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TRAFFIC FLOW MODELLING ON THE ROAD NETWORK IN THE CITIES

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Original scientific paper
Planning of road transport infrastructure is a complex process. One of the major issues is determining the design elements of road infrastructure (road type and number of traffic lanes, cross-sectional profile, etc.). When designing roads, parameters from the international literature are used, containing values derived empirically from local data on traffic flow (mostly from northern American cities). The goal of this paper was to explore traffic flows for the purpose of developing a model that will enable scientifically exact description of traffic flows in urban areas of Central Europe. Study of basic parameters of traffic flow included the selection of road location, survey time, traffic survey, analysis of video recordings, as well as statistical analysis and calculation of basic parameters of traffic flow. Added value of this research is demonstrated through the method of collecting and analysing the data for each lane (or roadway) separately in order to detect the difference in the values of the basic parameters of traffic flows. The research was conducted on various urban roads and in various traffic conditions and in this way the basic parameters of traffic flow were obtained. These parameters were used to develop diagrams of relations between speed, traffic density and volume, resulting in cumulative functions of traffic flow parameters for the entire urban traffic network. This made it possible to develop new equations enabling theoretical determination of flow volume, speed and density for a given road. Methods established in this work and the results of the research present a useful and applicable tool for benchmarking road capacity and finding relevant coefficients significant for dimensioning the road cross-sections in urban areas, but also on all other categories of roads.

Keywords: *density and volume; road infrastructure design; road network; traffic flow; traffic modelling; traffic speed*

Modeliranje prometnog toka na prometnoj mreži u gradovima

Izvorni znanstveni članak
Planiranje cestovne prometne infrastrukture je složen proces. Jedan od najvećih problema je određivanje projektnih elemenata cestovne infrastrukture (vrsta ceste i broj prometnih traka, poprečni profil i sl). Za potrebe dimenzioniranja prometnica koriste se parametri iz strane literature s vrijednostima koje su empirijskim metodama derivirane iz lokalnih podataka o prometnom toku (najčešće sjevernoamerički gradovi). Cilj ovog rada bio je istraživanje prometnih tokova radi izrade modela koji će pružiti mogućnost egzaktnijeg opisa lokalnih karakteristika prometnih tokova na području srednjoeuropskih gradova. Istraživanje osnovnih parametara prometnog toka sastojalo se od izbora lokacije cesta, vremena snimanja, snimanja prometa, analize video zapisa istatističke analize i proračuna osnovnih parametara prometnog toka. Posebnost provedenog istraživanja sadržana je u načinu prikupljanja i analizi podataka za svaki prometni trak (ili kolnik) radi uočavanja razlike u vrijednostima osnovnih parametara prometnih tokova. Istraživanje je obavljeno na različitim gradskim prometnicama i u različitim prometnim uvjetima te su dobiveni osnovni parametri prometnog toka. Pomoću tih parametara napravljeni su dijagrami odnosa brzine, gustoće i propusne moći i dobivene su kumulativne funkcije parametara prometnih tokova za cjelokupnu prometnu mrežu grada. Time je omogućeno da se izrade nove jednadžbe pomoću kojih je moguće teoretski odrediti kapacitet, brzinu i gustoću toka prometnice.Razvijena metoda kao i rezultat ovog znanstvenog istraživanja pouzdan je, koristan i primjenljiv alat za određivanje kriterija propusne moći ceste i proračun vrijednosti relevantnih koeficijenata mjerodavnih za dimenzioniranje poprečnog presjeka cesta u urbanim sredinama, ali i svih ostalih kategorija cesta.

Ključne riječi: *brzina prometa; cestovna mreža; dizajniranje cestovne infrastrukture; gustoća i kapacitet; prometno modeliranje; prometni tok*

1 Introduction

Planning and design of road infrastructure is based on determination of traffic flow parameters and their distribution in the observed area in terms of space and time. For the purpose of selecting the optimal solution for the planned period, it is necessary to conduct research of relevant traffic flow parameters in characteristic conditions on the observed road network. This research then enables that the suitable traffic flow model is determined. The concept of traffic flow modelling implies defining of relations between the basic parameters of traffic flow: speed (v), density (g) and volume (q). Determination of values of traffic parameters is based on surveying the traffic flow samples, i.e. sampling on relevant sections in characteristic peak and off-peak loads. The most frequently applied sampling procedure includes measurement of vehicle flow, i.e. by conducting traffic counts. However, reliable as it is, this procedure is not sufficient in the process of determining the actual and available capacity of future roads, as the capacity essentially depends on specific conditions of traffic operation on the road infrastructure. Reliable information on the capacity of any road and road infrastructure may be obtained by traffic count only after the road has been constructed. It is, therefore, necessary to conduct measurements and calculate coefficients and factors that will be used for determining road capacity in planning documentation that will meet the need of the future infrastructure.

In addition to traffic flow indicators, an essential factor in all stages of creating and evaluating design solutions is road capacity. Capacity is the basic indicator of a rational and deliberate policy for road construction, maintenance and operation. Not only does it directly influence the selection of road design elements and its cross section, but it also has an impact on operational costs of vehicles through the application of adequate designs of access roads. Road capacity is a significant planning tool for finding adequate criteria for determining the optimal peak hour traffic volume relevant for the design of road cross section based on programmed traffic volumes. Descriptive capacity parameters from the international literature is used for road design purposes, with values derived by empirical methods from local traffic flow data (e.g. HCM) [3, 9].

For the purpose of defining adequate traffic model that will enable a more accurate description of local characteristic of traffic flows in Central European cities, we have conducted research in Zagreb urban area. Basic traffic flow parameters measurements and computation of values of relevant coefficients characteristic categories of roads in the observed road network was conducted. This method can also be applied for local conditions in similar cities as it is reliable and does not require large investments.

2 Review of road capacity research to date

Traffic flow theory is a scientific discipline studying the conditions of movement of motor vehicles in traffic flows in a road network. In the analysis of complex issues concerning movement of motor vehicles in traffic flows, the traffic flow theory is used as a tool for researching and defining basic indicators. These indicators are then used for description of traffic flows by exploring characteristics of traffic flows in ideal and real conditions and by investigating the interdependence of basic parameters of traffic flow in ideal road and traffic conditions (11).

The practical application of the general knowledge of traffic flow theory is reflected in the evaluation of the existing network or its individual parts. That is, for the purpose of identifying actual needs for improvement of the existing network or parts of the network. This evaluation is a base for identification of bottlenecks in space (network) and time, identification of generators of bottlenecks, planning and distribution of traffic flows. It can also be used for planning of transport tasks in the network, traffic flow management, planning of network maintenance, taking appropriate measures for increasing safety level, etc.

