Study of the relationship between time and traffic flow on motorways

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Abstract. Mathematical modeling of traffic flow is necessary for development of the Intelligent Transportation Systems, increase in the efficiency of preventive road safety measures, as well as road maintenance planning. The paper presents the results of mathematical modeling of traffic flow on motorways. It bases on data analysis obtained from traffic sensors. In previous studies, a model was obtained for predicting the traffic volume on the roads of the suburban area. However, it is not fully suitable for the assessment of similar processes on the roads outside settlements. The multiplicative model is adopted as the basis. The graphic patterns of the traffic flow distribution, depending on the hour of the day and the day of the week, are given. It bases on the data of traffic flows from the A-322. As the result of approximation, functional dependences in the form of periodic functions were found. The adequacy of the model is evaluated by comparing actual and model data. The results indicate applicability of the proposed model for traffic flow forecasting on any sections of motorways.

1. Introduction

At present the rapid trend of motorization increases pressure on the environment, contributes to traffic accidents, reduces the time between repairs of the roadway and leads to traffic congestion of certain sections of roads [1, 2].

One of the main indicators of road network operations is traffic volume. Its prediction, as well as the determination of properties of the traffic flow, is a necessary aspect of the development of an intelligent traffic management system and intelligent transport systems [2, 3], which make it possible to increase the average speed and road safety. Determining the patterns of distribution of the vehicle number in time will give an opportunity to develop an automated traffic control system. In addition, forecasting traffic flow characteristics is necessary for the effective design, planning and operations of motorways [4].

Solving many traffic control problems and planning roadway maintenance work require information about the traffic flow on certain sections of roads at a predetermined time. Especially these issues are currently important for road sections outside settlements. Mathematical simulation is necessary to solve this problem, the development of which is based on computer analysis of the available data on the traffic flow.

This research is devoted to the construction of a mathematical model of traffic flow on motorways.
2. Theoretical basis of research

A lot of research confirms that traffic volume depends on what month, day of week and time of day is in [5 – 7].

The distribution of traffic volume may vary according to different road sections, among which are urban, suburban roads and motorways [8]. The characteristics of traffic conditions are represented in table 1.

| Urban | Suburban | Outside settlements |
|-------|----------|---------------------|
| low traffic speed | high relative average speed | high traffic speed |
| high relative amplitude of speed | high relative amplitude of speed | uniform motion |
| non-uniform motion (high number of acceleration or slowdown road areas) | non-uniform motion (high number of acceleration or slowdown road areas) | minimum number of acceleration or slowdown road areas |

Many papers devoted to studying the first two, including the works [2, 3, 5, 9], probably because of a better opportunity for observation. Urban road traffic is characterized by evident peaks of traffic volume at morning, evening and, in some cases, noon time. Suburban road traffic has two peaks, in the morning and evening. Motorway traffic is not analyzed enough, its distribution of traffic volume in dependence to hour of day is partially considered in the work [10], and in the works [6, 11] there is represented distribution of traffic volume by hour that showing two peaks.

An important step for construction the mathematical model is collection and analysis of data. To collect the information about motorway traffic volume we can conduct a field survey; however, it is more time-consuming and less effective than an automatic observation. The main data source is a developing network of traffic metering points that have automatic traffic sensors.

On the basis of previous research and analysis of other researches results there can be made an assumption that an optimal mathematical model is fairly simple and may be represented as a multiplicative model:

\[ F = \prod_{i=1}^{n} f_i, \]  

(1)

where \( F \) is a required parameter, \( f_i \) is a partial coefficient, \( n \) is a number of coefficients.

Previously the authors of the study [12] showed that the nature of the traffic volume distribution during the day within one day of the week in different months was similar, and the different amplitude was caused by seasonal fluctuations in traffic volume.

Therefore, a hypothesis of this research is in conclusion that traffic volume at a specific point in time \( t \) can be represented as follows (2):

\[ P(t) = P_{av}^i \times K_y \times K_m \times K_{wh}, \]  

(2)

where \( P_{av}^i \) is an yearly average traffic volume on the \( i \) road section; \( K_y \) is an yearly coefficient; \( K_m \) is a monthly coefficient; \( K_{wh} \) is a coefficient of weekday and hour.

The yearly average traffic volume \( P_{av}^i \) can be determined by several ways, the first one is using of traffic sensors data, collected in conditions when the distance between sensors and an observation road section is small and with sufficient data integrity, the second way is using a traffic mathematical model, for example, based on the population number in the nearest settlements, and in addition by the use of the given formula (2), if the partial coefficients are known.

