Abstract

This paper considers the problem of application of the soft-computing technologies for the fuzzy modeling and synthesis of traffic control systems in conditions of uncertainty and insufficient initial information on traffic flows. It proposes methods for formal description of the transport process on the controlled crossroads and tasks management them based on the modern mathematical apparatus of fuzzy sets and fuzzy logic. And, also this paper provides effective algorithms for adaptive fuzzy-logic traffic control systems and the simulation models of them and the results of computing experiments for real crossroads of the road network of Tashkent city (Uzbekistan).

Keywords: soft-computing technologies, intelligent transportation systems, traffic control systems, fuzzy systems, fuzzy modeling.

1. Introduction

Today, the world’s major cities have a problem related to the traffic management, ensuring the most effective use of existing road infrastructure and the functioning of the transport complex of the city. This is due to highly growth in car and insufficient capacity of the street and road networks, as well as highly dynamic changes in road conditions and poor predictability of the behavior of road users. In large cities, the problem becoming especially acute. The situation is complicated by such trends as the increasing mobility of the population, reduction of public transport and an increase in private transport, the growing gap between the increasing number of cars and the length of the road network.2,3

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The results of a prior research’s in transport management systems area demonstrate that the most promising direction of improving operational efficiency of transport systems and services is the development and implementation of intelligent transport systems (ITS). ITS is an integration of advanced information and communication technologies, computer-aided control and traffic management, transport infrastructure, vehicles and users, to improve safety and efficiency of road traffic.

The review of the existing ITS projects showed that the latest advances in information and communications technologies, control systems theory, data mining and analysis techniques are not widely implemented in road traffic management. The reason is the lack of extensive research and efficient methods of synthesis of multi-level intelligent systems in conditions of fuzziness of parameters of the road traffic. There are number of studies on automating the development of control systems and their components. They are focused on developing and improving the systems of coordinated traffic management on highways and adaptive management that addresses problems of vehicle throughput. Furthermore, there are number of studies that focus on optimizing the traffic-light management. A significant number of works are devoted to the development of technical methods for measuring the parameters of road traffic and their processing. However, these works are highly scattered and focus on solving local problems of automated control of road traffic. Another factor that is not considered by previous studies: synthesized parameters of traffic-light management systems are optimal only under certain conditions — when the parameters of road traffic do not change over time (or change in short intervals). In most cases, the synthesis of control systems of road traffic does not consider unpredictable traffic situations, fuzziness of the parameters of the road traffic.

Therefore, developing conceptual framework and effective methods of structural and parametric synthesis of control systems of road traffic based on soft-computing technologies is an important.

2. Statement of a problem

Below, we consider a class of traffic control systems with imprecise information about the object, in which the qualitative characteristics of the road traffic are dominant.

In general, for synthesis of the traffic control systems, the object of control can be formally represented as follows:

\[ M = \langle \Omega, G, X, Y, U, T, \rho, \gamma, \zeta \rangle, \]

where: \( \Omega = \{ \Omega_1, \Omega_2, \cdots, \Omega_n \} \) - range of conditions (e.g. object, output); \( G = \{(V, (D,W))\} \) - a model of the crossroad, represented by the graph \( G \) in the space \( \mathbb{R}^3 \); \( V = \{ v_i \} \) - vertices (nodes) of the graph, corresponding to the nodes of possible branches of the road traffic; \( D \subseteq V \times V \) - plurality of arcs of the graph (road section, connecting nodes of possible branches of road traffic) with corresponding weight coefficients as \( W = \{ \lambda, p, z \} \) (intensity of road traffic, density of road traffic and average speed on this particular road section); \( X = \{ X_1, X_2, \cdots, X_n \} \) - plurality of characteristics and determinants, describing the state of the control object \( \Omega \) and taking their values each in its own set of values \( \{ X_i \} \); \( Y = \{ Y_1, Y_2, \cdots, Y_m \} \) - range of output values (observed processes, parameters, estimates and etc.); \( U = \{ U_1, U_2, \cdots, U_r \} \) - range of controls (decisions); \( T = \{ t_1, t_2, \cdots, t_i, \cdots \} \) - time (discrete or continuous); \( \rho: X \times U \times T \rightarrow \Omega \) - description of the dynamics of the state of the object, the reaction of the dynamic system in a particular state to control actions; \( \gamma: \Omega \times T \rightarrow Y \) - the output, describing the observation process of the control object (obtaining estimates, opinions, etc.); \( \zeta \) - some external uncontrollable factors, conditions and others that have an impact on the dynamics of the control object.

