MATEC Web of Conferences **73**, 01010 (2016) DOI: 10.1051/matecconf/20167301010
TPACEE-2016

Development of Criteria for Transport Flow Efficiency Assessments of the City Street Road Network

Oleg Danilov[1,*], *Victor* Kolesov[1] and *Denis* Sorokin[1]

[1]Industrial University of Tyumen, 625001 Volodarskogo str. 38, Tyumen, Russia

Abstract. A mathematical model to quantify the efficiency of traffic flow on the road network was developed. The authors have developed a comprehensive criterion considering key performance indicators: the traffic flow performance, traffic safety, environmental safety.Study of the efficiency criterion is based on the analysis of the traffic flow dynamics. The problem of structural and parametric identification of the mathematical model is complex. The solution to this problem is based on the theory of traffic flow, regression analysis, simulation and dynamic programming.

1 Introduction

Modern research shows that the intensive development of motor transport (MT) is supposed to be both positive and negative nowadays. According to the World Health Organization report, road traffic injuries are the eighth leading cause of death in the world. Besides MT is the basic source of adverse environmental impact.

These problems are especially prevalent in large cities, where traffic jams, road traffic accidents (RTF) and smog have become commonplace. Thus, correct road traffic organization, transport safety and environmental risks management are a priority to improve the life quality of population at any modern city. The evaluation criterion of the traffic control efficiency, including the TF performance, the traffic safety level (traffic safety), environmental risk assessment should be the basic principles of traffic control (TC) of the city road network (MAC).

The evaluation criterion can be formed on the basis of dynamic characteristics of the TP study. Study of the TF dynamics, evaluation criteria development, structure and parameters of the model TS identification is of high priority. The final results will allow to efficiently solve the problems of the functioning processes of the TF optimization.

2 Assessment methodology the TF

---

[*] Corresponding author: tgasu.danilov.oleg@mail.ru

Contemporary approaches, broadly based on the fundamental study of traffic flows [1], indicate that the effective operation of TF is caused by three main indicators, acting as subtest: TF capacity, traffic safety and environmental risk [2].

Let us consider first subtest. TF performance optimization may provide two options. The first one maximizes the TF intensity, and the second one maximizes the TF kinetic energy. In the city it is advisable to use the first approach, since the main problem is overloaded roads. Thus, the first subtest can be written as

$$g_1 = \frac{N}{N_{\max}} \tag{1}$$

where N is the TF intensity, road vehicle units/h; Nmax is the maximum TF intensity, road vehicle units/h .

As for the second subtest, the traffic safety problems solution is the triad "Intensity of TF – the amount of RTA – the amount of victims" analysis. In Scandinavian researchers works [3] it is noted that relative change of road accident amount is linearly connected with relative change of movement intensity

$$\frac{N_{dtp}}{N_{dtp\max}} = k \cdot \frac{N}{N_{\max}} \tag{2}$$

N_{dtp} is the RTF intensity; N_{dtpmax} – maximum RTF intensity; k – constant (k≈0.8)

The transformation (2) allows to obtain the expression

$$N_{dtp} = \frac{N_{dtp\max} \cdot k}{N_{\max}} \cdot N \tag{3}$$

With this assumption the intensity of the RTF can be interpreted as

$$N_{dtp}(q) = N(q) \cdot RP \tag{4}$$

N(q) is the TF intensity as its density function; RP is the risk of accidents

Inhere it is assumed that the analyzed time interval (for example, year) RP is a fixed value.

The amount of people injured in RTF depends on the risk (probability) of injury (P). Considering the injury rate intensity, it should be noted that the risk is the same both for the driver and for passengers of the vehicle. The data on the probability of the driver's injury due to the driver's vehicle speed at the time of the RTF are given in [4].

The data processing showed that P (V) corresponds to the Weibull law (R2 = 0.99). At the same time, it should be taken into account that among the victims there is a significant proportion of pedestrians. The likelihood of pedestrians injury has been discussed in the report [5]. Identification of model Pped (V) showed that it complies with Weibull law (R2 = 0.93).

The resulting probability should be considered as a weighted sum of P (V) and Pped (V)

$$P(V) = (1-s) \cdot P(V) + s \cdot P_{ped}(V) \tag{5}$$

s - the proportion of injured pedestrians in the overall balance.

The results are shown in Fig. 1. Thus, knowing the speed of the TF connection with its density, it is possible to determine the function P (q).

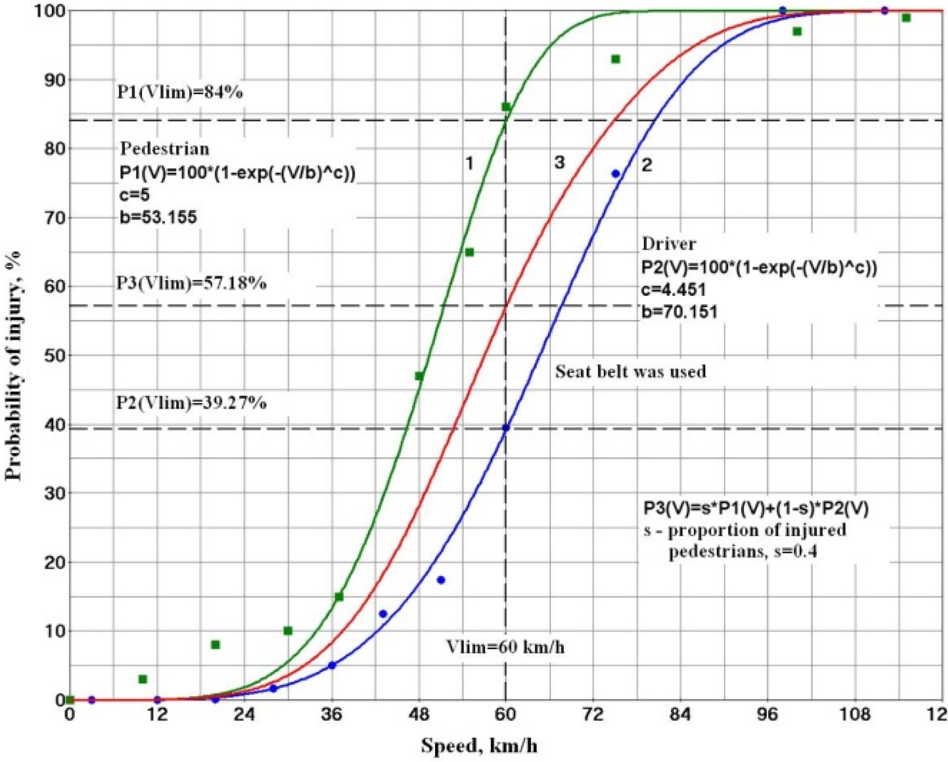


Fig. 1. The probability of injury of RTF participants.

The conditions under which the RTF intensity extremum of involving injury rate (Ntr) is achieved are of most interest. Such RTF include the larger or equal to one quantity of injured people. Intuitively it is clear that the function Ntr(q) is caused by two main indicators: the of the accident (Ndtp) intensity and the risk of injury in case of RTF P(q). This function then can be written in the form of

$$N_{tr}(q) = N_{dtp}(q) \cdot P(q) = RP \cdot N(q) \cdot P(q) \tag{6}$$

It is important to note that the maximum injury rate (Ntrmax) should be achieved in free movement of TF corresponding to high speeds.

