THE BALTIC JOURNAL
OF ROAD AND BRIDGE ENGINEERING

2013

8(2): 133–141

PROPORTION OF VEHICLES MOVING FREELY DEPENDING ON TRAFFIC VOLUME AND PROPORTION OF TRUCKS AND BUSES

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Abstract. Adequate description of traffic in all intersections where traffic is not controlled by traffic lights is substantially affected by the adopted model of proportion of vehicles which move freely in traffic flow. The present study attempts to evaluate the proportion of vehicles moving freely in traffic flow depending on traffic volume and the effect of proportion of trucks and buses on this parameter. The analyses were carried out with an example of flows of vehicles moving in small roundabouts. It was observed based on the results of the analyses that the proportion of vehicles moving freely in traffic flow depending on traffic volume is best characterized by a spline, composed of three components which include quasi-free traffic, uniform traffic and non-uniform traffic.

Keywords: traffic flows, traffic conditions, roundabouts, proportion of free headways in flow, heavy vehicles.

1. Introduction

One of the most important characteristics which describe the traffic flow, essential from the practical standpoint, is headway between vehicles. This distribution has a basic importance, especially in analyses of traffic capacity and traffic conditions in intersections. Therefore, adequate definition of this distribution is very important in road traffic engineering. From the mathematical point of view, each distribution can be easily enough illustrated by means of an individual model of distribution. This approach, as demonstrated by detailed analyses of the results of the studies on traffic, might contain a serious error, especially in case of small and medium traffic volumes. This results from the fact that not all the vehicles at this traffic volumes in traffic flow move at typically random headways since only a particular number of vehicles move in a typical random manner. The headways between these vehicles are sufficient enough for them to prevent interacting with each other. This traffic is termed an independent or free traffic. The proportion of these vehicles in traffic flow decreases with traffic density and traffic volume (up to the max volume), whereas, the remaining part of the vehicles moves in compact or partially compact groups. The former involves the movement of a motorcade, with all the vehicles totally interdependent. The latter case involves a group of vehicles which move with the headways greater than in case of a motorcade, but shorter than in vehicles moving freely. Interaction of the vehicles in these groups on each other is partial. Obviously, the percentage proportion of the two latter groups of vehicles in the flow increases with traffic density and volume (up to max volume).

These analyses lead to the conclusion that the headway between vehicles in traffic flow are best characterized by a combination of three distributions corresponding to the above groups of vehicles referred to as "uniform flows". From the mathematical point of view, this approach produces the smallest error since homogeneity of a group of headways in each of these distributions provides opportunities for choosing adequate models in individual distributions. In practice, however, the two types of uniform flows are adopted which substantially facilitate traffic analyses: flows of vehicles which do not move freely and flows of vehicles which move freely.

It should be emphasized that recent years have seen an increasingly popular and successful use of the single Covan's distribution for the analyses of traffic in both roundabouts and internodal sections (Akçelik, Chung 1994; Hagring 1996, 2002; Luttinen 2004; Sullivan, Troutbeck 1994, 1997; Szczuraszek, Macioszek 2010; Tanyel, Yayla 2003; Troutbeck, Kako 1999; Vasconcelos

ISSN 1822-427X print / ISSN 1822-4288 online doi:10.3846/bjrbe.2013.17

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et al. 2011, 2012). Its effectiveness and popularity result primarily from the fact that it take into consideration the proportion of vehicles which move freely and which do not move freely in traffic flow. Covan's distribution is a three-parameter distribution used for the description of time headway between vehicles in the flow of vehicles including both the vehicles which move freely i.e. individually and those moving in groups (motorcades) of several vehicles. In Covan's distribution, the distribution of columns is geometrical. The values of the headway between vehicles which move in the motorcade show constant values equal to the minimal time headway (t_p). The vehicles which move freely move with the headways greater than t_p, with its exponential distribution shifted. Distribution function for Covan's distribution function is given by:

$$F(t)=\begin{cases}0 & \text{if} \quad t<t_p,\\ 1-\phi\times e^{-\gamma(t-t_p)} & \text{if} \quad t\geq t_p,\end{cases} \tag{1}$$

where ϕ – the proportion of vehicles which move freely; γ – the scale parameter of Covan's distribution, also called "flow rate of flow"; t_p – the minimal value of headway in traffic flow, s; t – value of headway in traffic flow.

The Covan's distribution parameters are as follows:

a) the expected value of headway is equal:

$$E[T]=t_p+\frac{\phi}{\gamma}, \tag{2}$$

b) the scale parameter γ is:

$$\gamma=\frac{\phi Q}{3600-Qt_p}, \tag{3}$$

where Q – traffic volume in traffic flow of vehicles per hour, vph;

c) the proportion of vehicles which move freely:

$$\phi=\frac{Q_s}{Q}[-], \tag{4}$$

where Q_s – the number of vehicles which move freely in traffic flow, vph, :

$$Q_s=Q-Q_n\text{, vph}, \tag{5}$$

where Q_n – number of vehicles moving in a dependent (not free) traffic.

It should be noted that the analysis based on Covan's distribution necessitates the evaluation of minimal time headway (t_p) and the proportion of vehicles which move freely on the circular roadway (ϕ).