Analysis of existing and newly designed traffic control systems in real time shows, that optimizes a functional as a rule:

\[ \Psi(X, U) \rightarrow \min, \]

(2)
This functional often has a following type:

\[
\Psi(X, U) = \sum_{i=1}^{n} \left\{ w^\text{delay} D(v_i(x(k), u_i(k))) + K^\theta w^\text{stop} S_i(v_i(x(k), u_i(k))) + K^K w^\text{queue} Q(v_i(x(k), u_i(k))) \right\} \rightarrow \min
\]  

(3)

Where, \(D(v_i(x(k), u_i(k)))\) – time of vehicles’ delay in unit \(v_i\) street-road network (УДС), at crossroads; \(K^\theta\) – stop penalty factor; \(\Theta_i(v_i(x(k), u_i(k)))\) – the number of stops in unit \(v_i\); \(K^K\) – queue of penalty factor in node \(v_i\); \(Q(v_i(x(k), u_i(k)))\) - queue’s length in unit \(v_i\); \(w^\text{delay}, w^\text{stop}, w^\text{queue}\) – accordingly, unit weight coefficients \(v_i\) of UDS for delay, stop and queue; \(x_i(k), u_i(k)\) - respectively, state traffic in unit \(v_i\) at time \(t_k\).

Optimization of functional (3), in restrictions on managing traffic signal \(u_{\min} \leq u_i(k) \leq u_{\max}\), basically it allows for solution optimal control traffic flows in free traffic conditions.

In terms of saturated movement, prevention or elimination of possible traffic congestion is produced by an expert selection of the functional weight factors (3), with subsequent adjustment during operation, depending on the actual conditions. Of course, the quality of control in this case is largely dependent on the experience, skill and knowledge of experts7.

Management problems of saturated traffic flow, is fundamentally differs from the problems with the free movement and problems with transport networks complicates because of the inability to localize the oversaturation mode within a single crossroad, initially appeared in source of congestion. The negative role played by the factor of the connection between the individual intersections – the unlimited increase of queue in one crossroad blocks traffic flows during the previous movement in crossroad, which may block the operation of adjacent intersections, etc. Therefore, the main task of the control systems in terms of saturated movement should be to prevent cases of traffic congestion, and in the appearance - the most rapid liquidation of their consequences. The unique way to solve this problem is to evaluate the possible congestion and minimize downtime through predictive models and fuzzy adaptive algorithms12,18.

3. The concept of the problem synthesis model-based fuzzy traffic control systems

According to aforementioned requirements, a generalized dynamic model of the object controls (OC) can be defined as the following linear equation with fuzzy state space \(11,14:\)

\[
\tilde{x} = \tilde{A} \otimes x \otimes \tilde{B} \otimes u, \quad \mu^S(S), \quad S \subseteq \Omega,
\]

\[
\tilde{y} = \tilde{C} \otimes \tilde{x},
\]

(4)

with fuzzy initial conditions

\[
\tilde{x}_i(0) = \tilde{D}_1, \quad \tilde{x}_2(0) = \tilde{D}_2, \cdots, \tilde{x}_n(0) = \tilde{D}_n,
\]

