Functional model of expert traffic flow control system within high-speed transportation corridors

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Abstract. Recently, the number of vehicles on the roads has increased significantly, including within high-speed transportation corridors. Furthermore, the volume of cargo transportation increases annually not only within the country, but also between different countries. Taking into account these factors, as well as the possibility that unmanned vehicles will soon appear within high-speed transportation corridors, it is necessary to develop intelligent transportation systems that will effectively control traffic flows. Traffic flows are controlled by directional changes in its capacity. In order to interact with road users and road infrastructure, it is necessary to develop an expert system that will make recommendations using the predicted capacity value and information about the current value of the parameters describing the high-speed transport corridor. The article presents a neuro-fuzzy model for predicting capacity by known system parameters and conditions of its functioning, built using the concept of mathematical remodeling. There is also given the results of Sensitivity Analysis based on applying Analysis of Finite Fluctuations depending on external factors. In addition the conceptual and functional models of the developed expert system for regional intelligent transportation system module are proposed.

1. Introduction
Intelligent transportation systems (ITS) have been actively developed in various countries since the 1980s. Such systems with different functions exist in Europe and Asia. Due to the geographical location, Russia faces a serious challenge in developing its own ITS that takes into account the features of the current transportation network and its state. This system will be able to connect ITS-Europe and ITS-Asia to ensure efficient traffic flows control.

Expert systems are widely used to control the complex knowledge structure areas to develop solutions in response to situations that require specific knowledge and practical experience of experts. One of the main tasks of the developed system is to use the predicted freeway capacity and information about the current value of the parameters describing the high-speed transportation corridor to make recommendations for road users and infrastructure and control traffic flows.

Traffic flow can be controlled by a directional change in its parameters, such as, for example, freeway capacity, which can be considered as a certain stochastic number with a given distribution. The values of this parameter in some moments of the system functioning (traffic jams) can be obtained by direct measurements, and in the remaining moments can be calculated using empirical knowledge about this parameter. Combining these two possibilities
and using the concept of mathematical remodeling, the model to estimate the freeway capacity is constructed, which based on the current traffic situation and the control parameters.

2. Mathematical remodeling of the freeway capacity and sensitivity analysis of the model

Existing freeway section capacity models are deterministic and define capacity as the maximum number of vehicles that a particular section of the transportation system is able to serve during particular time interval. This idea is the main one in many world capacity estimation guidelines, however, in [1] it was determined and then repeatedly empirically proved that the desired parameter of the transportation system has a stochastic nature. Using a non-parametric statistical method (Kaplan-Mayer method), it is possible to estimate the probability that at a particular time the freeway capacity will exceed the nominal, and there will be traffic jam. It was found that the best statistical distribution describing this parameter is the Weibull distribution, according to which the distribution function of the freeway section capacity can be written as

\[
F_c(q) = 1 - \exp \left( - \left( \frac{q}{b} \right)^a \right),
\]

where \( F_c(q) \) is the distribution function of the capacity rate, \( q \) is the traffic volume of the vehicles (veh / h), \( a, b \) are Weibull distribution parameters, responsible for the capacity rate variation and for the systematic average value of the capacity rate caused by such constant factors as the number of lanes, the slope, the number of drivers, respectively.

As a stochastic parameter, the highway section capacity can only be measured in the time interval strictly preceding the traffic jam and is exactly equal to the number of vehicles which are within this section at the time of the traffic jam. Based on this available information, all observing highway dynamics time intervals can be divided into two subsets, such as, the observed capacity values (traffic jam) and the estimated values (free movement period), in which the values are obtained using the Weibull distribution (1).

Using the concept of mathematical remodeling [2] it is possible to build a neural network model to predict highway capacity

\[
y = \phi (w_0 + W_1 x),
\]

where \( y \) are capacity values (veh / h), \( x \in \mathbb{R}^8 \) is the inputs vector (eight input values are used that have an impact on highway capacity), \( \phi (\text{net}) = \tanh (\text{net}) \) is the hyperbolic tangent activation function, \( w_0 \) and \( W_1 \) are estimated weights for bias and input factors respectively.

The model (2) was trained by the method of back error propagation using the “nnet” package of the data processing language R. The model approximation error was 5.58%.

