th>(6; 10)</th>
<th>(10; 14)</th>
<th>(14; 18)</th>
<th>(18; 24)</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>38</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NS</td>
<td>0</td>
<td>38</td>
<td>38</td>
<td>13,4</td>
<td>11,4</td>
<td>9,8</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Z</td>
<td>0</td>
<td>0</td>
<td>11,2</td>
<td>26</td>
<td>19,5</td>
<td>20</td>
<td>13,2</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>26</td>
</tr>
<tr>
<td>PS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>8,7</td>
<td>18</td>
<td>18,6</td>
<td>19</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PB</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>13,2</td>
<td>19</td>
<td>38</td>
<td>38</td>
<td>38</td>
</tr>
</tbody>
</table>

The values of belonging functions are calculated according to the following formula:

\[
\mu_{ij} = \frac{v_{ij}}{v_{i,max}} \quad (2)
\]

Thus, the Table 3 of FP values is developed in respect of the linguistic variable \( \beta_2 \) and FP graph is shown on Figure 3.

**Table 3 - The table of estimated values for the linguistic variable \( \beta_2 \)**

<table>
<thead>
<tr>
<th>Linguistic term</th>
<th>-24; -18</th>
<th>-18; -14</th>
<th>-14; -10</th>
<th>-10; -6</th>
<th>-6; -2</th>
<th>-2; 2</th>
<th>2; 6</th>
<th>6; 10</th>
<th>10; 14</th>
<th>14; 18</th>
<th>18; 24</th>
</tr>
</thead>
<tbody>
<tr>
<td>NB</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>NS</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0,35</td>
<td>0,3</td>
<td>0,26</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Z</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0,56</td>
<td>1</td>
<td>0,98</td>
<td>1</td>
<td>0,66</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PS</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0,46</td>
<td>0,95</td>
<td>0,98</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>PB</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0,35</td>
<td>0,5</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
</tbody>
</table>

**Figure 3 – FP of the linguistic variable \( \beta_2 \).**

During the development of the graph each value \( \mu_{ij} \) was set for the original value of \( j \)-th interval, then the marked points were connected by straight lines, and took the form of polygonal FP.
Figure 4 shows FP for the linguistic variable $\beta_2$ "The rate of vehicle number change accumulating during a red signal", interpolated with respect to the graph on Figure 3.

![Figure 4](image)

**Figure 4 - FP for the linguistic variable $\beta_2$ "The change rate of vehicle number accumulated during a red signal".**

In order to describe the variable $\beta_3$ "Tire adhesion ratio with a road surface" the range of value change makes $0.2 - 0.8$.

Taking into account this fact the domain of linguistic variable $\beta_3$ is in the range $[0.2; 0.8]$. In order to describe the linguistic variable $\beta_3$ 5 FP is introduced, uniformly distributed over a range of variable values:

- **VS (Very Small)** – $[0.2; 0.2; 0.25; 0.35]$;
- **S (Small)** – $[0.2; 0.35; 0.5]$;
- **M (Medium)** – $[0.35; 0.5; 0.65]$;
- **B (Big)** – $[0.5; 0.65; 0.8]$;
- **VB (Very Big)** – $[0.65; 0.75; 0.8; 0.8]$.

Figure 5 demonstrates FP for the linguistic variable $\beta_3$.

![Figure 5](image)

**Figure 5 – FP for the linguistic variable $\beta_3$.**

«The adhesion ratio with a road surface»

According to the conditions of CO control signal development, we accept the range of values for the output linguistic
variable $\beta_4$ in the range $[20; 72]$. In order to describe the variable $\beta_4$ 5 FP are introduced, uniformly distributed across the change range:

- VS (Very Small) – [20; 20; 23; 33];
- S (Small) – [20; 33; 46];
- M (Medium) – [33; 46; 59];
- B (Big) – [46; 59; 72];
- VB (Very Big) – [59; 69; 72; 72].

Figure 6 demonstrates FP for the linguistic variable $\beta_4$ "Green signal duration".

![Figure 6 – FP for linguistic variable $\beta_4$.](image)

Then let's develop the base of fuzzy rules. There are many different ways for the development of fuzzy rules during a fuzzy model creation. The quickest and the easiest way is based on the study of operation experience concerning the system of operator activity modeling and management in order to achieve the set goals, i.e. the analytical calculations for the generation of some control actions are not required.