Thus, the second subtest is determined by the injury rate intensity, the growth of which reduces the TF efficiency, therefore, it can be represented in the form of

$$g_2 = 1 - \frac{N_{tr}}{N_{tr\max}} \tag{7}$$

Let us consider the third subtest. When assessing the environmental risk level generated by urban TF, the approach established in the works [6, 7] is used. These works proved the linear relationship between the concentration of pollutants in the surface layer and TF capacity, ie the product of the TF intensity on its density

$$C_{bb} = k \cdot e \tag{8}$$

where Cbb is concentration of harmful substances in a ground layer of the atmosphere; k is the coefficient depending on average running emission of the vehicle and average speed of a wind stream; e is TF capacity($e = N \cdot q$).

We assume that the environmental risk is proportional to the parameter Cbb, and hence the TF capacity, then the third subtest can be logically written in the form of

$$g_3 = 1 - \frac{e}{e_{\max}} \tag{9}$$

In this case, it is a necessary to identify extrema emax and analyze its dependence on the TF operating conditions.

When assessing the TF efficiency the form of its representation (additive or multiplicative) should be pre-engaged.

Multiplicative assessment, by definition, is equal to zero if at least one of the subtests is zero, but it is hardly consistent with actual practice, therefore, the additive generalized assessment representing the weighed sum of subtests has been chosen. In this case, there is an opportunity either to minimize the negative effect generated by risks or to maximize an advantage due to their decrease. Thus, the criterion function (CF) should be presented in the form of

$$Eff = \sum_{i=1}^{n} \alpha_i \cdot g_i \Rightarrow \max \tag{10}$$

where ai is weight coefficients corresponding to the condition $\sum_{i=1}^{n} \alpha_i = 1$; g_i is a subtest

Formation of subtests is impossible without use of the TF adequate mathematical models allowing to define and to predict TF dynamics of characteristics. Such a model has to consider specifics of functioning of TF in various conditions. Authors have developed a mathematical model of TF dynamics for speed limit [8, 10, 11]. The model is based on longitudinal dynamic dimension of safe driving. The coefficients of the above have been considered by the authors in detail in work (Danilov, etc., 2014).

In work [8] the alternative model of continuous TF allowing to trace dynamics of TF characteristics in the vehicle speed limit for a rather low density has been offered. TF speed - density relationship has a form of [9].

$$V_l(q) = V_{\lim} - K_l \cdot q^2 \tag{11}$$

where Vlim is maximum speed with the limit, km/h; Kl is constant.

When studying TF dynamics in the city it is necessary to consider discrete movement in time. The flow is split internally into groups of cars. Each separate group is formed at the enabling signal of the traffic light which operating mode defines the amount of cars in group. Thus, on roads with the adjustable movement it is advisable to investigate TF dynamics by means of average dynamic characteristics (for a certain period).

Thus, it is advisable to study TF dynamics on roads with traffic control by means of average dynamic characteristics (for a certain period). In this case TF parameters values will be much lower, than in model of continuous TF.

Adaptation of a ratio (11) to city traffic makes it possible to form

$$V(q) = V_{\lim E} - K_E \cdot q^2 \tag{12}$$

where VlimE is the average maximum speed of the TF in a flow; KE is the coefficient considering traffic conditions.

The VlimE parameter is caused by drivers psychology. Theoretically VlimE value has to be equal to speed limit on the studied stage (Vlim), however part of drivers deliberately underreport the speed (VlimE<Vlim), and others exaggerate it (VlimE>Vlim). In the first case the driver *obviously* opts for a more comfortable speed and in the second one he/she violates traffic regulations which extremely negatively affects traffic safety.

The parameter KE should take into account the road surface, its condition, the flow pattern, the conditions of the traffic light regulation and other hindrances.

The first three factors account for the ratio DG m2 [11], and the rest should be described by the empirical laws obtained at TF monitoring in different parts of the Street-road network. Then, the coefficient KE is represented in the form of

$$K_E = F(m_2, K_{sv}, K_{pr}) \tag{13}$$

where Ksv is the coefficient considering an operating mode of the nearest traffic light and distance to it; Kpr is the coefficient considering other factors (the crosswalk, the likelihood of the pedestrian and others).

3 Results

To assess the developed models pilot studies of the TA dynamics in the city of Tyumen have been conducted. a section of Respubliki Street (the area of crossing with Permyakov Street) and a section of Melnikayte Street (the area of crossing with Kotovskogo Street) were investigated as the Street-road network elements. On the chosen sections, 2 one direction lanes have been explored. The database for pilot studies has been received by means of the Traffic-Monitor complex developed by scientific and technological center "Module".

The integral condition of an objective assessment of the TF parameters under studies is collecting sufficient volume of information. Therefore experimental study sample representativeness is significant. At the first stage, histograms of empirical distribution of speed values of the TF have been constructed at various TF density. The analysis of data for two sections (Melnikayte St., Respubliki St.) has shown that the speeds distributions are bimodal. It is obvious that the "peak" of low speeds is caused by higher density of a flow, and the "peak" of high speeds is caused by lower density respectively, which gives a driver a big freedom of choice.

The analysis has shown that distributions of speeds should be considered in two intervals: 0<V<25 km/h and 25<V<65 km/h. Herein in both intervals distributions obey the normal law. Thus it is advisable to study great values of speeds as the error of measurements will be higher: the detector has to record the TF parameters and software process for a smaller period.

Further studies have shown that speeds distributions in the range of 25<V<65 km/h are approximated by the normal law of distribution with an average quadratic deviation of 7.2 km/h. The empirical histogram is illustrated by Fig. 2.

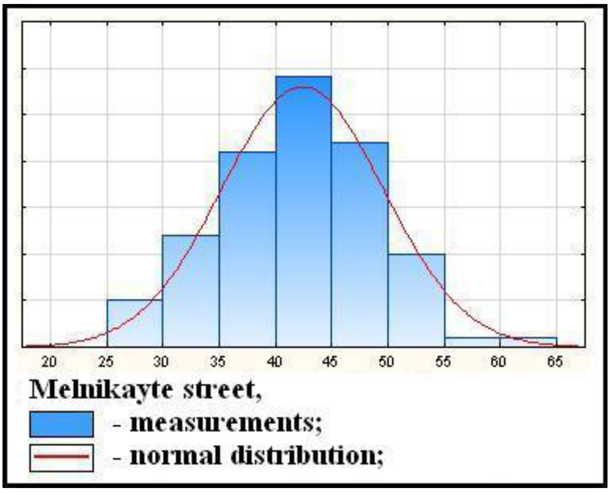


Fig. 2. Histogram of distribution of speeds of the vehicle.

