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City is a dynamic organism and communication between its parts is provided by a circulatory system – an urban road network. Its proper functioning can be organized only when the road network capacity is sufficient for the traffic value.
Precise assessment of roadway capacity and understanding of its nature are still the actual questions as there are various approaches but a reliable and meaningful estimation method is still not identified for today.
The method based on fundamental diagram and first car-following model allows evaluating the impact of a number of factors on maximum free flow capacity and has been chosen for this purpose. Coefficient of road adhesion φ and driver's perception-reaction time t' are determined as the most influencing factors what gives the directions for the following studies in capacity increase.
The earliest car-following model created a branch of genealogical model tree and is still included in its ancestor versions used in traffic simulation software.

KEYWORDS: degree of influence, factors, maximum free flow (theoretical or design) capacity.

Introduction

How much traffic can the road carry? The answer to this question has been of interest since 1920s when the first studies of road capacity estimation have been conducted (May 1990).

Capacity of facility (HCM 2000) is defined as the maximum hourly rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, traffic and control conditions.

Estimation of capacity is necessary for:

- design of new facilities (number and width determination of lanes);
- identifying the areas with unsatisfactory functioning for new developments;
- evaluation of traffic efficiency;
- choice of traffic regulations and control types;
- assessment of service levels and operational characteristics.

According to V. Babkov (1993), there are two types of capacity:

- maximum theoretical, which is determined for ideal conditions;
- and practical that reflects actual traffic conditions.

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Other classification of capacity was given elsewhere (Minderhoud et al. 1997):

- design capacity is used for planning and designing roads (maximum theoretical as in the classification above);
- strategic capacity as maximum traffic volume a segment can handle, which might be useful for conditions analysis in road networks (its value is derived from capacity distribution);
- operational capacity (actual maximum value) is assumed to be useful in representing the dynamic nature of flow rate in real conditions and in short-term forecasting for determination of traffic control measures.

Due to importance of capacity estimation in roadway design and traffic control different approaches were created. In the study (Minderhoud et al. 1997), these methods were grouped into direct empirical (based on observed headways, volumes, speeds and densities) and indirect empirical (based on guidelines or simulation models) categories. The first category represents the stochastic estimation methods. Guidelines in the second one are based on deterministic approach. As for simulation, the traffic flow models contain deterministic and stochastic levels in its formulae, what makes it closer to real traffic on the roads.

The conservative capacity concept (in guidelines such as HCM 2000; DBN V.2.3-4:2007; DBN V. 2.3-5-2001) is based on free-flow diagram and represents the reasonable expectancy of maximum flow rate at the locations with similar conditions (roadway parameters, traffic volumes and control measures) (Kittelson et al. 2001). In this case capacity is a constant value and its obvious stochastic nature is ignored.

Recent studies (Elefteriadou et al. 2001; 2003; 2006) represented stochastic capacity analysis methods which are based on field observation results and show that freeway capacity is a random variable even under constant roadway conditions. The concept of traffic breakdown probability is used for freeway capacity determination. The maximum observed volume in certain period of time, after which traffic breakdown is observed, is considered to be the capacity of facility. Stochastic methods use the capacity distribution function to calculate the probability of traffic breakdown for different volume represented on the freeway.

Nowadays traffic simulation software is widely used by traffic engineers. It is based on different microscopic car-following models which reflect stead-state and non-steady-state behaviour of traffic flow. Steady-state component mostly determines: desirable speed for different traffic volumes and capacity of facility. The second component describes the traffic behaviour between steady-state conditions applying acceleration and deceleration models (Rakna et al. 2011).

In this study the focus will be on the method which is applied for calculations of the maximum free flow (theoretical or design) capacity of one lane on a uniform segment in Ukraine. It is based on fundamental diagram (the relationship between three variables *q* (traffic volume), space-mean speed *v* and density *k*) and the earliest car-following model (Pipes 1953; Forbes 1958). This approach gives us an opportunity to follow the influence of a number of factors it considers and its routes are tracked in traffic simulation models on the steady-state level.