(5)

where \(\otimes, \oplus\) – fuzzy operations of multiplication and addition; \(u\) – a control signal (scalar) that accepts discrete numerical value; \(\tilde{x} = \{\tilde{x}_1, \tilde{x}_2, \cdots, \tilde{x}_n\}\) – state space vector; \(\tilde{y} = \{\tilde{y}_1, \tilde{y}_2, \cdots, \tilde{y}_n\}\) – output variables vector, \(\mu^S(S)\) – membership function (MF) of the state space of the object controls , \(\tilde{S} = \{s_1, s_2, \cdots, s_\alpha\}\); \(\tilde{A}, \tilde{B}, \tilde{C}\) - matrix of the fuzzy coefficients of the model:

\[
\tilde{A}^1 = \{A^1_i / \mu^1(\tilde{A}^1_i)\}, \cdots, \tilde{A}^n = \{A^n_i / \mu^n(\tilde{A}^n_i)\},
\]

where, \(\tilde{B} = \{B_i / \mu^B(\tilde{B}_i)\}, \cdots, \tilde{B} = \{B^n / \mu^n(\tilde{B}^n)\}\),

\[
\tilde{C}^1 = \{C^1_i / \mu^1(\tilde{C}^1_i)\}, \cdots, \tilde{C}^n = \{C^n_i / \mu^n(\tilde{C}^n_i)\}.
\]

Some \(i\)-th state space vector as a time function \(t\) can be described as fuzzy relation \(10,16:\)

\[
\tilde{x}_i(t) = \tilde{D}_i, \quad \tilde{x}_2(t) = \tilde{D}_2, \cdots, \tilde{x}_n(t) = \tilde{D}_n,
\]
At a fixed time, this variable can be expressed as a fuzzy set:

$$\overline{x}_i(t) = \{ t, x_i / \mu_{\overline{x}_i}(t, x_i) \}, \quad i = 1, 2, \cdots, n $$ (6)

A similar description is $j$-th output variable:

$$\overline{y}_j(t) = \{ t, y_j / \mu_{\overline{y}_j}(t, y_j) \}, \quad j = 1, 2, \cdots, m $$ (7)

Initial conditions and the number of variables of the state vector also can be described as the following fuzzy sets:

$$\overline{D}_i = \{ x_i / \mu_{\overline{D}_i}(x_i) \} \quad \text{and} \quad \overline{S} = \{ s / \mu_{\overline{S}}(s) \}. $$

Suppose that the membership functions of the input and output linguistic variables are defined as the following analytical functions:

$$\mu_{\overline{x}_i}(x_i) = \phi(x, a_{\overline{x}_i}, b_{1\overline{x}_i}, b_{2\overline{x}_i}, \beta_{1\overline{x}_i}, \beta_{2\overline{x}_i}), $$ (10)

$$\mu_{\overline{y}_j}(y_j) = \phi(y, a_{\overline{y}_j}, b_{1\overline{y}_j}, b_{2\overline{y}_j}, \beta_{1\overline{y}_j}, \beta_{2\overline{y}_j}), $$ (11)

In the equations (10) and (11), the coefficients $a_{\overline{x}_i}, \quad a_{\overline{y}_j}, \quad b_{1\overline{x}_i}, \quad b_{1\overline{y}_j}, \quad b_{2\overline{x}_i}, \quad b_{2\overline{y}_j}, \quad \beta_{1\overline{x}_i}, \quad \beta_{1\overline{y}_j}, \quad \beta_{2\overline{x}_i}, \quad \beta_{2\overline{y}_j}$ are mood, width, and slope of the membership functions of the input and output linguistic variables. These coefficients allow forming high variety of shapers of membership functions. They can also act as indicators of information fuzziness for a formal model of the control objects, which are provided as state space equation (4).

If we assume that the indicators of quality of the control system (e.g. time of transient process, overshoot, bug tracking) are given as the following utility functions generated by experts:

$$Q = \{ q_1 / \mu_{Q}(q_1), q_2 / \mu_{Q}(q_2), \cdots, q_k / \mu_{Q}(q_k) \}, $$ (12)

under certain limitations for variables’ state space and control signal:

$$g_1(\overline{x}, u, \gamma, t) < x_{\text{max}}, \quad g_2(\overline{x}, u, \gamma, t) > x_{\text{min}}, $$

$$g_{2n-1}(\overline{x}, u, \gamma, t) < x_{\text{max}}, \quad g_{2n}(\overline{x}, u, \gamma, t) > x_{\text{min}} $$ (13)

where $\phi$ - is membership function of the quality index of the control system, provided as the equation (6). Then, the problem of the synthesis of control system, for control objects provided as in a fuzzy state equation (4), with the quality evaluation indicator (12) and the system of constraints (13), can be formulated as described below.