Traffic flow theory is a comparatively new scientific discipline [10, 11]. A significant development of Traffic Flow Theory was observed after 1930, in connection with the application of probability theory in describing certain traffic flow characteristics and in improving first mathematical models for describing the flow-speed relations.

In practice, there is no such thing as ideal traffic flow. Similarly, road and ambience conditions are rarely ideal or nearly ideal. This is why the relations between the basic parameters of traffic flow have no direct usage value in describing the conditions of vehicle movement in real traffic flows, nor can they be used to solve practical engineering tasks.

Looking for adequate way of applying general theoretical relations between basic parameters of traffic flow to the real road conditions, several researchers have performed numerous empirical studies. They were primarily researching the dependence of speed of vehicles in the flow, traffic flow density and dependence of the speed of vehicles in the flow and the flow capacity in real conditions.

In early empirical research, one of the key goals was to verify fundamental relations between the basic parameters of traffic flow. This is why this research was mainly conducted in conditions that were as similar as possible to the conditions for which the theoretical relations in patterns of basic traffic flow parameters were formulated. Empirical research is prevailingly based on ideal or near-ideal road and ambience conditions and one-way traffic flow of passenger cars.

Basic results of empirical research were presented through empirical models of the dependence of space-mean speed of traffic flow on the density of the flow and empirical models of dependence of space-mean speed of flow on the vehicle flow. One of the first significant publications was Greenshield's (10) paper titled "A Study of Highway Capacity" in 1934. Greenshield is one of the first experts in the world to research patterns including basic parameters of traffic flow. He explored the possible interpretation through linear dependence of measured values of space-mean speed of traffic flow on flow density. In this way, he developed the interdependence of space-mean speed and density of traffic flow starting with the general form of linear dependence. The linear model provided for satisfactory matching with empirical data for low and medium density flows. He also observed that the linearity of the speed-density relation is increased in cases when the real flow is nearing the size of the ideal flow.

In 1959, Greenberg [11] explored the traffic flow with the assumption that the flow of vehicles may be observed as one-dimensional fluid. Greenberg is one of the first experts who explored the interdependence of basic parameters of traffic flow based on results of practical measurements and employed a logarithmic model to interpret the dependence of space-mean speed of the flow on the flow density (Fig. 1).

This logarithmic model, however, does not provide sufficiently satisfying results for low-density flows. This disadvantage of the logarithmic model is particularly prominent when flow density tends towards zero, as in this case the space-mean speed of flow tends towards an infinitely large value. In this marginal domain, the model is not applicable in practical conditions.

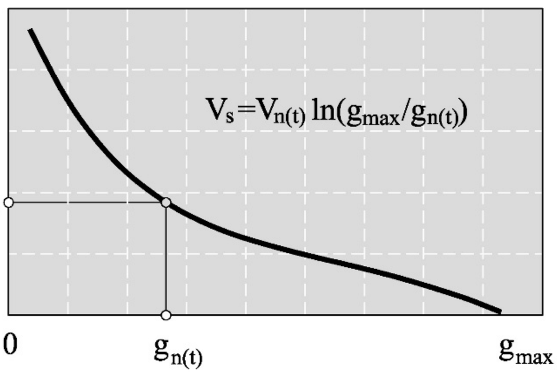

Figure 1 The logarithmic speed-density model

In 1961, Underwood in his model [14] proposed an exponential connection between speed and density, while May [1] proposed a bell shaped curve. Also known is the research of Drew, Underwood and Edie [2]. In addition to the mentioned single-regime traffic flow models there are also the multi-regime models, where one regime applies to one domain of density value, whereas to the next domain another regime of speed-density relation applies.

Recent research either relates to the existing research [23, 26] or represents a certain modification of existing speed-volume, speed-density and volume-density models, provided by Helbing in 2009 [25].

The research in this paper [28] is likewise focused on modifications of the mentioned models, in order to obtain relationships better suiting the local conditions of traffic operation. The research was conducted in the Croatian capital, where the conditions (road infrastructure, types of vehicles and homogeneity of traffic flow) and modes of traffic flows are roughly equivalent to conditions and modes in other similar Central European cities.

3 Methodology

The methodology of measuring basic parameters of traffic flow for individual vehicles may be divided in four main parts, i.e. it consists of the following steps:

- Selecting location (road, intersection) and time of survey (morning or afternoon peak load);
- traffic survey;
- analysis of video recordings (collecting input data); and
- statistical analysis and calculation of basic parameters of traffic flow (traffic flow volume and structure; headways; distance gaps, vehicle speed, tabular and graphical representation of analysed values of traffic flow parameters; definition of classes and classification of data; analysis of relevant statistical indicators - absolute and relative frequency; cumulative sequence; full and positional mean values measures of dispersion and shape; testing of statistical hypotheses - binomial, Poisson, normal and exponential distribution; correlation and regression analysis).

3.1 Methodology for collecting data on headways and vehicle speeds in traffic flow

For the purpose of collecting data on headways and speed of individual vehicles in the traffic flow, we have developed the methodology of traffic survey on characteristic points of the observed transport network [28].

By surveying traffic flows in morning and afternoon peak traffic loads we have collected relevant data that we have used as input for further statistical analysis. Surveying was conducted with digital video cameras with MTS and MP4 format video recordings and the recording velocity of 25 and/or 50 fps (frames per second).

In the analysed area a road segment is selected (Fig. 2) by marking the lines of the first and the second observed road cross-section and the distance between these lines is measured (Fig. 3).

Video recordings were then analysed for each individual vehicle in the traffic flow and the data on the passing times of the vehicle through the first and the second line of the observed road segment were collected. The digital video recording was stopped on the screen at the moment when each of the vehicles passed the first/the second line of the observed road segment and the respective frame numbers were recorded. The vehicle passed the observed line at the moment when either the front or the rear axle of the vehicle was aligned with the observed line.

Frame numbers at the moment of passage through the first and second line are stored into the database. Additional data collected at the passage of vehicles through the observed lines included data on vehicle type (passenger car, motorcycle, light truck, heavy truck or bus), in order to gain insight into the current structure of traffic flows in the researched area.

Data have been collected and analysed for each of the traffic lanes (or carriageways) in order to detect differences in values of basic parameters of traffic flows.

With input collected (length of the observed road segment, frame numbers) for each vehicle it is possible to calculate other relevant traffic flow indicators.

The database (Tab. 1) includes tabular representation of calculated values of headway, distance gap and speed for all vehicles in the traffic flow. Extreme values of headway obtained by analysis were eliminated and not used in further analysis, and all other vehicles were classified in packages (groups).