An important aspect of many applied problems related to the construction of mathematical models of real objects is the Sensitivity Analysis of these models by factors [3]. This analysis is based on statistical and probabilistic approaches that allow us to estimate the influence of each model input factor on the model output. Considering the existing mathematical model

\[
y = f(X),
\]

where \( X \in \mathbb{R}^n \) are inputs, \( y \in \mathbb{R} \) is output and \( f(\cdot) \) is a functional (can be a function, a system of differential equations, etc., even a program code). A lot of well-known approaches of Sensitivity Analysis have drawbacks, such as, stochastic nature or high computational costs. However, it is possible to use the Analysis of Finite Fluctuations [4, 5], which is based on applying Lagrange mean value theorem to solve the task.

The most used form to represent finite fluctuation \( \mu(x) \) of the variable \( x \) during the transition from an initial instant of time \( t_0 \) \((x(t_0))\) to a final instant of time \( t_1 \) \((x(t_1))\) is the absolute
increment $\mu(x) = \Delta x = x^t - x^0$. Analysis of Finite Fluctuations is aimed at solving the problem of the constructing based on the model $y = f(X)$ the new model $\mu(y) = \phi(\mu(X))$, linking the fluctuation of the output $\mu(y)$ and the fluctuation of its factors vector $\mu(X)$. In case of small increments Mathematical Analysis gives an example of such approximation

$$\Delta y = f(X^{(0)} + \Delta X) - f(X^{(0)}) = f(x_1^{(0)} + \Delta x_1, ..., x_n^{(0)} + \Delta x_n) - f(x_1^{(0)}, ..., x_n^{(0)}) \approx$$

$$\approx \sum_{i=1}^{n} \frac{\partial f(X^{(0)})}{\partial x_i} \cdot \Delta x_i.$$

(4)

On the other hand, in many applied problems the fluctuations could not be considered as small values, but could be interpreted as finite values. In this case, the problem can be solved by Lagrange mean value theorem. It is formulated in the following manner:

$$\Delta y = \sum_{i=1}^{n} \frac{\partial f(x^{(m)})}{\partial x_i} \cdot \Delta x_i,$$

$$x^{(m)} = (x_1^{(m)}, ..., x_n^{(m)}),$$

$$x_i^{(m)} = x_i^{(0)} + \alpha \cdot \Delta x_i, \quad 0 < \alpha < 1.$$

(5)

Thus, using the formula (5), it is possible to obtain the following factorial decomposition for the model

$$\Delta y = \sum_{i=1}^{n} A_i \cdot \Delta x_i = A_1 \Delta x_1 + ... A_n \Delta x_n,$$

(6)

where $A_i$ are impact indexes, determining the influence, that each input factor fluctuation $i$ has on the output fluctuation.

As the initial data set for the numerical study, the traffic flow values presented in the study [6] were used: the location of the highway (in the city or outside it), the grade (%), the percentage of heavy vehicles, the repair zone layout, the number of lanes (in one direction), the lane widths (m), the lane reduction and the speed limit.

The proposed Sensitivity Analysis was implemented to the model (2). It should be noted, that the approach gives $N - 1$ estimates of the factors sensitivity (figure 1) (because of existing $N - 1$ finite fluctuations for $N$ input values realizations in the dataset) and their median values were taken as a sensitivity measure. It is also important to note that the signs of obtained measures were not taken into account, so the only degree of sensitivity without its direction was considered.

The calculated estimates of the factors sensitivity allow building an expert system which uses the production rules base for the traffic flows control within high-speed transportation corridors.

3. Conceptual and functional models of expert traffic flow control system within high-speed transportation corridors

The proposed expert system is one of the functional parts of the regional intelligent transportation system module. The large amount of observable data is stored it this system. Data were received from heterogeneous sources and allows determining estimated or observed values for the factors describing the current state of the high-speed transportation corridor. The expert system will allow controlling the traffic flows within high-speed transportation
corridors as an arrangement of recommendations for road users and control actions for the road infrastructure (e.g. traffic lights). Recommendations for road users will be transmitted to real-time information boards or via wireless interfaces (Internet via mobile application, Wi-Fi modules installed in the transport corridor) within the connected cars and pedestrians’ frameworks (drivers, passengers and other participants connected devices and control modules of unmanned vehicles).

The logical inference algorithm of the expert system will calculate the recommended values of the output factors values based on the processing of expert information and input factors values which determines the current and predicted state of the system.