First, it is necessary to synthesize control systems with embedded adaptive adjustment parameters of the controller for object controls (4). All signals should be limited in (13) and the transient processes in the system have to satisfy the predetermined quality parameters (12).
For a given statement of the problem, gradient speed search algorithm in the parametric form, with a proportional-integral controller and circuit bootstrapping can be selected\cite{15,17}. Among available methods of adaptive control with robust characteristics, the gradient speed search algorithm is the least complex. It also fits the constraints on the control signal and its velocity. Then, the control signal is generated based on the fuzzy set values of state space parameters, according to the following modified control signal:

$$u(t+1) = k_u(t) \cdot u_m(t) + \sum_{i=1}^{n} k_{xi} \sum_{i=1}^{n} x_i \sum_{i=1}^{n} (t) \cdot x_i \sum_{i=1}^{n} (t),$$  \hspace{1cm} (14)$$

where $t = m \omega$, $\omega > 0$ is discretization step, $\gamma = \{\gamma_1, \gamma_2, \gamma_3, \gamma_4, \gamma_5, \gamma_6\}$-parameters of the adaptive controller; $e_i = \sum_{i=1}^{n} \mu_\gamma (e_i)dx_i$ - a signal mismatch between the actual parameters of the state vector and desirable model parameters; $\mu_\gamma (e_i) = \phi(e_i, a_n, b_m, b_2, v_{m1}, v_{m2})$ - membership function of the signal mismatch, provided as the equation (8); $a_n = a_n - x_{m1}, v_{m1}, v_{m2} = v_{m2}$; $b_m = b_m, b_2 = b_2$; $x_i \sum_{i=1}^{n} = \sum_{i=1}^{n} x_i dx_i$ - integrated parameters of the state vector; $\delta^*[t] = \sum_{j=1}^{n} h_j \cdot e_i \sum_{j=1}^{n} h_j$ - coefficients, obtained by Lyapunov’s decision equation and the matrix equation with reference model $B_m$.

The synthesis of the control law based on fuzzy model can increase the robustness of the gradient speed search algorithm; it can also maintain limitations of the phase trajectories in a certain areas under uncompensated information fuzziness\cite{11,12}.

Quality indicators of the control systems are based not only on the best possible dynamic characteristics of object controlling $a_n(t), a_n(t)$, but also on the parameters of its fuzziness $a_n, a_\gamma, b_{m1}, b_{21}, b_{2m}, b_{2m}, b_{2m}, b_{2m}$, $b_{2m}, b_{2m}, b_{2m}, b_{2m}, b_{2m}, b_{2m}, b_{2m}$, $b_{2m}, b_{2m}, b_{2m}, b_{2m}$, provided as the equations (10) and (11).

Reducing the information fuzziness and, consequently, improving the quality control can be achieved by optimizing the parameters of the membership functions of the input and output linguistic variables and fuzzy-logic controllers. This is the core idea of the algorithm for traffic control systems in crossroads, presented in this study.

4. Simulation modeling and analysis of fuzzy traffic control system

In general, the process traffic control system at the T- shaped crossroads can be rearranged as a feedback control system with adaptive fuzzy-logic controller. In fuzzy traffic control system, the input vector is converted into fuzzy logic controller (FLC) through fuzzification block. Next, fuzzy inference is performed based on rule base, which results in a fuzzy output variable. The output values from the FLC are then transferred from the fuzzy region to accurate region through defuzzification block\cite{12,18}.