Methods

The maximum free flow (theoretical or design) capacity per one lane of uniform segment without intersections, on the straight and horizontal section is determined by a formula:

$$P = kv = \frac{3600 \times v}{L}, \quad (1)$$

(passenger cars per hour per lane)

where:

k – is density (pc/km);

v – is design speed of motion (m/s);

L – is conditional value that provides a safe distance, which is enough for complete braking of a car when the ahead going car has stopped (m).

First models based on safe following distance L were proposed by L. A. Pipes (1953) and T. W. Forbes (1958).

This theory is based on the following statements and applies for fairly dense traffic:

- value of the capacity P is calculated in passenger cars, equivalents of which are used to take into account the differences of dynamic size of trucks, buses, RVs and other vehicle types;
- the flow of vehicles is considered uniformly distributed;
- all vehicles move with constant speed $v = const$ without overtaking (Konoplyanko 1991).

Since then scientists proposed the formulae that differ by determination of time interval between the start of braking of two vehicles moving one after another and braking factor c.

As for nowadays application of Pipes-Forbes car-following model, there are several microscopic simulation software in which different steady-state behaviour is identical to it. Among them there are CORSIM (Pitt model; based on vehicle spacing and speed differential between the lead and following car), VISSIM (Wiedemann74 and 99 models, action point or psychological model), Paramics (Fritzsche model, action point or psychological model) and INTEGRATION (Van Aerde model, nonlinear functional form). Detailed study on this topic was done elsewhere (Rakha et al. 2002; 2003; 2011).

For this research the formula of safe distance will be used that is specified in the works of D. Samoilov and E. Dubrovin (Samoilov et al. 1981; Dubrovin et al. 1981):

$$L = l_0 + vt' + \frac{v^2\left(K_r + K_f\right)}{2g\left(f \pm i + f\right)} + l_2 \qquad (2)$$

where:

l_0 – is length of the car, m;

t' – is driver's perception-reaction time of the rear car after the front one starts braking, s;

g – is acceleration due to gravity, m/s^2;

$K_o=K_r+K_f$ – is coefficient of operating braking conditions of rear and front cars introduced by prof. D. Velikanov;

φ – is adhesion coefficient of automobile tire with road surface;

f – is coefficient of rolling resistance for roads with different types of pavement at normal air pressure in a pneumatic tire;

i – is road longitudinal slope;

l_2 – is clearance (reserve safety segment between the cars after their stopping), m.

This method allows us to determine the degree of influence on roadway capacity of such factors as: speed v, longitudinal slope i, coefficient of road adhesion φ, coefficient of rolling resistance f, driver's perception-reaction time t' and clearance l_2.

For this purpose the reference design capacity should be taken under ideal conditions. Its value is calculated by formulae 1, 2 for i=0, t'=1 s, f=0.01 – for asphalt concrete in good condition, φ=0,7 – for dry rough surface, v=60 km/h (16.67 m/s) – design speed for arterial roads in the cities with population in range 100,000 – 250,000 citizens according to Table 7.1 DBN 360-92** (State Construction Standard of Ukraine), l_2 = 2.5 m.

$$P_r = \frac{3600 \times 16,67}{5 + 16,67 \times 1 + \frac{16,67^2 \times 1,2}{2 \times 9,81\left(0,7 + 0,011\right)} + 2,5} = 1248 \ \text{(pc/h/l)} \qquad (3)$$