To justify the necessary amount of measurements Student distribution is used at which, having provided the level of confidential probability, it is possible to determine the necessary volume of measurements of n. In Fig. 3 dependence of n from σ for the level of confidential probability 0.9 (at various values of accuracy of measurements Δ) is given. In experimental studies, the value of an average quadratic speed deviation is 7.2 km/h. Accepting the accuracy of measurements Δ=1 km/h, it is possible to claim that the volume of speed selection doesn't exceed 143 values.

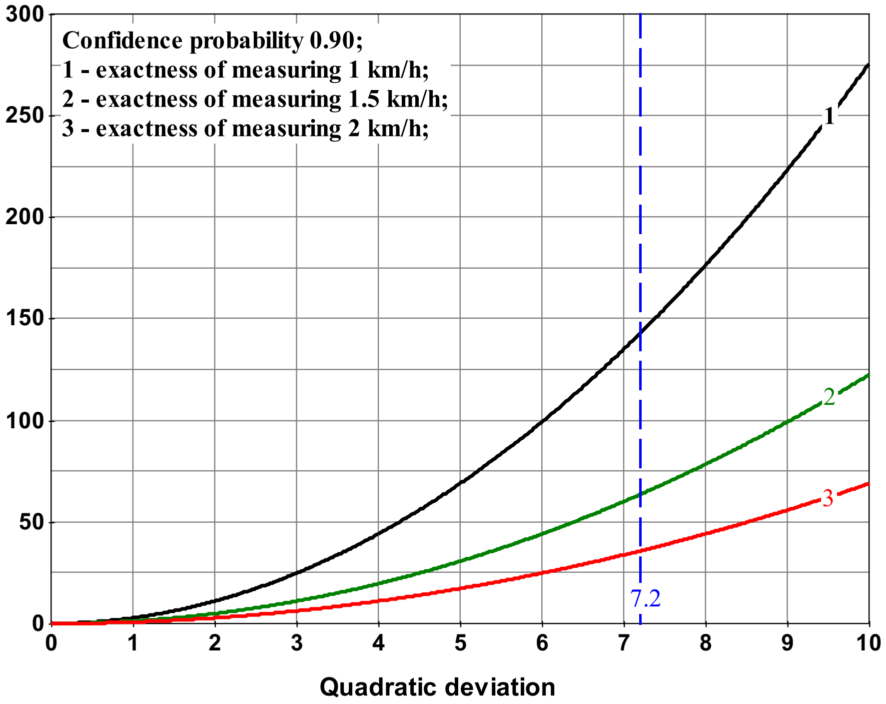
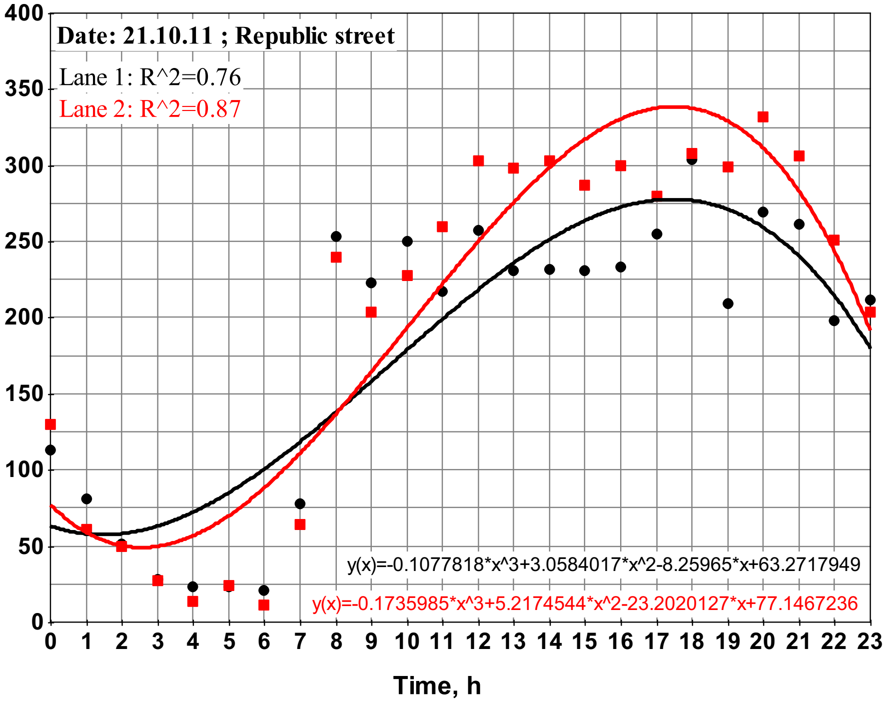


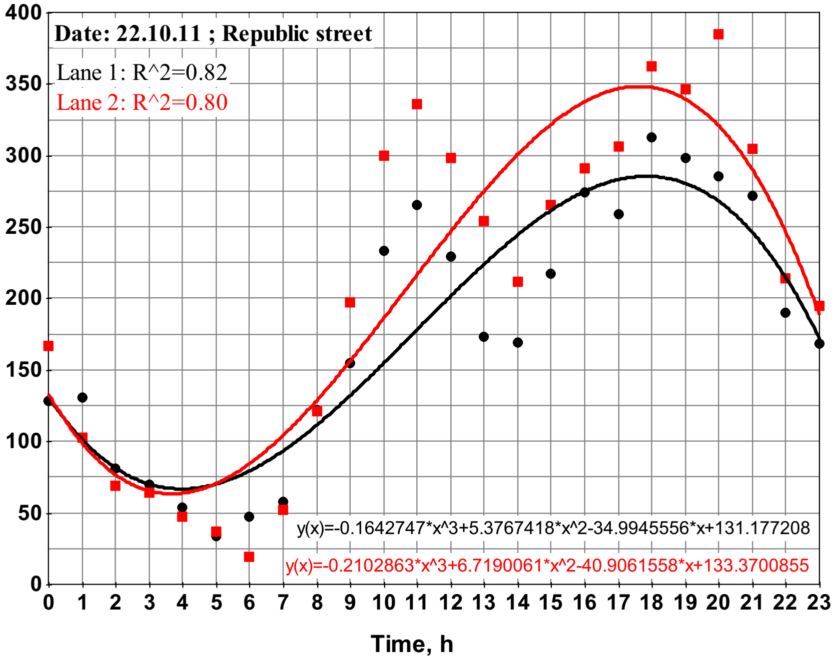
Fig. 3. Definition of necessary amount of speed measurements.