Figure 2 The observed road segment with marked lines for passage time readings - Slavonska Avenue (Source: edited by the authors)

For this purpose vehicle package was defined as a group of vehicles successively passing the observed road segment in headways of less than 5 seconds. All vehicles with headways longer than 5 seconds were marked as individual vehicles. Individual vehicles were excluded from further statistical analysis in order to improve the accuracy in calculating the relevant average values. By analysing vehicle packages we calculated mean interval values and mean speed of vehicles within the package. By calculating the arithmetic mean of mean headways and speeds of vehicle packages we obtained relevant average values for the observed traffic lane.

The vehicles were additionally classified by type, to obtain information on traffic flow structure. Each vehicle was marked with an adequate index (A-passenger car, M-motorcycle, LT-light truck, TT-heavy truck, B-bus) to mark the vehicle type. Groups of vehicles with intervals shorter than 5 seconds were included in vehicle package and separately marked in the database. Individual vehicles with intervals longer than 5 seconds represent extreme values and were therefore excluded from further statistical analysis.

Database also included the analysis and representation of mean values of interval and speed of individual vehicle packages. Based on the average values of vehicle packages we calculated the arithmetic mean of average intervals and speed of vehicles for each traffic lane.

In statistical analysis the calculated values of headway and speed were classified in ascending order (from minimal to maximal value) and percentile values of observed characteristics were calculated. Value grouping resulted in frequency distribution. Speeds and headways were grouped into classes whose width and number were determined pursuant to Sturges rule. Sturges rule is applied to determine the number of statistical classes k, whereby the statistical sample consisting of N elements of statistical set is grouped in k numerical groups.

The standard number of k numerical groups ranges from 5 to 15 (maximum of 25). If the classes are equal, their width is approximately determined by the division of variation ranges and number of classes:

$$\Delta X = \frac{X_{\max} - X_{\min}}{k}, \tag{1}$$

$$k \approx 1 + 3{,}3 \cdot \log N, \tag{2}$$

where:
k – number of classes;
N – number of elements of statistical set;
r – class width;
$X_{\max}$ – maximum value of observed characteristic; and
$X_{\min}$ – minimal value of observed characteristic

Based on the grouped speed and headway values the absolute and relative frequencies of each observed class were computed.

Other relevant statistical indicators were computed as well, including the cumulative sequence of frequency distribution, full mean values (weighted arithmetic mean, geometric mean and harmonic mean), positional means (mode, median) and dispersion measures (variation range, variance, standard deviation, variation coefficient) and shape measures (asymmetry and kurtosis coefficient) of grouped values of characteristics. Statistical analysis was conducted separately for individual vehicles and for mean values of vehicle packages. The paper includes only the end results of the conducted analysis.

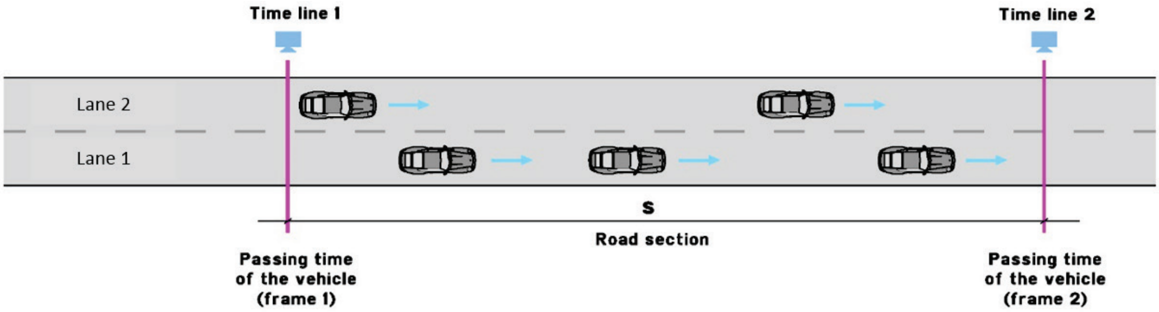

Figure 3 Schematic representation of the observed road segment with marked lines for passage time readings

Table 1 Example: Portion of database of surveyed vehicles according to frames with headways, gaps and speeds (extract from the survey database for the first ten vehicles)

Veh. no.	Type	Frame		Package no.	Headway		Gap		Line distance		Vehicle speed	
		Timeline 1	Timeline 2		t_{h1} (s)	t_{h2} (s)	S_{h1} (m)	S_{h2} (m)	S (m)	dt (s)	v	V
1	A	12	70	Individ. veh.	8,32	7,92	120,86	115,04	33,7	2,32	14,5	52,29
2	B	220	268	Package 1	1,04	0,96	18,25	16,85	33,7	1,92	17,5	63,19
3	A	246	292		1,36	1,40	24,91	25,64	33,7	1,84	18,3	65,93
4	A	280	327		1,08	1,04	19,36	18,64	33,7	1,88	17,9	64,53
5	A	307	353		1,84	1,88	33,70	34,43	33,7	1,84	18,3	65,93
6	A	353	400	Individ, veh,	7,88	7,60	141,25	136,23	33,7	1,88	17,9	64,53
7	A	550	590	Package 2	0,92	1,04	19,38	21,91	33,7	1,6	21,0	75,83
8	A	573	616		1,60	1,68	31,35	32,92	33,7	1,72	19,5	70,53
9	A	613	658		1,28	1,04	23,96	19,47	33,7	1,8	18,7	67,40
10	A	645	684		2,12	2,20	45,80	47,53	33,7	1,56	21,6	77,77
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Source: edited by the authors

The analysis of video recordings included readings of respective frames at the moment of each vehicle's passing the first and the second line of observation on the road segment. It has been defined that a vehicle has passed the observed line at the moment when its front/rear axle has passed the observed line, depending on the direction of movement of the vehicle in the traffic flow. Input data then enable the analysis and tabular representation of intervals, gaps and speeds of individual vehicles.

Time headway in the traffic flow is the time between the passages of two successive vehicles through an imaginary cross-section of the observed road segment. Passage of vehicles through the observed line is defined as the passage of the front or rear axle. Interval values on the first t_{h1} and the second t_{h2} observed line were calculated. The average interval value for vehicle packages was determined as the arithmetic mean of all intervals of vehicles in the package.

For calculation of headways the following equations were used:

$$t_{h1} = \frac{frame\mathrm{A2L1} - frame\mathrm{A1L1}}{fps}, \mathrm{s} \tag{3}$$

$$t_{h2} = \frac{frame\mathrm{A2L2} - frame\mathrm{A1L2}}{fps}, \mathrm{s} \tag{4}$$

where:
t_{h1} – headway A1 on the first line (s) and

t_{h2} – headway A1 on the second line (s)
*frame*A1L1 – frame number at the moment of passage of vehicle A1 over the L1 line;
*frame*A1L2 – frame number at the moment of passage of vehicle A1 over the L2 line;
*frame*A2L1 – frame number at the moment of passage of vehicle A2 over the L1 line;
*frame*A2L2 – frame number at the moment of passage of vehicle A2 over the L2 line; and
fps – number of frames per second in the observed video recording (frame/s).