$$f_v = 0,01[1 + 0,01(60-50)] = 0,011$$

Fig.1

Dependence of capacity *P* from speed *v*

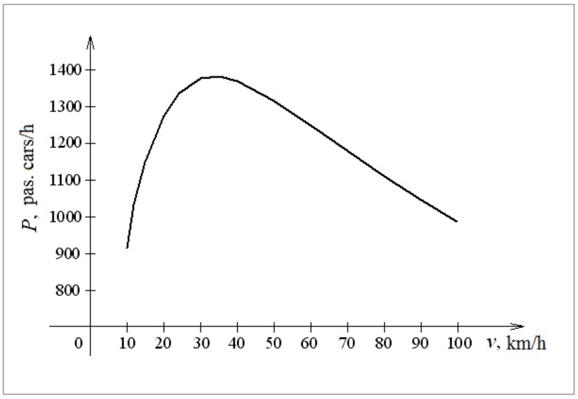


Fig. 2

Dependence of capacity *P* from coefficient of road adhesion *φ*

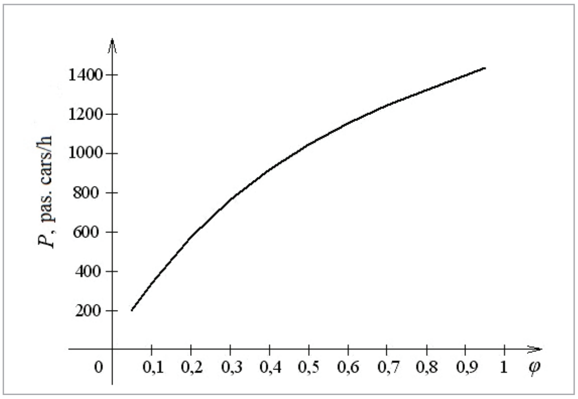


Fig. 3

Dependence of capacity *P* from rolling resistance coefficient *f*

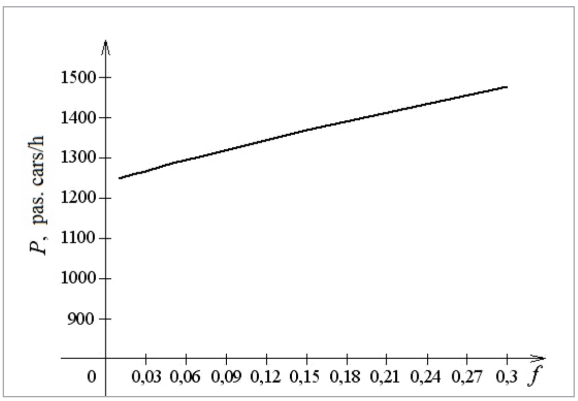
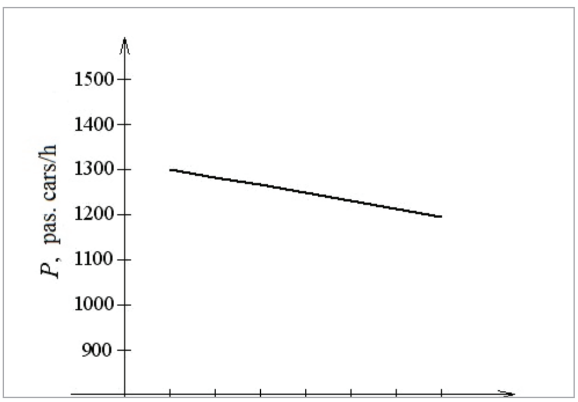


Fig. 4

Dependence of capacity *P* from longitudinal slope coefficient i



- <u>*speed v*</u>. Let us consider how the capacity *P* will be changing with speed *v* in the range from 10 up to 100 km/h. The maximum value of capacity obtained at speed *v*=30 km/h – *P=1376 pc/h*, the minimum one – at *v*=10 km/h – *P=914 pc/h* (Fig. 1).

When the speed exceeds 30 km/h, the capacity begins declining gradually due to a rapid rise of the braking distance *S* length, in the numerator of which formula the speed is squared;

- <u>*coefficient of road adhesion φ*</u>. Let us consider how the capacity *P* will be changing when the ratio of the coefficient of road adhesion *φ* will be in the range from 0.05 up to 0.95. The maximum value is obtained when *φ*=0.95 – *P=1434 pc/h* for dry crushed stone pavement processed by organic binders, the minimum – at *φ*=0.05 – *P=198 pc/h* for pavement covered with ice (Fig. 2).