Fig. 4-5 show dependences of intensity of TF on daytime. Experimental data are well described by polynomial regression (with order of n=3, R2>0.75).

a)



b)



c)

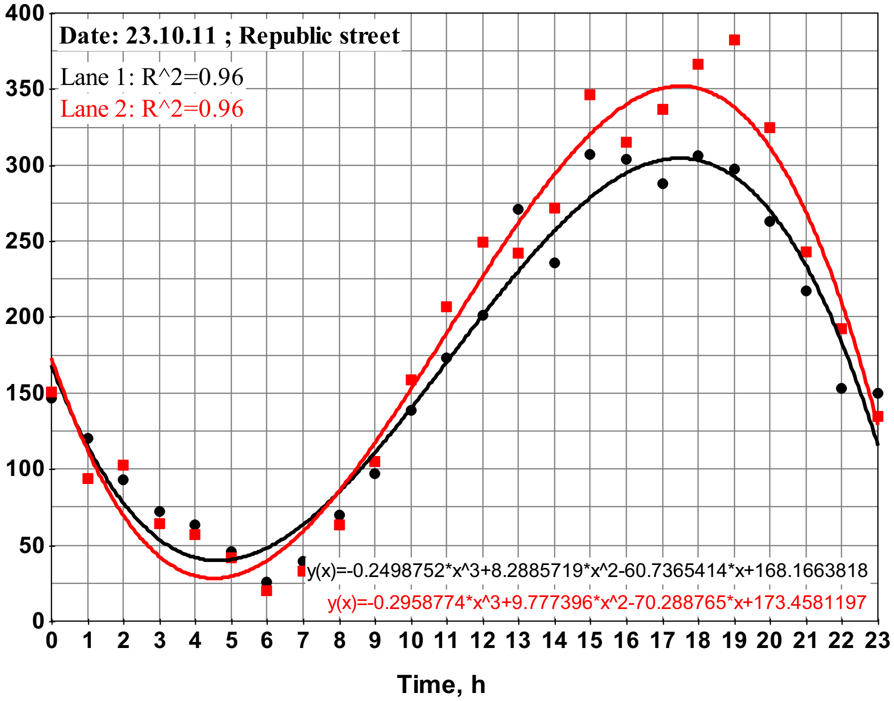
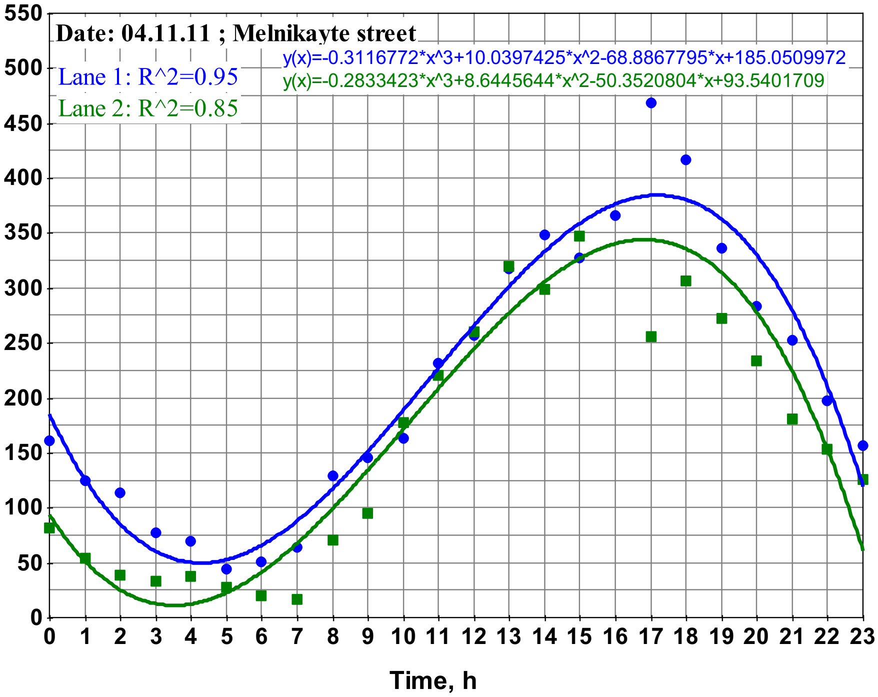
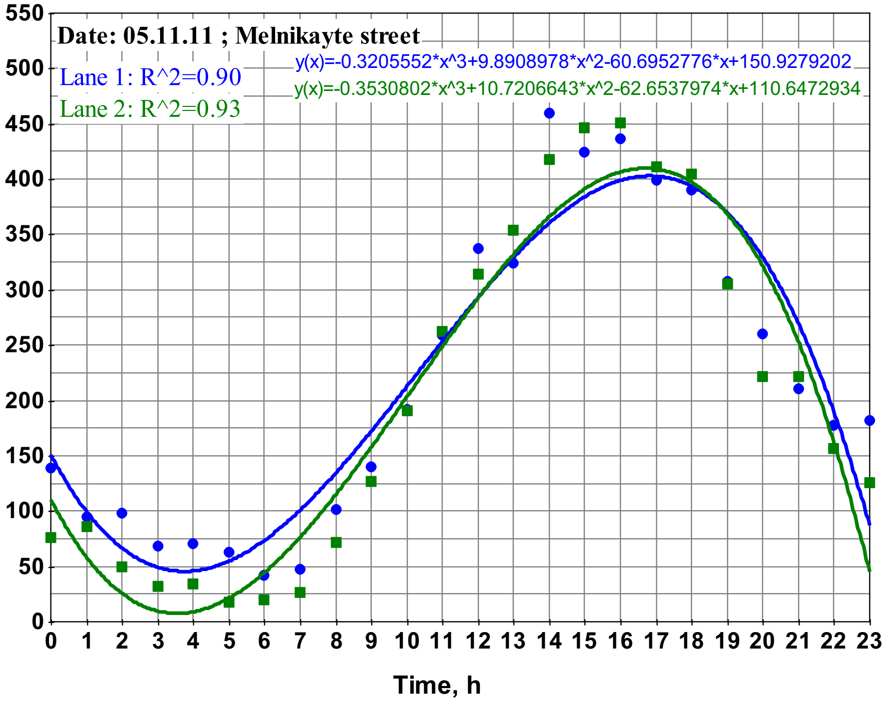


Fig. 4. a), b), c) Dependence of N(t) (Respubliki St.).

a)



b)



c)