Space headway represents the spacing between two successive vehicles in a traffic flow. For the analysis of headways the following equations were used:

$$S_{h1} = v_1 \cdot t_{h1}, \text{m} \tag{5}$$

$$S_{h2} = v_1 \cdot t_{h2}, \text{m} \tag{6}$$

where:
S_{h1} – distance gap between vehicles on the first line (m)
S_{h2} – distance gap between vehicles on the second line (m)
v_1 – vehicle speed A1 (m/s)
t_{h1}, t_{h2} – headway of vehicle A1 on the first and the second line (s).

Traffic flow speed represents a mean value of speed of all vehicles participating in the observed traffic flow. Speeds of individual vehicles in the traffic flow were computed using the following equation:

$$V_i = \frac{s}{\mathrm{d}t} = \frac{s}{\left(\dfrac{frame\text{A1L1} - frame\text{A1L2}}{fps}\right)} \cdot 3{,}6,\ \text{km/h} \tag{7}$$

where:
V_i – speed of vehicle Ai (km/h)
s – length of the observed road segment (m)
dt – time required for the vehicle A1 to pass over the observed road segment
*frame*A1L1 – frame number at the moment of passage of vehicle A1 over the L1 line
*frame*A1L2 – frame number at the moment of passage of vehicle A1 over the L2 line and
fps – number of frames per second in the observed video recording (frame/s).

Mean values of the headway in the package were computed using the equation:

$$t_{hsr} = \frac{\sum_{i=1}^{n1} t_{h1i} + \sum_{j=1}^{n2} t_{h2j}}{N}, \text{s} \tag{8}$$

where:
t_{hsr} – mean value of headway
$\sum t_{h1}$ – sum of all headways of vehicles in the package (on the first line) (s)
$\sum t_{h2}$ – sum of all headways of vehicles in the package (on the second line) (s) and
N – number of vehicles in the observed package (veh).

Mean values of speed of vehicles in the package were computed using the equation:

$$V_{sr} = \frac{\sum_{i=1}^{N} V_i}{N}, \text{km/h} \tag{9}$$

where:
V_{sr} – mean speed of the observed vehicle package (km/h)
V_i – speed of the i^{th} vehicle within the package (km/h)
N – number of vehicles within the observed package (veh).

Arithmetic mean of all mean values of headways and speeds of package of vehicles for the observed traffic lane was computed using the following equation:

$$T_{hsruk} = \frac{\sum_{i=1}^{N_p} T_{hsri}}{N_p}, \text{s} \tag{10}$$

$$V_{sruk} = \frac{\sum_{i=1}^{N_p} V_{sri}}{N_p}, \text{km/h} \tag{11}$$

where:
T_{hsruk} – mean value of headway for the observed lane (s)
V_{sruk} – mean value of vehicle speed for the observed lane (km/h)
T_{hsri} – mean headway of the observed package of vehicles (s)
V_{sri} – mean speed of package of vehicles (km/h) and
N_p – number of packages (groups of vehicles) on the observed lane.

Based on the computed empirical frequencies of speed and headway we tested the hypotheses on frequency distribution according to various distributions (binomial, Poisson, normal, exponential).

In the last step we determined the level of correlation between empirical values of speed and headway. The correlation of speeds and headways was described by the optimal regression function, which most accurately describes the connection between the observed characteristics (linear, polynomial, logarithmic or exponential function).

4 Methodology for identifying traffic load intensity

Through survey analysis the values of traffic load on characteristic points of the Zagreb road network were identified. The research included traffic counts in peak traffic loads over the day to identify the peak hour, as well as daylong and weeklong traffic counts to collect data on daily and weekly non-uniformities of vehicle flow. Traffic loads were identified on roads of all categories and expressed as vehicle flow rates on the observed cross-sections of the road.

Vehicle flow (q) means the number of vehicles passing the observed cross-section of the road in a unit of time, in one direction for one-way roads or in both directions for two-way roads. Vehicle flow may be measured on the observed cross-section of the road in the unit of time and may be computed by counting vehicles on the segment or section of the road representing the arithmetic mean of the flow on n – cross-sections on the segment or section. The accuracy of the established flow rate can be improved by increasing the number of observed cross-sections n. The relations refer to the flow on the segment in one line, in one sequence and in one direction. Unit of measure for vehicle flow is number of vehicles per hour (veh/h). In practice larger time units are used, too, such as day (veh/day).

4.1 Traffic survey on characteristic points of the Zagreb traffic network

Traffic flow is a simultaneous movement of several vehicles on the road in a certain sequence. To describe traffic flows and regularities of movement of motor vehicles in traffic flows on roads it is necessary to define indicators, i.e. basic parameters of traffic flow. The key difference in conditions of vehicle movement in traffic flow in comparison with conditions of movement of individual vehicle is that in traffic flow the vehicle movement is affected by interaction of vehicles in the flow.

To establish the values of basic parameters of traffic flows we have conducted traffic survey on characteristic points of the Zagreb traffic network. The survey was conducted on roads of five different categories:

- Category 1 - urban highway
- Category 2 - multi-lane roads
- Category 3 - two-lane roads
- Category 4- single-lane roads and
- Category 5 - side streets.

In defining the values of basic parameters of traffic flows we analysed movement of individual vehicles in the traffic flow and the average values of packages of vehicles. Based on data collected from reviewed surveys the speeds of individual vehicles were computed through the analysis of other known parameters. With identified values of speeds of individual vehicles in the traffic flow we conducted statistical analysis of movement speed of individual vehicles measured on certain measuring points on the observed road segment. Survey analysis made it possible to identify values of the following parameters necessary for description of traffic flows:

- Vehicle flow, (q)
- Density of traffic flow, (g)
- Speed of traffic flow, (v)
- Travel time of vehicles in the flow, (t)
- Unit travel time of vehicles in the flow
- Time headway of vehicles in the flow (t_h) and
- Distance gap between vehicles in the flow (s_h).

Regularities (patterns) of movement of motor vehicles in traffic flows on roads depend on many factors, which means that a description of such patterns is a highly complex process. The most significant factors affecting the patterns of movement of motor vehicles in traffic flows on roads include: road conditions, flow size, flow characteristics, driving dynamics characteristics of vehicles, psychophysical characteristics of drivers, drivers' motivation level, condition and characteristics of traffic regulation and management system as well as atmospheric conditions (visibility, climate, relief, etc.). General conditions of vehicle movement in traffic flows on roads can be classified as conditions of free flow, normal flow, saturated flow and forced (breakdown) flow.