The capacity increases, when road surface is dry and rough (respectively value of coefficient of road adhesion *φ* rises) and decreases, when it is wet and smooth (values of the coefficient are smaller, since on the surface of a street or a road a film from dust and water is formed, that worsens gripping of wheels of the car to the roadway surface);

- <u>*rolling resistance coefficient f*</u>. Let us consider how the capacity *P* will be changing when rolling resistance coefficient *f* will be in the range from 0.005 up to 0.3. The maximum value is obtained when *f*=0.3 – *P=1476 pc/h*, the minimum – at *f*=0.005 – *P=1244 pc/h* (Fig. 3).

As well as in the case of the coefficient of road adhesion *φ*, increasing of the rolling resistance coefficient *f* leads to an increase in capacity *P* of one traffic lane of the street or road due to reduction of braking distance *S* length;

- <u>*longitudinal slope i*</u>. Let us consider how the capacity *P* will be changing when longitudinal slope *i* will be in the range from 0 up to 60‰. The longitudinal slope has an essential influence on the value of capacity *P*, the maximum value of which is obtained when a slope will be 60 ‰ on the rise – *P=1299 pc/h*, and the minimum value – when 60 ‰ slope – *P=1194 pc/h* (Fig. 4).

So, on the rise, when the value *i* is taken with the sign "+", the capacity increases due to shortening of braking distance *S*. And conversely, on the slope, when the value *i* is taken into account with the sign "-", the capacity decreases.

The influence of driver's psychological features in the formulae for calculation of capacity is taken into account by special coefficients and individual members:

- _driver's perception-reaction time t´._ Let us consider how the capacity *P* will be changing when driver's perception-reaction time *t´* will be in the range from 0.5 up to 2 sec. The maximum value of capacity *P* is obtained when *t´*=0.5 sec. – *P=1510 pc/h,* and the minimum, when *t´*=2 sec. – *P=927 pc/h* (Fig. 5).

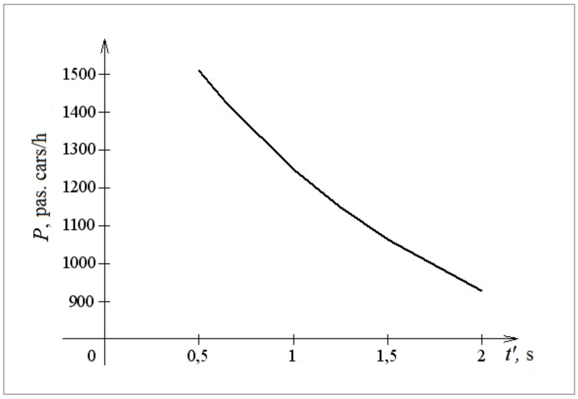


Fig. 5

Dependence of capacity *P* from driver's perception-reaction time *t´*

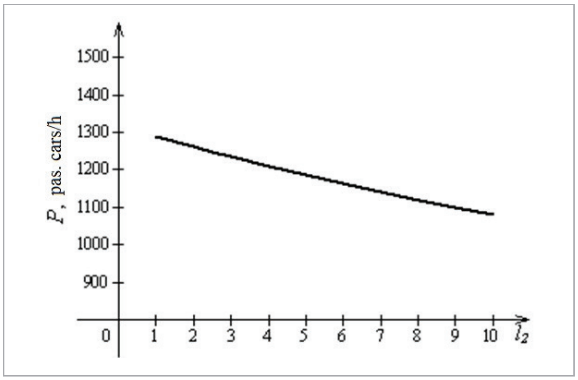


Fig. 6

Dependence of capacity *P* from clearance l_2

When the driver's perception-reaction time increases, the value of capacity *P* is reduced through the increase of the distance length, for which the rear vehicle moves, from the moment of awareness of the need to braking and according to the safe distance *L*.