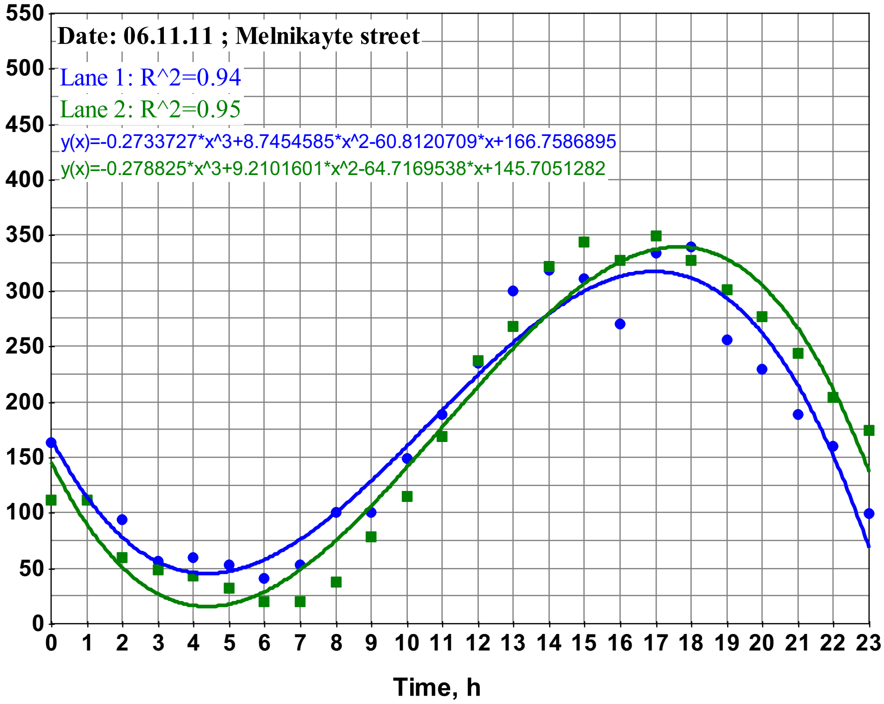
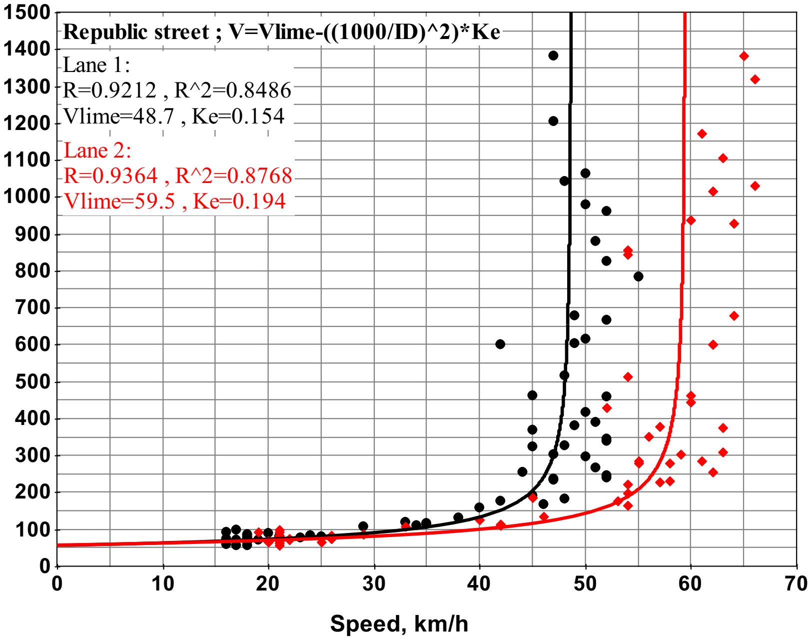


Fig. 5. a), b), c) Dependence of N(t) (Melnikayte St.).

The analysis of Fig. 4-5 suggests that the form of the line N(t) is stable and has both a minimum and a maximum. Thus, the average dynamic TF characteristics vary cyclically with time, obeying similar laws, both on different lanes and at different stages of Street-road network. Approximation of dynamic characteristics interrelations of a real flow provides search of two parameters: VlimE and KE. At the same time, the regression equations have to correspond to the developed models. For automation of the regression analysis, the method of nonlinear assessment of a software package "STATISTICA" has been applied. This method is the universal approximating procedure assessing any kind of dependence between "a response variable" and a set of independent variables. The regression equation corresponding to the developed theoretical models TF dynamics has been put in the program. Theoretical model adequacy is assessed by multiple coefficient of correlation which characterizes narrowness of correlation communication between variables. Fig. 6 illustrates dependences of an average movement interval (ID) on vehicle speed for Respubliki street and Melnikayte street. For Respubliki St. R12=0.85, VlimE1=48.7, KE1=0.154 and R22=0.88, VlimE2=59.5, KE2=0.194 for the first and second lanes respectively, for Melnikayte St. R12=0.71, VlimE1=46.0, KE1=0.068, R22=0.66, VlimE2=52.2, KE2=0.084, with the level of confidential probability 0.95. Actually, ID values are exaggerated because of cyclic stops of cars flow (influence of traffic light regulation). Time of functioning of the main TF part depends on operating mode of the next traffic light.

On the other hand, some drivers keep the greater distance from the vehicle ahead than the theoretical value of confidence limit instructs. There's a simple explanation to it: the driver consciously chooses a greater range of motion. Thus, the regression curve passes through the "cloud" of empirical data and asymptotically tends to the average value of the maximum speed (VlimE) developed in the flow. It is important to note that the values of the coefficient KE for the studied stretch is different for each of the lanes, which indicates the heterogeneous structure of the TF within the considered area of Street-road network. While the KE can vary greatly for the different spans that are caused by the difference in traffic.

a)



b)

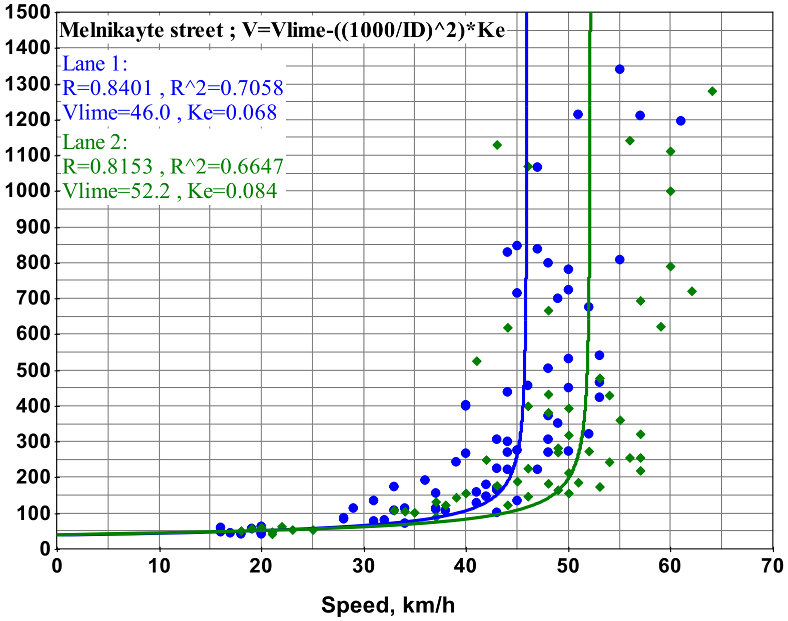


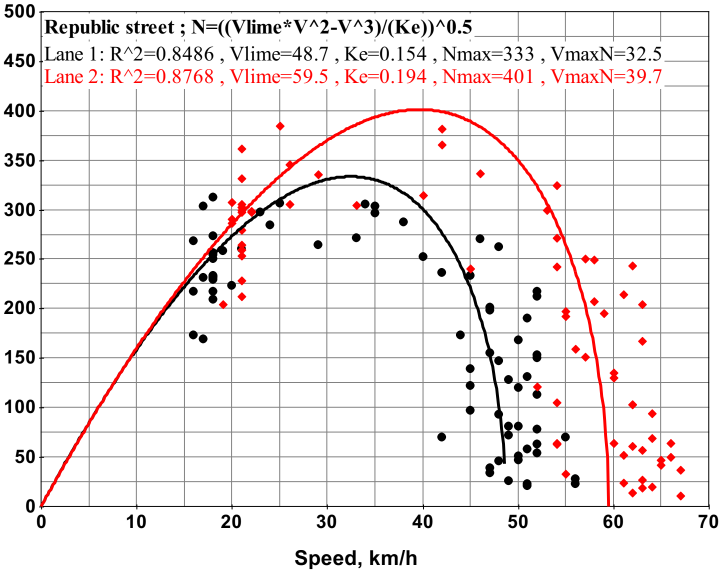
Fig. 6. a), b) Dependence of ID(V).