In free flow conditions all vehicles on the observed segment are moving freely, i.e. the speed of each individual vehicle is not affected by other vehicles on the road. Considering the fact that the flow is by its nature highly uneven, the free flow conditions occur at significantly lower flow volumes of 450 (veh/h) and at headway values of up to 5 (s).

In normal flow conditions vehicle movement is partly affected by other vehicles on the road. Overtaking is not possible at any given moment or at any given point. Mathematical description of overtaking in normal flow is significantly more complex than in free flow environment. Considering mean values and ignoring the fact that the flow is uneven in terms of time, limits of normal flow per lane are defined with 450 to 2,100 (veh/h).

In saturated flow all observed vehicles (practical limit is over 75 % of vehicles) move in a queue. In terms of interaction of vehicles, a queue (line) consists of at least two or more vehicles moving successively on the same traffic lane. The speed of the queue is set by the first vehicle, i.e. the vehicle heading the queue. Generally, speed of every single vehicle in the queue depends on the speed of the vehicle in front of it, regardless whether such vehicle is the very first and is heading the queue or there is another vehicle in front of such vehicle. Considering the mean values and disregarding the flow unevenness in terms of time, values of saturated flow range from 2100 to 2200 (veh/h) per lane with headway values ranging from 1,6 to 1,7 seconds.

Forced flow conditions include highly oscillating flow with significant presence of shockwaves. Similar as with saturated flow, forced flow is about the conditions of the traffic in the queue, and the difference between the two is that forced flow – unlike the saturated flow – includes higher densities and lower speeds with frequent traffic jams.

Time headway of vehicles in the traffic flow (t_h) is the time between the passages of two successive vehicles through the imaginary cross-section of the observed road segment (frontal passage). The relation between the time headline and vehicle flow is shown in the following equation:

$$q = \frac{3600}{t_h}, \text{ veh/h} \tag{12}$$

where:
q – average vehicle flow (veh/h)
t_h – average time headway of the vehicle (s/veh)

Space headway (s_h) is a spatial gap between two successive vehicles in the traffic flow expressed in meters. Average gap between vehicles in traffic flow can be determined from the known average time headway using the equation:

$$q_h = t_h \cdot v, \text{ m} \tag{13}$$

where:
s_h – average gap between vehicles in a sequence (m)
t_h – average time headway of vehicles (s/veh) and
v – average speed of traffic flow (m/s).

The mentioned characteristics of time headway and space headway are microscopic, considering that they relate to individual pairs of vehicles within the traffic flow. Within each traffic flow time headway and gap between vehicles are confined to a certain set of values and are mainly dependent on traffic flow speed and the prevailing conditions.

Microscopic parameters, when viewed collectively, are connected with macroscopic parameters of traffic flow – density and flow rate.

Traffic flow density (g) denotes number of vehicles per unit of road length. The average traffic flow density is calculated by dividing the length of the observed road segment (usually 1000 m) by the identified average gap between vehicles in the sequence.

The size of gap between vehicles in the sequence is defined by the sum of safety gap between vehicles in motion and the length of the vehicle in front. The relation between average density of traffic flow and average gap between vehicles in sequence is shown in the following equation:

$$g = \frac{1000}{s_h}, \text{ veh/km} \tag{14}$$

where:
g – average density of traffic flow (veh/km) and
s_h – average gap between vehicles in a sequence (m).

5 Review of conducted measurements and their results
5.1 Selection of area for surveying traffic flows

The obtained values of traffic flow parameters measured on characteristic points of the Zagreb traffic network were used for computation of levelled out values for five observed road categories as well as cumulative average values for the entire observed traffic network.

Fig. 4 shows average values of vehicle flow over the day according to road categories and the cumulative levelled out flow values. Fig. 5 shows the comparison of determined average values of time headway of vehicle packages on observed road categories.

Fig. 6 shows a comparison of determined regression functions for all road categories, i.e. it includes obtained cumulative functions of traffic flow parameters for the entire Zagreb traffic network.

Fig. 7 shows the cumulative curve of percentile speeds and time headways. Cumulative empirical diagrams flow-speed and speed-density are shown in Figs. 8 and 9.

In order to simplify the expression of established empirical equation, the obtained empirical functions were approximated to approximate curves with acceptable deviation level. Approximate curves of empirical diagrams flow-speed and flow-density are shown in Figs. 10 and 11.

Relative departure of empirical values from theoretical values on the flow-speed curve occurred due to certain assumptions employed in determining theoretical models for describing relations between basic parameters of traffic flow.

The end result of this research is the relation between speed of movement of vehicles on urban roads and the capacity of these roads. This relation is shown in the Eq. (15).

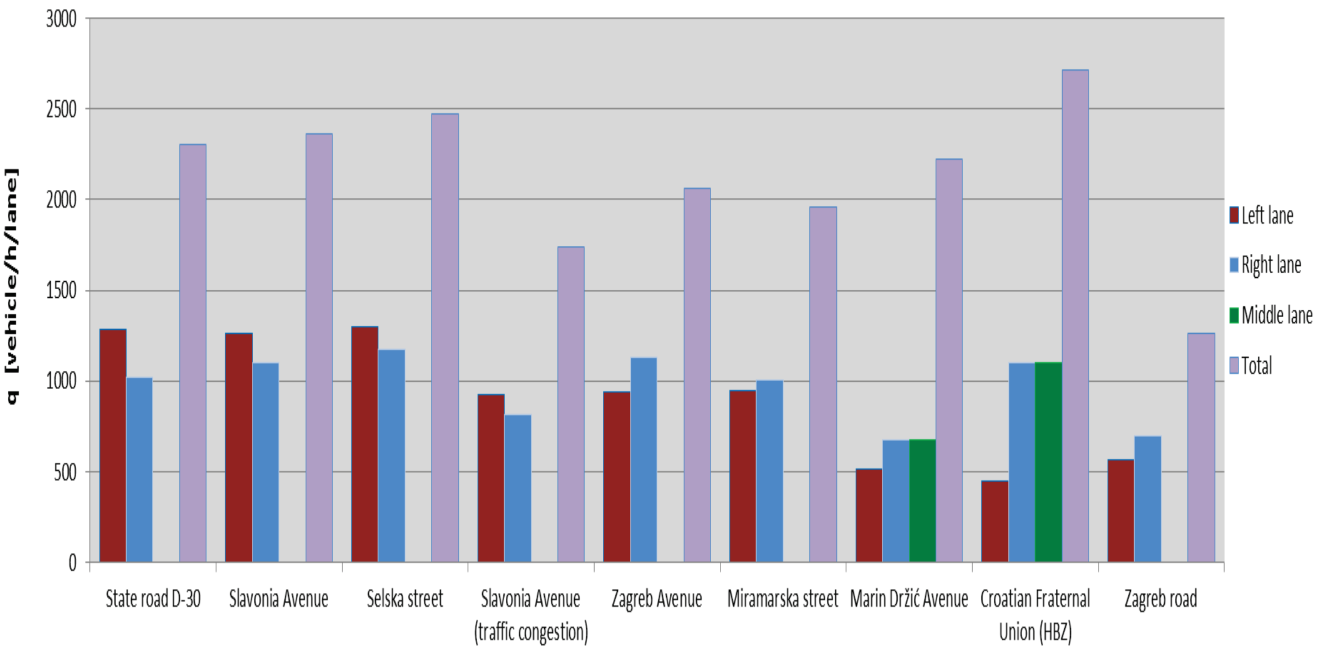

Figure4 Average vehicle flows with traffic load distribution per individual traffic lanes at characteristic points of Zagreb traffic network