This system provides minimum total delay of cars at the crossroads. That is:
under the constraints
\[
e_i^{13} = q_i^{\text{leaving}(13)} - q_i^{\text{arriv}(13)} \leq 0, \quad e_i^{24} = q_i^{\text{leaving}(24)} - q_i^{\text{arriv}(24)} \leq 0;
\]
(18)

\[
0 \leq u_{\text{min}}^{13} \leq u_{\text{max}}^{13}, \quad 0 \leq u_{\text{min}}^{24} \leq u_{\text{max}}^{24},
\]
(19)

\[
0 \leq l_{i1}^{13}, \quad 0 \leq l_{i2}^{24} \leq L_{\text{max}}^{24};
\]
(20)

where, \( \lambda_1, \lambda_2, \lambda_3, \lambda_4 \) - traffic intensity, the direction of the traffic 1 and 3 are perpendicular to the direction of 2 and 4; \( f^*(u_i, \lambda_i) \) and \( f_{pm}^*(u_i, l_i) \) - delay evaluation function and penalty function for the length of queue in front of the stop line of the traffic light in directions 1 and 3 respectively; \( f^*(u_i, \lambda_i) \) and \( f_{pm}^*(u_i, l_i) \) - delay evaluation function and penalty function for the length of queue in front of the stop line of the traffic light in directions 2 and 4 respectively; \( u_i \) - duration of green signal of traffic light in the \( i \)-stage; \( q_i^{\text{leaving}(13)} \), \( q_i^{\text{leaving}(24)} \), \( q_i^{\text{arriv}(13)} \), \( q_i^{\text{arriv}(24)} \) - number of vehicles entered and left the control zone at the crossroad in the \( i \)-th phase respectively; \( u_{\text{min}} \) and \( u_{\text{max}} \) - the minimum and maximum duration of the green signal of the traffic light respectively; \( l_{i1}^{13} \) and \( l_{i2}^{24} \) - the length of the queue in front of the stop line at directions 1 and 3, 2 and 4 in the \( i \)-th stage respectively; \( L_{\text{max}} \) - maximum allowed length of the queue in front of the stop line.

We develop a simulation model of the adaptive fuzzy control system of road traffic on MatLab software package. The simulation model is used to tests the efficiency of the fuzzy control system through series of computational experiments. As an object of simulation, we chose one of the heavy-loaded and problematic crossroads in Tashkent city, Uzbekistan. The simulation model considered the road traffic intensity, observed at the crossroad during the peak-hours from 07:00 to 10:00 on May 5, 2016. The experiment consisted of two phases. At each phase of the simulation, various patterns of traffic-light management were used. In the first phase, the traffic lights with fixed cycles, which are used in real life, are simulated. In the second phase, traffic lights controlled with adaptive fuzzy system were simulated. For this purpose, the rules of fuzzy control system with a module for adaptive adjustment of parameters were synthesized using the proposed method.

The simulation results are: the road intersection that is managed by traffic lights with fixed cycles; the synthesized fuzzy control system successfully solved the problem of queues at traffic lights and performed more effective than the current traffic control system with fixed-cycle traffic lights. Particularly, the length of queue for the synthesized fuzzy control system is less than 2.6 times than for traffic control system with fixed-cycle traffic lights. Also, delay time for synthesized fuzzy control system is 27% less than traffic control system with fixed-cycle traffic lights.

Based on the results of computational experiments, we can conclude that the synthesized adaptive fuzzy control system of road traffic in conditions of intensive traffic is robust and allows to control road traffic within a wide range of parameters.

5. Conclusion

In this study, we formally described the problems of synthesis of adaptive fuzzy traffic control systems in conditions of intense of road traffic. We developed efficient algorithms of the synthesis of the adaptive fuzzy-logic traffic control systems. We also developed a simulation model of adaptive fuzzy-logic control system for managing road traffic and conducted a series of computational experiments.

The results showed that the synthesized fuzzy-logic traffic control system, based on the proposed method, allows to control crossroads more effectively compared to traffic control system with fixed-cycle traffic lights. We conclude that adaptive fuzzy-logic controller can successfully function in the condition of information
fuzziness. It can also successfully function when exposed to uncontrolled external and parametric impacts. The implementation of the solution in heavy-loaded crossroads allows to reduce the length of queues at the traffic lights up to 2.6 times and the delay time up to 27%.

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