According to the research which are conducted and described above, the following input factors can be selected to describe the current and predicted state of the high-speed transportation corridor:

- the estimated capacity (which can be calculated by the proposed neural network model (2));
- the average vehicles speed in lanes;
- the high-speed transportation corridor location;
- the grade of the highway;
- the percentage of heavy vehicles;
- the repair zone layout;
- the number of lanes in one direction;
- the lane widths;

Figure 1. Results of Sensitivity Analysis of model (2).
the lane reduction;
the speed limit.

It is considered to use following factors as changeable output expert system parameters which allow controlling traffic flows within high-speed transportation corridors:

- the percentage of heavy vehicles;
- the number of lanes in one direction (shoulders or reverse lanes can be used as additional lanes);
- the speed limit (using variable traffic signs).

Task-specific knowledge of experts can be presented as a set of production IF-THEN rules and allows formalizing the process of traffic control. Each production rule can include information about one or several input factors in the condition part and in the conclusion part. These parameters can be involved in the production rules in the following forms:

- linguistic variables: the estimated capacity, the average vehicles speed in lanes, the speed limit, the lane widths, the percentage of heavy vehicles, the grade of the highway;
- quantitative variable: the number of lanes in one direction; including the logical variables: the lane reduction and the high-speed transportation corridor location (TRUE value is for city limits);
- string variable: the repair zone layout (the value format has following form: total numbers of provisional lanes on the right+left carriageway, s = shoulder use, n = no work zone on this side).

Here are some examples of production IF-THEN rules.

- IF “the average vehicles speed in lanes” variable exceeds liminal value STRONGLY, THEN “variable should BE REDUCED OR “the number of lanes in one direction” variable should BE INCREASED.
- IF “the high-speed transportation corridor location” variable is TRUE AND “the lane widths” variable is NARROW, THEN “the speed limit” should BE REDUCED.
- IF “the repair zone layout” variable contains “s” OR “the estimated capacity” variable exceeds liminal value STRONGLY, THEN “the percentage of heavy vehicles” variable should BE REDUCED.

The proposed conceptual model of the expert traffic flow control system is presented on figure 2.

According to the IDEF0 standard the proposed functional model of the expert traffic flow control system is presented on figure 3 and figure 4.

Production rules which were formulated on the expert task-specific opinions are stored into the knowledge base. Data which can help to calculate inputs factors are collected from heterogeneous data sources [7, 8]. The values of the system parameters are calculated and aggregated into Data collecting and aggregating subsystem taking into account time stamps and GPS coordinates [9]. Then data is transferred to the data warehouse. In the Prediction subsystem, the estimated capacity is determined using a neural network model. Data coming from the database as a crisp values and corresponding linguistic variables are converted into fuzzy values in the Fuzzificator subsystem. Then, the values of the variable parameters (the percentage of heavy vehicles, the speed limit, the number of lanes) are determined into the Logical inference subsystem using the Mamdani algorithm. In the Defuzzification subsystem fuzzy values of the output factors are converted to the crisp values. The Recommendation transmission subsystem send recommendations to the devices of road users and road infrastructure objects via wireless interfaces and the Internet.
Figure 2. Conceptual model of expert traffic flow control system within high-speed transportation corridors.

Figure 3. Functional model of expert traffic flow control system within high-speed transportation corridors. A-0 diagram.
Figure 4. Functional model of expert traffic flow control system within high-speed transportation corridors. A0 diagram (child diagram).
4. Conclusion and outlook
The reported study describes the highway capacity stochastic nature and, as result, the designed neural network model which were constructed using Mathematical Remodeling approach (allows taking into account the specificities of this system parameter) and enable its prediction. Then, there are described results of Sensitivity Analysis based on Analysis of Finite Fluctuations to the neural network model of highway capacity. This analysis is a basis to control traffic flows within high-speed transportation corridors in the expert traffic flow control system. In the next part conceptual and functional models of the proposed system are described. This expert system’s main task is to calculate the impact which should be applied to changeable parameters (output factors). Then it should be represented in the recommendation form and be transferred to road users and infrastructure objects. In the future it is supposed to carry out parametric identification of the developed system, to identify the criteria that allow determining the quality of the knowledge base, and also, using the criteria highlighted in the work [10], to evaluate the effectiveness of the built system.

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