Table 3 Identified daily time irregularities of vehicle flow for observed road categories with analysed share of peak hour in daily traffic volume

Time (h)	Traffic volume during the day by hours					
	1. class	2. class	3. class	4. class	5. class	Average
0	345	278	446	296	155	304
1	187	143	301	218	59	182
3	119	96	219	196	48	136
4	126	86	243	155	45	131
5	239	145	314	119	71	178
6	3139	1961	443	281	876	1340
7	3345	2384	559	414	970	1534
8	3095	2363	1029	835	784	1621
9	2872	2164	1310	1581	930	1771
10	2769	2375	1345	2122	923	1907
11	2772	2435	1315	2321	969	1962
12	2897	2626	1628	2136	969	1962
13	3007	2733	1827	2044	1015	2125
14	2764	2813	1911	1718	1065	2054
15	2961	3110	2006	1791	1214	2216
16	2977	3322	2007	1735	1258	2260
17	2813	3128	2416	1763	1244	2273
18	2749	2791	2269	1503	1095	2081
19	2673	2631	2115	1112	977	1902
20	2461	2191	1737	758	830	1595
21	1999	1625	1051	582	580	1167
22	1181	1175	451	388	415	722
23	807	724	296	249	247	465
Daily traffic volume						
q_{TOTAL}(veh/day)	49 249	43 913	27 545	24 494	17 073	32 454
Peak hour						
q_{MAX}(veh/h)	3345	3322	2416	2321	1258	2273
Peak hour share in daily traffic volume						
% q_{MAX}(veh/day)	6,79	7,56	8,77	9,48	7,37	7,99

Table4 Identified weekly time irregularities of vehicle flow for observed road categories

Day	Traffic volume by days during the week q_{D}(veh/day)							
	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday	Total
1. class	43,379	43,913	45,544	46,002	47,198	41,305	33,847	301,188
2. class	42,173	39,865	42,456	40,907	40,856	33,226	27,545	267,028
3. class	36,416	24,724	38,756	30,682	38,077	37,105	28,231	233,991
4. class	27,928	24,023	29,505	26,839	29,846	27,444	21,728	187,312
5. class	16,706	18,673	16,757	17,679	21,470	17,809	12,247	121,341
Average	33,320	30,240	34,604	32,422	35,489	31,378	24,719	222,172

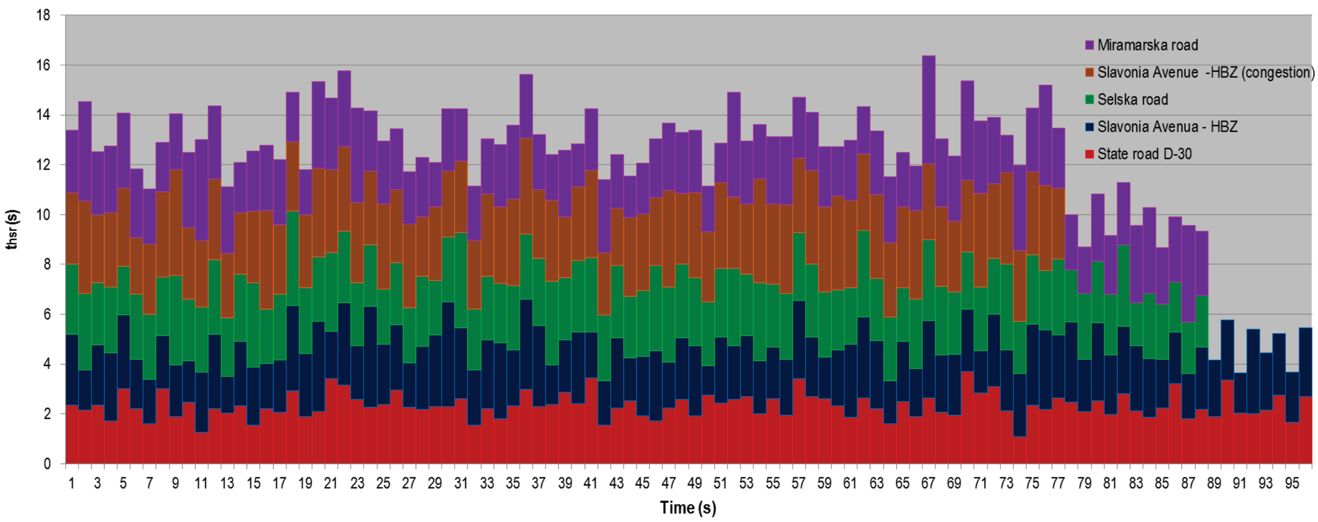

Figure 5 Comparison of determined average values of time headway of vehicle packages for five observed road categories (left lane) (Category 1 – blue, Category 2 – red, Category 3 – green, Category 4 – purple, Category 5 – orange)

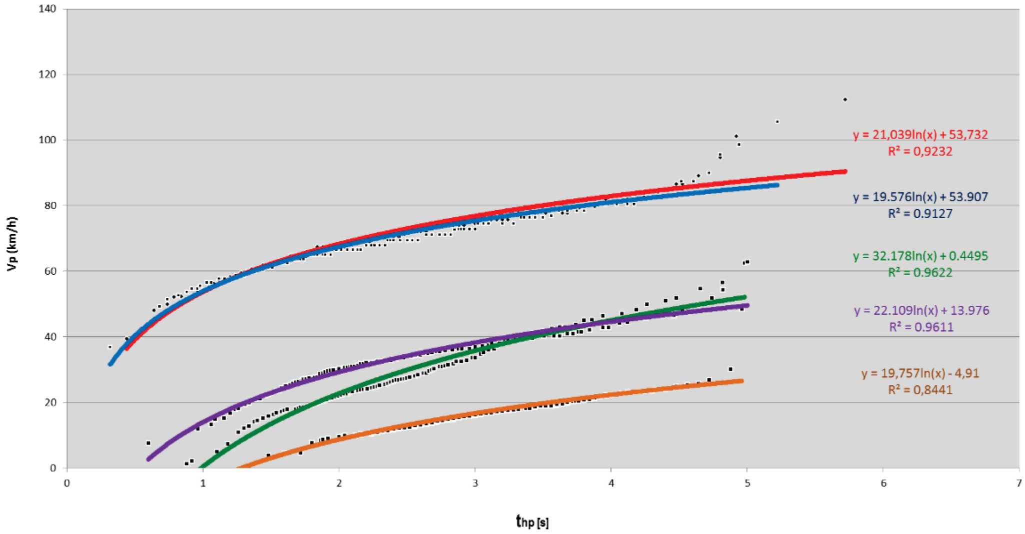

Figure 6 Comparison of determined regression functions for five observed road categories