The driver's perception-reaction time has been a subject of investigations of many scientists. As E. Lobanov (1980) established, the driver's response time varies in different conditions – on the roads with two traffic lanes from 0.4 up to 2.3 sec. and on highways with a distribution zone from 0.5 up to 2.5 sec. Further study and taking into account of drivers' mental and physical qualities will lead to decrease in response time *t´* and, consequently, increase of the capacity *P*;

- _clearance l_2._ Let us consider how the capacity *P* will be changing when reserve safety segment l_2 will be in the range from 1 up to 10 m. The maximum value of capacity *P* is obtained when l_2=1 m – *P=1289 pc/h,* the minimum, when l_2=10 m – *P=1080 pc/h.* (Fig. 6).

When the clearance l_2 length increases, the value of capacity *P* is reduced through the increase of the safety distance value of the vehicle.

For each driver depending on his individual characteristics and qualifications (unless he moves in a column, when all drivers have to go with the common speed of the flow) there is an optimal safety segment, respecting which he confidently drives a car, responding to changing of road conditions in due time (Babkov 1993).

Results and discussion

The obtained values of capacity *P* are compared with the reference theoretical capacity P_r.

In order to determine the degree of influence of each of the factors mentioned above, one shall choose the maximum and minimum values of capacity *P* from the calculated by each of them and write data in Table 1, 2.

Table 1

Degree of influence of road-traffic conditions

Factors	Reference theoretical capacity P_r, *pc/h*	The maximum (minimum) capacity *P* by factor, *pc/h*	Excess, *pc/h*	Degree of influence max (min), *%*	Average value of degree of influence, *%*
Speed *v*	1248	1376 (914)	128 (334)	20 (23)	21.5
Coefficient of road adhesion *φ*	1248	1434 (198)	186 (1050)	28 (73)	50.5
Rolling resistance coefficient *f*	1248	1476 (1244)	288 (4)	44 (0.3)	22.15
Longitudinal slope *i*	1248	1299 (1194)	51 (54)	8 (3.7)	5.85

Table 2

Degree of influence of driver's psychological features

Factors	Reference theoretical capacity P_r, *pc/h*	The maximum (minimum) capacity *P* by factor, *pc/h*	Excess, *pc/h*	Degree of influence, max (min), *%*	Average value of degree of influence, *%*
Driver's perception-reaction time *t'*	1248	1510 (927)	262 (321)	86 (66)	76
Clearance l_2	1248	1289 (1080)	41 (168)	14 (34)	24

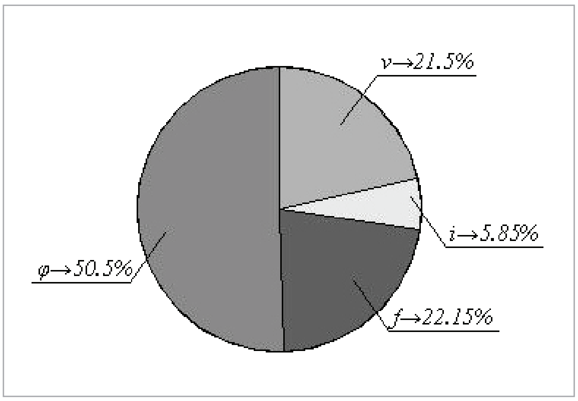


Fig. 7

Degree of influence of speed of motion *v*, longitudinal slope *i*, coefficient of road adhesion *φ*, rolling resistance coefficient *f* on the capacity *P*