Fig. 7 illustrates experimental data of traffic intensity from vehicle speed for Respubiliki and Melnikayte streets. Inhere data are approximated by alternative model

$$N(V)=\sqrt{\frac{V_{\lim E}\cdot V^{2}-V^{3}}{K_{E}}} \tag{14}$$

It is obvious that the extremum of intensity can be reached both at rather high speed of the movement (35-45 km/h), and at low (15-25 km/h).

a)



b)

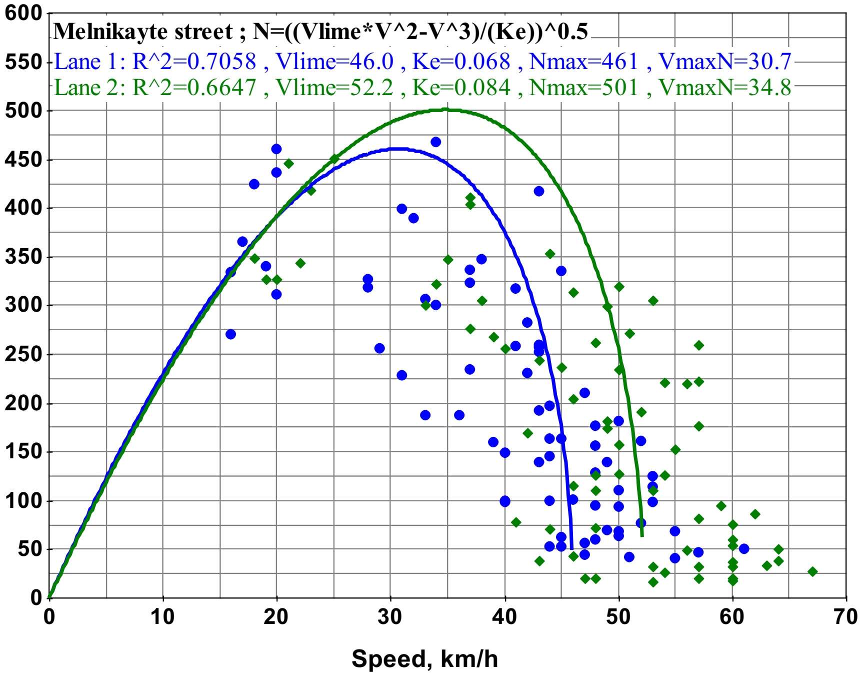


Fig. 7. a), b) Dependence N (V).

To explain this phenomenon, it is necessary to analyze the psychology of the driver at various vehicle speeds. At low speeds the driver obviously keeps lower distance from the vehicle ahead than at high values of V (Fig. 6) as this situation is perceived as safer. Then the average flow density becomes higher than the regression curve directs, whereby the intensity of the movement increases. In the second case (high speed), the situation is more adverse from the traffic safety view point and the driver prefers to keep a longer distance to vehicle ahead, which leads to some decrease of average density. For Respubliki street Nmax1=333 vehicle units/h, VmaxN1=32.5 km/h (first lane) and Nmax2=401 vehicle units/h, VmaxN2=39.7 km/h (second lane). For the Melnikayte street Nmax1=461 vehicle units/h, VmaxN =30.7 km/h, Nmax2=501vehicle units/h, VmaxN2=34.8 km/h. The obtained results allow to assess the first and second subtests of TF efficiency.

Capacity dependences on TF speed have been studied to analyze the third subtest. The greatest capacity values are reached at speeds of 15-30 km/h. For Respubliki street Vmaxe1=24.4 km/h, Vmaxe2=29.8 of km/h. For Melnikayte street Vmaxe1=23.0 km/h, Vmaxe2=26.1 of km/h. Thus, research of real dynamic characteristics of TA creates prerequisites for the analysis of criterion of their efficiency. For an assessment of weight coefficients the following priorities have been placed: a1=0.65, a2=0.28, a3=0.07.

Fig. 8 shows the dependence schedule of Eff (V) created on the basis of average dynamic characteristics models of TF. Maximum efficiency for the front lane (Respubliki St.) makes Effmax1=0.870 (this extremum is expected at a speed of a flow of VmaxEff1=28 of km/h). For the second lane these parameters are Effmax2=0.861, VmaxEff2=33 of km/h. respectively. Parameters for Melnikayte st. are Effmax1=0.871, VmaxEff1=26 km/h, Effmax2=0.868, VmaxEff2=30 km/h. The analysis of fig. 8 allows to claim that flow speed increase in the range VmaxEff<V<Vlim leads to efficiency of his work decrease.