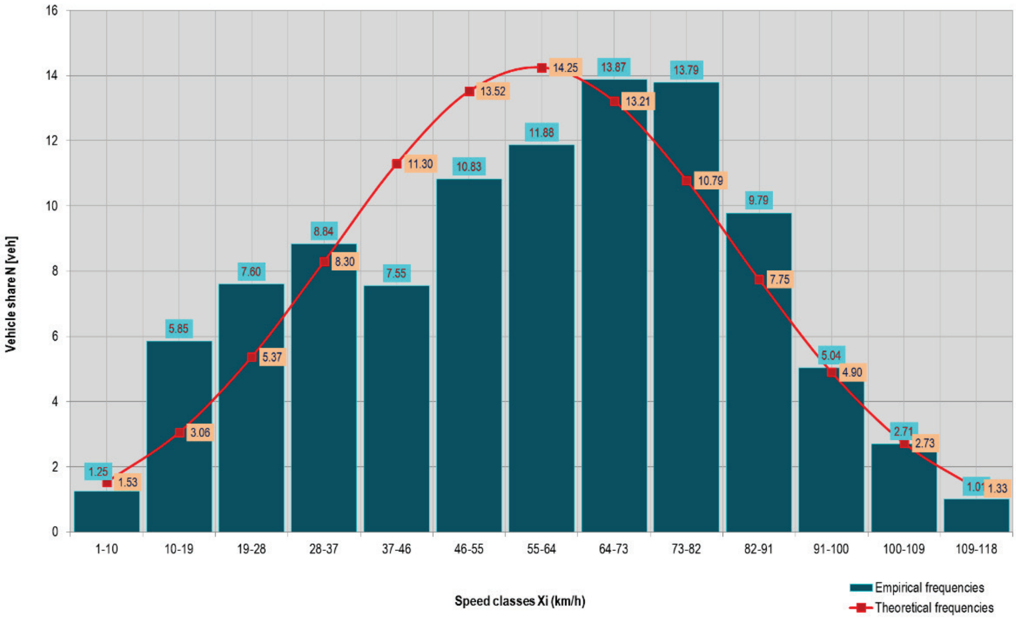

Figure 7 Cumulative curve of percentile speeds and time headways

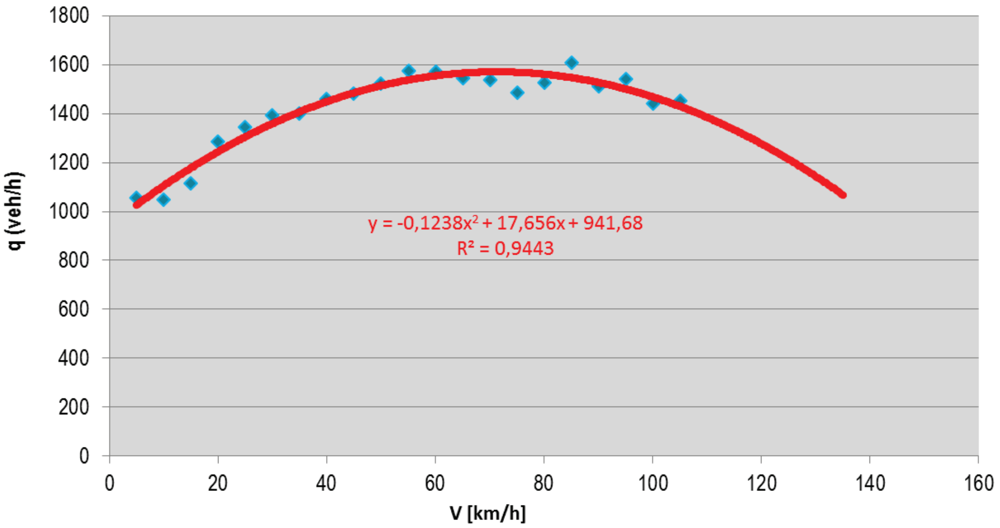

Figure 8 Cumulative empirical flow-speed diagram

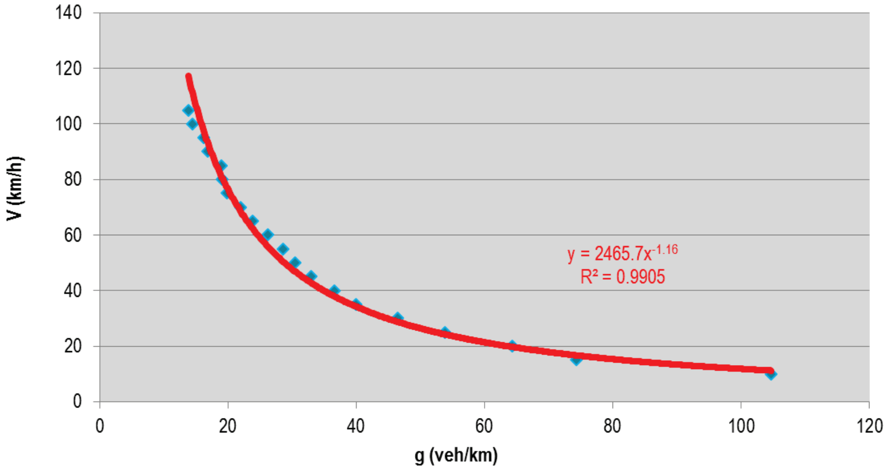

Figure 9 Cumulative empirical speed-density diagram

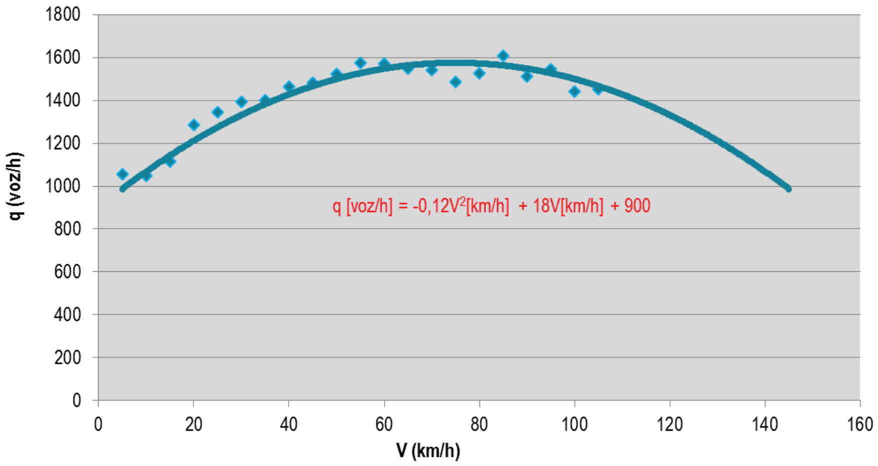

Figure 10 Approximate curve of empirical flow-speed diagram

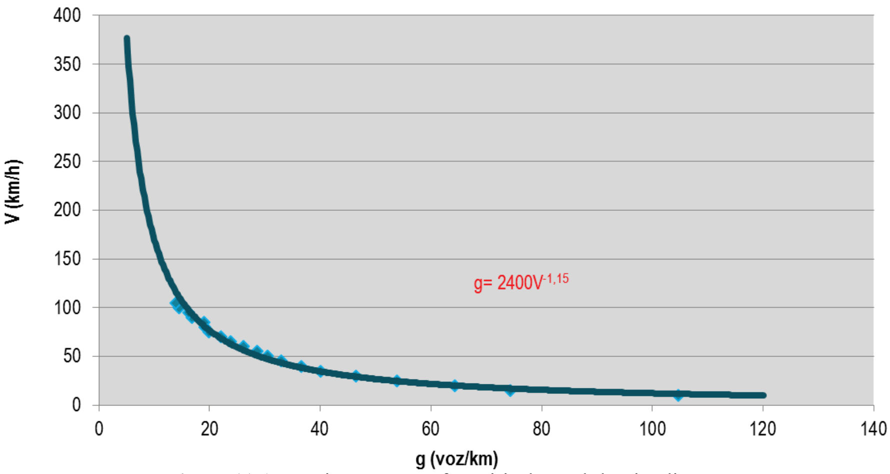

Figure 11 Approximate curve of empirical speed-density diagram

In addition, the mentioned expression of quadratic equation can be used to obtain values for flow speed V (km/h) or density of traffic flow:

$$q = -0{,}12 \cdot V^2 + 18 \cdot V + 900,\ \text{veh/h} \tag{15}$$

$$V_{1,2} = 75 - 4{,}17\sqrt{756 - 0{,}48 \cdot q},\ \text{veh/h} \tag{16}$$

$$g = 2400 \cdot V^{-1{,}15},\ \text{veh/h} \tag{17}$$

Traffic flow speed and capacity can also be expressed in terms of traffic flow density:

$$V^{1{,}15} = \frac{2400}{g},\ \text{km/h} \tag{18}$$

$$V = \left(\frac{2400}{g}\right)^{0{,}87},\ \text{km/h} \tag{19}$$

$$q = -0{,}12 \cdot \left(\frac{2400}{g}\right)^{0{,}7569} + 18 \cdot \left(\frac{2400}{g}\right)^{0{,}87} + 900,\ \text{veh/h} \tag{20}$$

In this way the end expressions derived from research of flows on urban network were developed. By applying these expressions we have developed a new tool for dimensioning of road infrastructure. This in turn makes it easier to choose adequate road elements (number of carriageways, number of traffic lanes, traffic lane width, etc.).

6 Conclusion

The contemporary traffic development has raised the complexity of interaction between traffic branches and intensified the interdependence within the road traffic subsystem, as well as their interaction with the surrounding systems. The complexity of these relationships has led to an urgent need to consider the plans for construction of new roads, establishment of new segments of road system or rehabilitation of existing segments of road system as parts of a comprehensive system and to consider the traffic system as part of a broader economic and social system. This is additionally supported by the fact that significant financial assets need to be invested for construction and betterment of roads and for creation of optimal road network that will satisfy the growing traffic demand.

A misdirected investment decision not only ties the invested funds for a long term, but it also creates a series of negative effects. Each road infrastructure project should therefore be primarily based on arguments important in making investment decisions, regardless whether it is about an individual road or an entire road network. The decision on investment should always be adequately directed in terms of space and timeline.