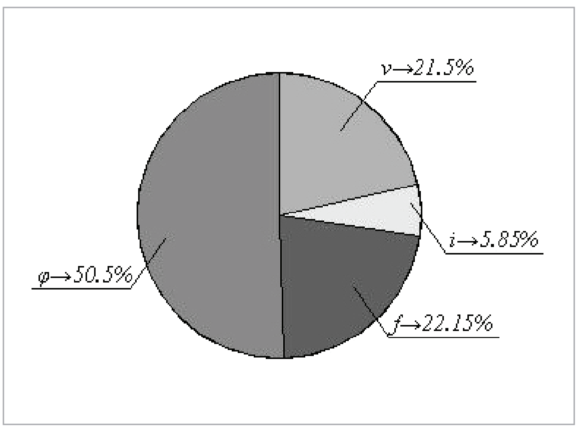


Fig. 8

Degree of influence of driver's perception-reaction time *t'* and clearance l_2 on the capacity *P*

Excess of capacity *P* relative to the reference theoretical carrying capacity P_r is calculated and it is determined for how many % *P* may increase or decrease depending on changes of the values of the speed *v*, the longitudinal slope *i*, the coefficient of road adhesion *φ*, the coefficient of rolling resistance *f*, the driver's perception-reaction time *t'*, the clearance l_2.

Proceeding from **Tables 1, 2** the diagrams are plotted **(Fig. 7, 8)**.

As the diagrams show, the most influence on the value of capacity *P* has the coefficient of road adhesion *φ* and driver's perception-reaction time *t'*.

The adhesion (or friction) between vehicles tyres and road surface (represented in the safe distance formula 2 by the coefficient of road adhesion *φ*) is very important for traffic safety and helps to perform not only the essential braking in case of emergency and under normal circumstances, but also the motion of a vehicle itself. Every driver tries to reach the certain safety level and adapts his behaviour according to the perception of changing friction conditions of road surface (its state of repair, roughness and whether it is wet or not) (Wallman et al. 2001).

Improvement of road surface materials and materials of automobile tyres can provide better friction conditions and safer travels.

While driving a car, the driver uses visual, auditory and kinaesthetic information. But how different drivers will behave at the same situation on the road? This is the most difficult question to answer in transportation studies.

There are two approaches in driver's behaviour research: concentrated on the study of driver's stimuli or driver's reactions. In the first approach the effect of certain pre-selected stimuli is determined on the behaviour of the driver, the second releases stimuli that cause a reaction (Drew 1968).

Driver's reaction approach is represented in formula 2 as perception-reaction time *t'*. One of the first studies says "we drive as we live" (Tillmann et al. 1949), expressing that character and style of behaviour are reflected in our way of driving. But not only this, also gender, age, psychological and health conditions.

The most promising way for decrease of perception-reaction time (and, of course, increase of capacity due to smaller safety gaps) lies in implementation of autonomous cars. This is a fast developing technology, which exists now in the form of prototypes and demonstration systems.

Conclusions

For the assessment of factors influence on free flow capacity the estimation method was used, which is based on fundamental relationship between volume-speed-density and on safe-distance car-following model (Pipes-Forbes model). This method was chosen because of possibility to assess the number of factors presented in its formulae. They were grouped in two categories, which consider:

1. road-traffic conditions (speed v, longitudinal slope i, coefficient of road adhesion φ, coefficient of rolling resistance f);
2. driver's psychological features (driver's perception-reaction time t', clearance l_2).

It was found that in first group the biggest influence on free flow capacity has the coefficient of road adhesion φ (50.5%), in second – driver's perception-reaction time t' (76%).

The result shows that the studies for improvement of traffic conditions on city road network should go in the direction of change for the better of these two factors, which will lead to safer motion and increase of capacity.

The Pipes-Forbes model, which is used for this study, is still applied in CORSIM, VISSIM, Paramics and INTEGRATION traffic simulation software for description of steady-state behaviour of the flow. As it states that flow speed remains the same for different traffic volumes, its modified versions are included along with non-steady-state components.

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