In general, the rule of fuzzy products is as follows:

$$(i): Q; P; A \Rightarrow B; S, F, N,$$  

where $(i)$ – a fuzzy product name; $Q$– the scope of fuzzy production application; $P$ – the condition of fuzzy product core application; $A$ – core condition (or antecedent); $B$ – core result (or consequent); "$\Rightarrow$" – logical sequence sign (or following); $S$ – the method or the way to quantify the degree of truth for a core result; $F$ – certainty or confidence factor for fuzzy products; $N$ – the postconditions of products.

In our case 125 rules of fuzzy production were composed on the basis of statistical data obtained as the measurement result for SO control system.
Let's provide five typical fuzzy output rules as an example:

1) \( \text{ЕСЛИ } \beta_1 = \text{VS И } \beta_2 = \text{NB И } \beta_3 = \text{VS ТО } \beta_4 = \text{S} \);
2) \( \text{ЕСЛИ } \beta_1 = \text{S И } \beta_2 = \text{PS И } \beta_3 = \text{B ТО } \beta_4 = \text{M} \);
3) \( \text{ЕСЛИ } \beta_1 = \text{B И } \beta_2 = \text{Z И } \beta_3 = \text{B ТО } \beta_4 = \text{M} \);
4) \( \text{ЕСЛИ } \beta_1 = \text{VB И } \beta_2 = \text{NS И } \beta_3 = \text{VB ТО } \beta_4 = \text{B} \);
5) \( \text{ЕСЛИ } \beta_1 = \text{VB И } \beta_2 = \text{PB И } \beta_3 = \text{VB ТО } \beta_4 = \text{VB} \).

The first rule can be interpreted in a natural language as follows: If "the number of vehicles accumulated during a red signal" \( \beta_1 \) is "very small" (VS) AND "the change rate of vehicle number accumulated during a red signal" \( \beta_2 \) - "a negative big" (NB) and "the coefficient of tire adhesion with a road surface" \( \beta_3 \) - "small" (S), THEN "the green signal duration" \( \beta_4 \) is "small" (S).

The development of a fuzzy output surface for the developed fuzzy model \( \beta_4 \) "Green signal duration" is implemented in Matlab system.

There is a special package Fuzzy Logic Toolbox in order to implement the fuzzy inference system within Matlab environment. It includes the following graphical tools to edit the elements of fuzzy inference systems:

1. Fuzzy inference system editor FIS;
2. FP Editor for fuzzy inference systems (Membership Function Editor);
3. The rule editor of fuzzy inference system (Rule Editor);
4. The viewer of fuzzy inference system rules (Rule Viewer);
5. Программа просмотра поверхности системы нечеткого вывода (Surface Viewer).

The viewer of fuzzy output system surface (Surface Viewer).

FIS Editor is the primary tool for the creation and editing of fuzzy output systems in a graphical mode. The graphic interface of FIS editor is shown on Figure 7.
In the bottom part of FIS editor you need to select the algorithms of fuzzy logic multiplication and addition performance. Let's determine min algorithm for fuzzy logic multiplication and the algorithm max for fuzzy logical addition.

Then using Matlab editor FP terms are defined for each of fuzzy inference system variables. The graphic interface of FP editor for the input variable is shown on Figure 8.

![Figure 8 - Graphic interface of FP editor for the input variable "The number of vehicles".](image)

FP for other variables are developed similarly. The editor of rule system Matlab is applied to set 125 rules of the developed fuzzy output system. The weighting ratio for each rule is equal to one. The relation of sub-conditions in fuzzy production rules is performed by logical multiplication operation.

In order to evaluate the work of fuzzy output developed system for SO control it is necessary to open the rule system viewer Matlab and enter the values of input variables.

The result of SO control signal calculation based on the fuzzy output is illustrated by the following example: \( \beta_1 = 44 \) - the number of vehicles; \( \beta_2 = 5 \) - this indicates that the intensity change pace has different characters; \( \beta_3 = 0.4 \) - the value of adhesion coefficient. Thus, the process of fuzzy inference showed that \( \beta_4 = 47 \) is the control signal. The graphic interface of rule viewer after the performance of fuzzy output procedure is shown on Figure 9.

![Figure 9 - Graphical interface of rules viewer after the performance of fuzzy output procedure.](image)

The visualization of the respective fuzzy output surface is useful for the general analysis of the developed fuzzy model for SO control.
Conclusions

Thus, the problem of a control signal obtaining for SO can be solved using a fuzzy output system. A fuzzy output surface presented on Figure 10 allows to establish the dependence of the output variable value $\beta_4$ on the input variables $\beta_1$, $\beta_2$ and $\beta_3$ of the fuzzy model for SO control system. This dependence can be the basis for a controller programming or a hardware implementation of the corresponding fuzzy control algorithm in the form of a decision table.

References