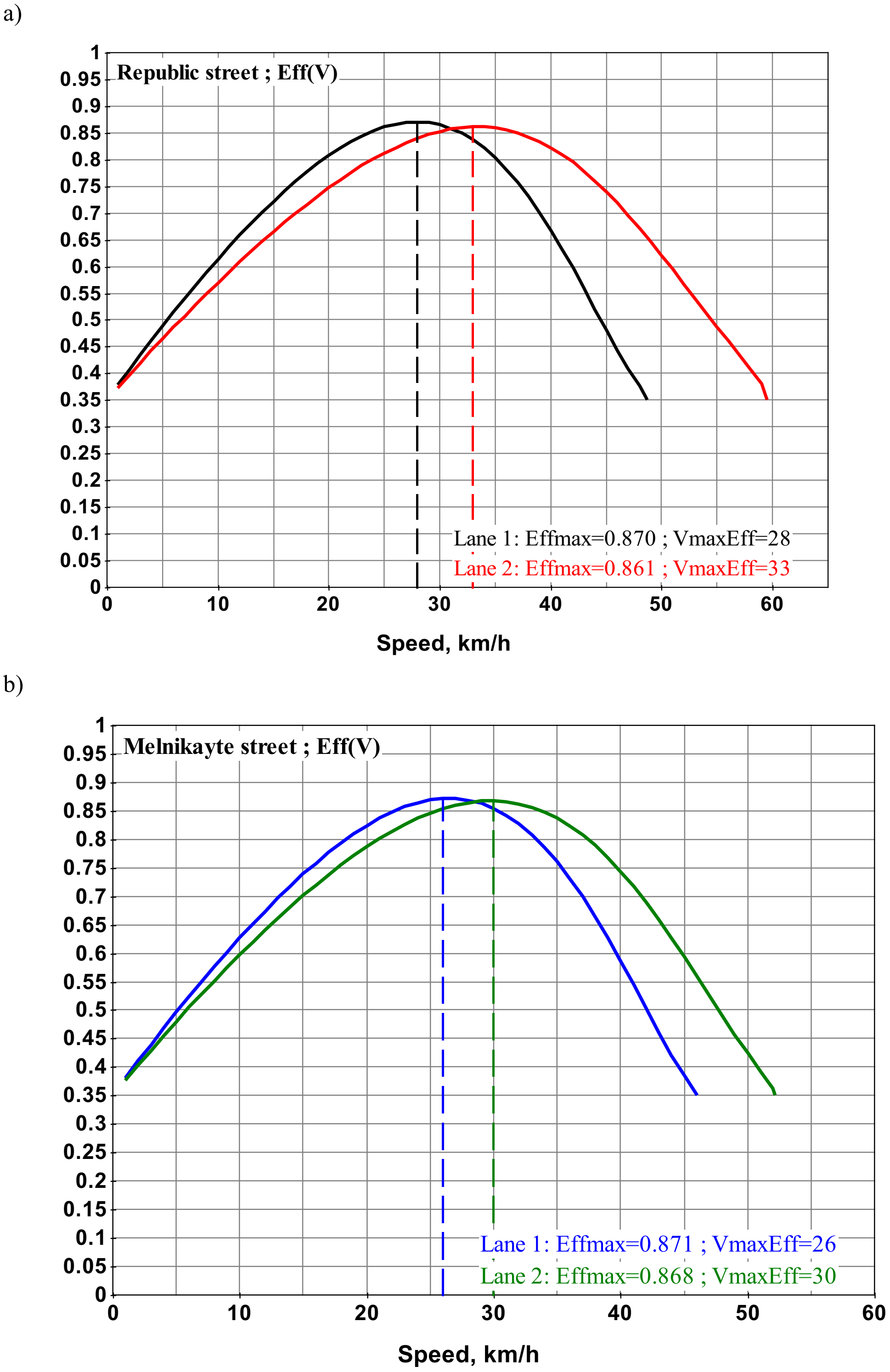
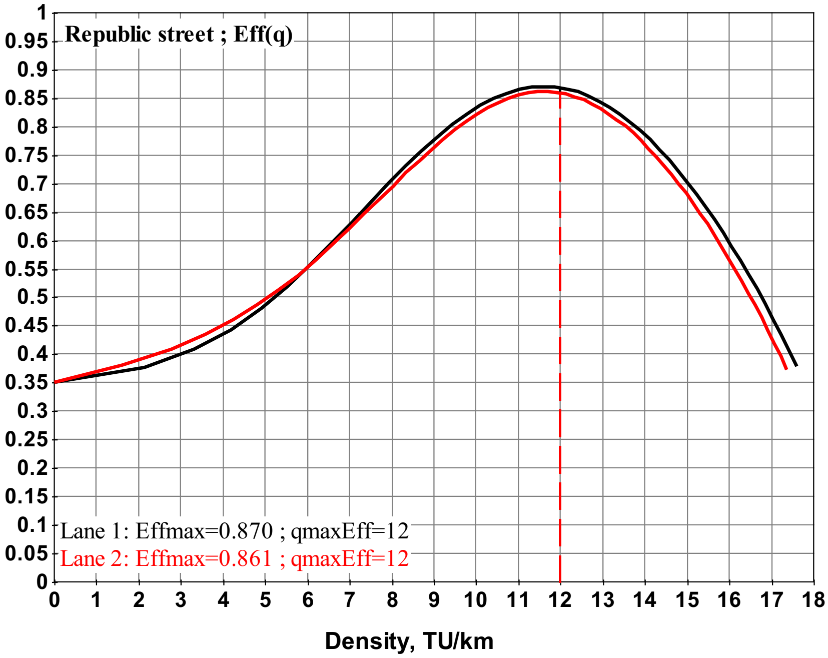


Fig. 8. a), b) Dependence Eff (V).

Fig. 9 illustrates dependence of efficiency on the TF density. Settings for the Respubliki street: qmaxEff1=12 vehicle units/ km, qmaxEff2=12 vehicle units/km. The parameters for the Melnikaite street.: qmaxEff1=17 = 17 vehicle units/ km, qmaxEff2=16 vehicle units/ km.

a)



b)

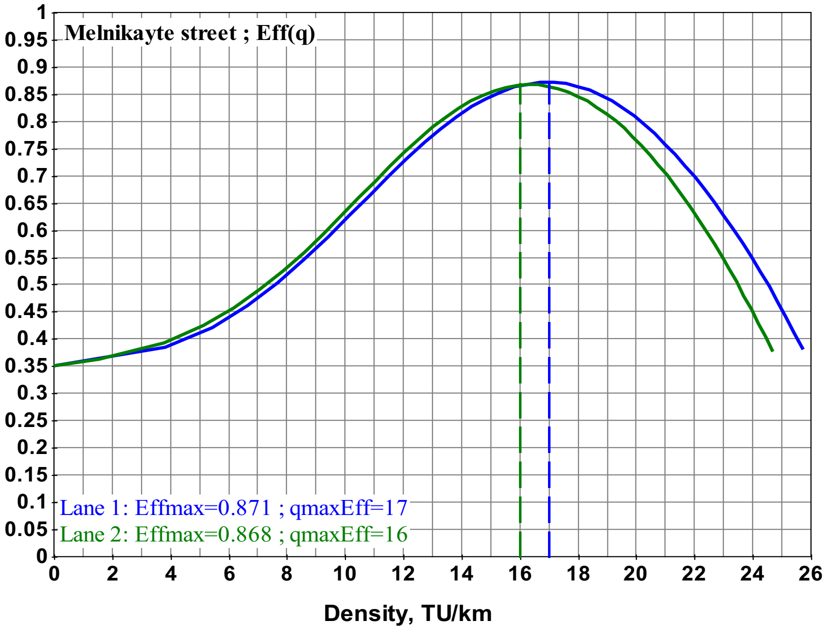


Fig. 9. a), b) Dependence Eff(q).

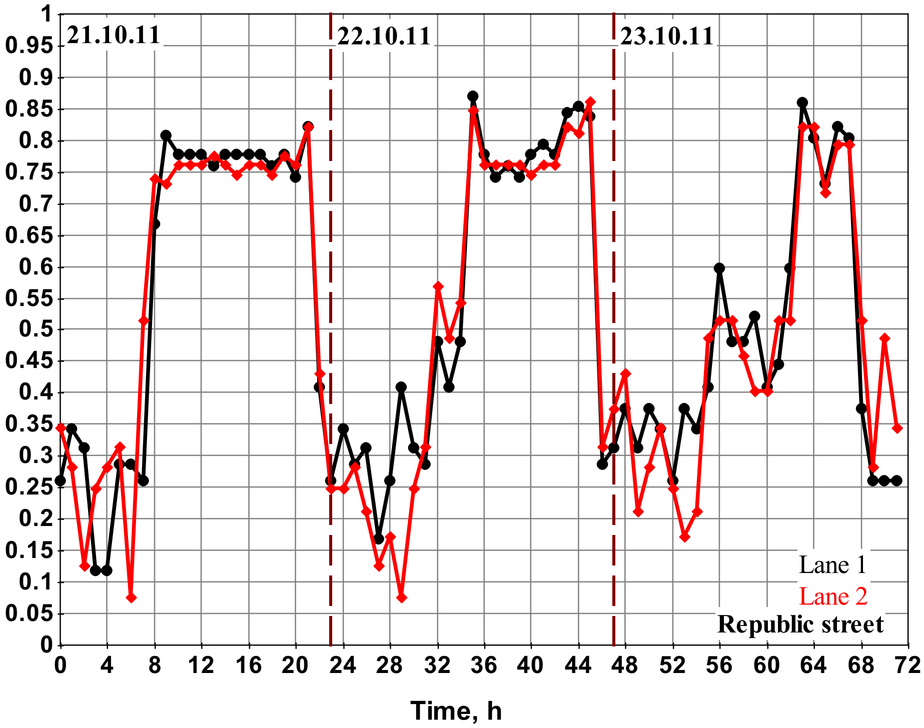
The analysis of fig. 9 allows to determine the optimum TF density at which maximum efficiency is achieved. However, it is difficult to operate the flow density, as it demands traffic reorganization. It is important to note that the real flow can have three operating modes depending on the actual average density. The first mode provides a flow with its optimum density ($q=q_{max}Eff$).