Evaluation of proposed solutions plays an important role in the process of planning, designing and defining arguments for investments in road infrastructure. This includes the creation of elements for deciding whether and when individual solutions may be implemented. In this context the capacity of the road is a key indicator contributing to rational and prudent policy of planning, construction, maintenance and operation of roads. Road capacity directly affects the choice of plan view and elevation elements of the road and its cross-section, which then significantly affects the external costs in traffic (costs relating to traffic accidents, traffic flow congestion and environmental pollution). Consequently, road capacity is a very significant planning tool for finding adequate criteria that will make it possible to consider the programmed traffic volume and define the optimal peak hour traffic volume relevant for dimensioning of ground plan and elevation road elements.

By conducting research on various urban roads and in various traffic conditions we have obtained basic parameters of traffic flow. We used these parameters to develop diagrams for relations between speed, density and capacity on the road. Based on these diagrams we derived cumulative functions of traffic flow parameters for the entire urban traffic network. This made it possible to develop final equations, which can be used for theoretical determination of road capacity and flow density for the road in any urban road network.

Parameters determined were used for plotting the diagram representing the relationship between speed, density and capacity on analysed roads. The diagram was then used to represent the traffic flow parameters cumulative function on the entire analysed road network. This yielded with the final model that can be used for theoretical determination of the capacity of roads in urban areas. The empirical relationship between speed and density can also be derived from the formulation of the model. It is important to emphasize that the method established herein and the results of this scientific research present a reliable, useful and applicable tool for establishing the capacity of the roads and the values of the relevant coefficients used for dimensioning the cross-section of roads in urban areas, but also on other road categories.

Further research should be directed towards including more road types within different environments and cross-sections in order to gain more detailed relationship between specific conditions in which traffic flow operates and consequential relationship between basic traffic flow characteristics. Automatic counters and measuring tools should be used in order to minimize field work and reduce the measuring error possibility. Automated analysis of traffic flow would enable development of software that could be used for automated computation of road capacity. Once a certain amount of digital recordings of traffic flows has been entered into the database, such software would additionally compute other important parameters relevant for traffic flow modelling.

The methodology applied here is suitable for researching traffic parameters of traffic flows in urban areas. At comparatively low cost it gives results that significantly contribute to designing optimal elements of road infrastructure.

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