The yearly coefficient \( K_y \) shows a change of traffic volume for a year comparing with a period for which the yearly average traffic volume on a specific road section is already known:
\[ K_y = \frac{P_{\text{avg}}}{P_{\text{year}}} \]  

For motorways the yearly coefficient \( K_y \) usually is a constant value; therefore, the formula take the form of this expression \( K_y = K_y^i = K_y^n = \text{const} \), where \( i \in I, I \) – a section of road between cities. If yearly average traffic volume on a given road section has a known value for the current year, then \( K_y = 1 \).

The monthly coefficient \( K_m \) displays a seasonal non-uniformity of traffic volume and can be expressed as the following formula (4):

\[ K_m = \frac{P_m}{P_{\text{avg}}} \]

where \( P_m \) is an average traffic volume for a given month.

The monthly coefficient also may be consider as a constant value for motorways.

A coefficient \( K_w^h \) shows an influence of week day and hour on traffic volume. It is accepted, that a relative value of traffic volume for the same day of the week during the year is constant.

For convenience, all traffic volume is expressed by the average hourly value, i.e. the number of vehicles passing through the section of the road per hour.

3. Results and Discussion

The Russian Federal road A-322 (Barnaul – Rubtsovsk – the state border with the Republic of Kazakhstan) was chosen as an object of research. There were the analyzed data of the traffic sensor installed on 214th km of the road. The distance from this road section to big or large cities (with a population of more than 100 thousand people) is 200 km to Barnaul, the capital city of the region, and to 85 km Rubtsovsk, respectively.

The changes in the traffic volume relative to the average value, depending on the time \( t_i \) of the \( i \)-th week day, is shown in figure 1.

![Figure 1. Day-of-Week Patterns for the selected road section (214 km A–322).](image)

Fluctuations of the traffic volume from Monday to Thursday differ inconsiderably, the hypothesis of similarity is confirmed by the calculation of F criterion, and is taken at the significance level of 0.05. This indicates the identity of the traffic volume distribution from Monday to Thursday. Friday is characterized by increasing of the traffic volume to evening time. Saturday has a more pronounced peak at noontime. Sunday is characterized by a pronounced amplitude.

The changing of traffic volume during the week is a cyclic process, and it's reasonable to describe it applying periodic functions.

Using the data analysis tools of the Matlab software package, there was obtained distribution that describes changing of the relative traffic volume most representatively (\( R\text{-square} > 0.93 \)) and calculates the numerical values of the distribution coefficients \( a_i, b_i, c_i \). The values of the coefficients differ depending on the day of the week (table 2).
Table 2. Distribution coefficients and R-square value.

| Day of week       | Coefficients | R-square |
|-------------------|--------------|----------|
|                   | $a_i$ | $b_i$ | $c_i$ | $a_i$ | $b_i$ | $c_i$ |
| Monday – Thursday | 5.172 | 0.008 | 2.907 | 0.937 | 0.186 | 4.943 | 0.968 |
| Friday            | 268.4 | 0.135 | 1.167 | 268.1 | 0.135 | 4.310 | 0.963 |
| Saturday          | 1.534 | 0.125 | -0.093 | 0.139 | 0.769 | 0.198 | 0.934 |
| Sunday            | 1.470 | 0.106 | 0.027 | 0.516 | 0.359 | 2.565 | 0.994 |

The law of changing of the week day and hour coefficient $K_{w}^{h}$ takes the form of following formula:

$$K_{w}^{h} = \sum_{i=1}^{3} a_i \cdot \sin(b_i \cdot t + c_i),$$

(5)

where $t$ is the hour of day.

Substituting the expression (4) in the formula (1), we obtain the distribution law for traffic volume in any day of the week and hour:

$$P(t) = P_w^h \times K_y^h \times K_m^h \times \sum_{i=1}^{3} a_i \cdot \sin(b_i \cdot t + c_i).$$

(6)

To check the adequacy of the model, there were chosen random dates for two sections of the road (214 km and 166 km). Then we calculated the traffic volume according to the formula (4). The results that we got in the simulation were compared with the actual data, obtained from the traffic sensor (figure 2).

Figure 2 displays the similarity of model and actual data. Calculation of F criterion also confirmed the adequacy of the model.
4. Conclusion
As a result of the research we receive the mathematical model that gives an opportunity to calculate approximate value of traffic volume on motorways depending on month, day of week and hour. It is proved that the distribution of traffic volume during the day on motorways differs from the distribution for urban and suburban roads and is characterized by one peak in the afternoon.

The difference from the results of other researchers, whose works are devoted to the analysis of the hourly traffic volume, can be explained by the peculiarities of the Russian road network, where a distance between cities is often more than 100-200 km and the motorways are widespread.

The resulting model can be used to calculate the traffic volume on sections of roads outside the settlements characterized by a typical suburban traffic, and can also become an element of Intelligent Transportation Systems on such roads. However, to predict the considered parameter in areas near cities, large settlements or large objects of attraction, the model must be refined.

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