The second mode is caused by efficiency decrease (Eff<Effmax) due to reduction of actual density (q<qmaxEff). Inhere it is possible to say that the resource of a lane is used incompletely.

The third mode is caused by efficiency decrease due to the density increase ($q>q_{max}Eff$). This situation is most negative as the lane becomes too "overloaded" with cars. Dependences of performance criteria on time are of the greatest value.

Fig. 10 illustrates values of performance criteria within 72 hours for Respubliki and Melnikayte streets respectively (average value in one hour of a flow functioning).

a)



b)

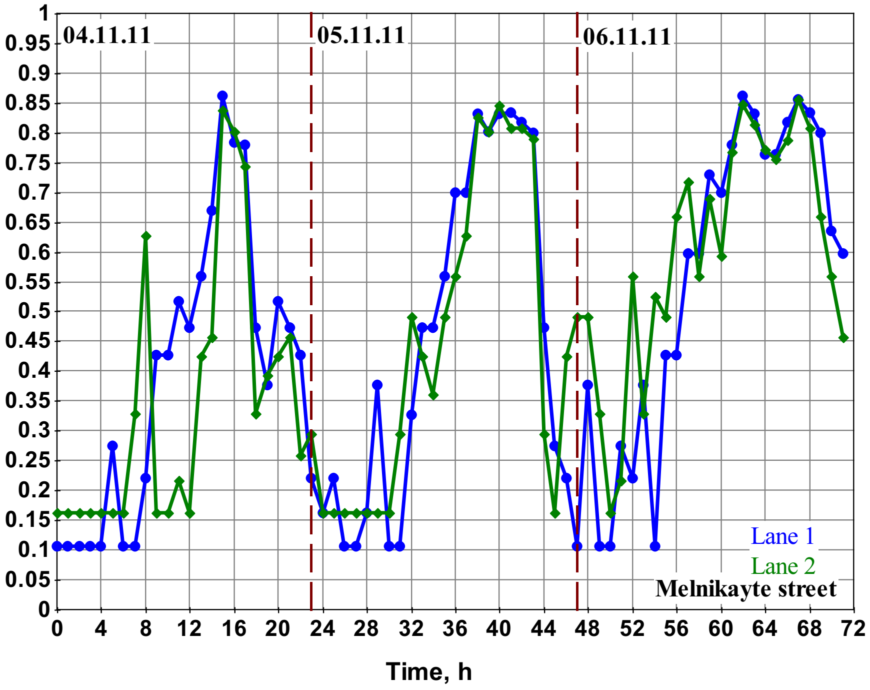


Fig. 10. a), b) Dependence Eff(t).

It is important to note that the chronology of overall any TF performance is caused by two major factors. First, the criterion of Eff significantly depends on dynamics of the flow under study therefore at an initial analysis stage dependences of dynamic characteristics on time have to be known. Secondly, the form of curves of Eff (V) (fig. 8) and Eff(q) (fig. 9) is very sensitive to scales of efficiency subtests (a1, a2, a3).

4 Conclusion

Worldwide researchers have conducted numerous studies of functioning processes of motor transportation flows. Optimization of TF productivity, traffic safety and environmental risks are key tasks against growth of a motor transport role in region the and country economic capacity formation. The results of studies received by authors allow to estimate in a complex the overall TF performance taking into account key efficiency indicators, to mode optimum operating conditions of TF, to develop a program maximizing the subtest taking into account specifics of Street-road network under analyses [11, 12, 13]. All mathematical models have been tested [14]. The program "Effective Transport Stream" allowing to apply various production scenarios on modeling TF dynamics and an assessment of efficiency of its work has been developed.

References

1. D. Drju, *Teorija transportnyh potokov i upravlenie imi* (Transport,Moscow,1972)

2. V. Kolesov, *Transportnye i transportno-tehnologicheskie sistemy. Materialy Mezhdunarodnoj NTK*, 94-103 (2014)
3. R. Jel'vik, B. Anne, V. Trule, Spravochnik po bezopasnosti dorozhnogo dvizhenija: per. s norv. IJeT Norvegii, MADI (GTU), Sovet ministrov severnyh stran. Oslo, Moscow, Hel'sink, 746 (2001)
4. V. Krutov, *Osnovy nauchnyh issledovanij: uchebnik dlja tehnicheskih vuzov* (Vysshaja shkola, Moscow, 1989)
5. Vsemirnyj doklad o preduprezhdenii dorozhno-transportnogo travmatizma: perevod s anglijskogo, Ves' Mir», Moscow (2004)
6. V. Zhdanov, Metod ocenki tehnogennoj opasnosti transportnyh potokov na ulichno-dorozhnoj seti goroda. Avtoreferat dissertacii na soiskanie uchenoj stepeni kandidata tehnicheskih nauk. MADI (Moskovskij Avtomobil'no-Dorozhnyj Institut), Moscow, (2008)
7. V. Zhdanov, *Sovershenstvovanie metodov rascheta jekologicheskih harakteristik gorodskih transportnyh makroistochnikov* (Mashinostroenie, Moscow, 2010)
8. V. Kolesov, D. Sorokin, M. Guljaev, **5**, 89-95 (2012)
9. V. Kolesov, *Neft' i gaz Zapadnoj Sibiri: materialy mezhdunarodnoj NPK – TjumGNGU*, **43**, 26-30 (2013)
10. V. Kolesov, *Materialy 5 Vserossijskoj NTK – TjumGNGU*, 25-31 (2012)
11. O. Danilov, V. Kolesov, *Materialy mezhdunarodnoj nauchno-prakticheskoj konferencii – TjumGNGU*, **44**, 402-405 (2010)
12. A. Moor, O. Danilov, V. Kolesov, *Materialy mezhdunarodnoj NTK.– TjumGNGU*, **45**, 182-193 (2011)
13. A. Moor, O. Danilov, V. Kolesov, Transportnye i transportno-tehnologicheskie sistemy, **4**, 167-171 (2012)
14. D. Sorokin, Vektor Buk, **12**, 126-129 (2010)