The present study attempts to evaluate the proportion of vehicles which move freely in traffic flow depending on traffic volume, i.e. function $\phi(Q)$ and the effect of trucks and buses on this function. These analyses were carried out with an example of vehicle flows which move on small roundabouts. The investigations involved the following characteristics of traffic: traffic volume in circular roadway in roundabouts in hourly intervals, time headway between vehicles and type-based structure of vehicles.

Measurements consisted of recording time headways between vehicles which move through a selected cross-section of a circular roadway in a small one-lane roundabout. They were carried out in five selected small roundabouts: three- and four-inlet, one-lane roundabouts located in five medium-size cities (Macioszek 2006). External diameter of intersections amounted from 25 to 34 m. Traffic was characterized by the traffic volume of 50–1200 vph. From 0.3% to 22% of trucks were observed in traffic flow. Measurements were carried out under weather conditions convenient for road traffic (no precipitation, good visibility). Number of samples for analyses was selected based on Lyapunov's assuming the significance level 0.05.

Based on the literature reports (Tanyel, Yayla 2003; Troutbeck 1997), the passenger and delivery cars move freely if the headway between each other is greater or equal to 4 s. Other vehicles, with the distances shorter than 4 s were adopted as vehicles moving in a motorcade. The assumption in case of trucks and buses was that the vehicle moved freely if the headway between the two vehicles was greater than 8 s.

2. Previous models which described the proportion of vehicles which move freely in traffic flow

In the literature reports, the proportion of vehicles which move freely as a function of traffic volume is usually modelled by means of linear distribution or exponential distribution. The investigations aimed at determination of proportion of vehicles which move freely have been carried out either in internodal sections (Sullivan, Troutbeck 1997; 1994), and in mainlines in different types of intersections (Akçelik 1998; Hagring 1996; Hagring *et al.* 2003; Luttinen 2003, 2004). The following models may be emphasized among the linear relationships which describe the proportion of vehicles which move freely.

Tanner's model which describes the proportion of vehicles moving freely in mainlines of intersections without traffic lights (Tanyel, Yayla 2003):

$$\phi=1-t_p\frac{Q}{3600}[-] \text{ for } Q<\frac{3600}{t_p}. \tag{6}$$

O. Hagring's model which provides the description of vehicles which move freely in one-lane circular roadways in roundabouts (Hagring *et al.* 2003):

$$\phi=0.886-0.760\left(\frac{Q}{3600}\right)[-]. \tag{7}$$

O. Hagring's model which provides the description of vehicles which move freely in two-lane circular roadways in roundabouts (Hagring *et al.* 2003):

$$\phi = 0.914 - 1.549\left(\frac{Q}{3600}\right)[-]. \quad (8)$$

R. Troutbeck's model which describes the proportion of vehicles which move freely in roundabouts (Troutbeck 1989):

$$\phi = 0.9 - 0.0005\left(\frac{Q}{n}\right)[-] \text{ for } Q \le 1600 \text{, vph,} \quad (9)$$

where n – number of lanes in circular roadway.

R. Akçelik's model (used in SIDRA) which determines the proportions of vehicles which move freely in circular roadways in roundabouts (Akçelik, Chung 2003):

$$\phi = 0.75\left(1 - t_p \frac{Q}{3600}\right)[-] \text{ for } Q < \frac{3600}{t_p}. \quad (10)$$

The model used in aaSidra Intersection for traffic flows in circular roadways in roundabouts (Akçelik 2003):

$$\phi = \frac{\left(1 - t_0 \frac{Q}{3600}\right)}{\left[1 - (1 - k_d) t_0 \frac{Q}{3600}\right]}[-] \text{ for } \phi \le 0.001, \quad (11)$$

where t_0 – mean time headway between vehicles which move freely, s; k_d – constant which characterizes the status of traffic flow moving in a motorcade.

S. Tanyel's and N. Yayl's model for traffic flows in circular roadways in roundabouts (Tanyel, Yayla 2003):

$$\phi = \begin{cases} 1.25 - 1.13 t_p \frac{Q}{3600} \ [-] & \text{for } \frac{t_p Q}{3600} > 0.22 \\ 1 & \text{for } \frac{t_p Q}{3600} < 0.22 \end{cases}. \quad (12)$$

Furthermore, the group of exponential models used for the description of vehicles which move freely in a traffic flow comprises the two models:

W. Brilon's model (based on shifted exponential distribution) (Sullivan, Troutbeck 1997):

$$\phi = e^{-A \frac{Q}{3600}}[-], \quad (13)$$

where A – parameter [–] (A= 6–9 [–]).

R. Akçelik's model (Akçelik 2007; Akçelik, Chung 2003):

$$\phi = e^{-b t_p \frac{Q}{3600}}[-], \quad (14)$$

where b – parameters which characterize vehicles which do not move freely (in motorcades).

Table 1 presents a comparison of the values of parameters adopted in the model by R. Akçelik for the description of the proportion of vehicles which move freely in mainlines of intersections without traffic lights and roundabouts varied in terms of the number of lanes and parameters t_p and b.

3. Analysis of the function $\phi(Q)$ for the traffic flow of passenger car units

Function which determines the proportions of vehicles which move freely is closely related to the fundamental relationships in road traffic which occur between the volume, speed and density of traffic flow. Hence, the dependency of the value of the proportion of vehicles which move freely on traffic density ($\phi(k)$) should adopt the form of a decreasing function, starting from $\phi = 1$ for $k \cong 0$, whereas, depending on traffic volume ($\phi(Q)$), of approx a parabola shape, similarly to the relationship between traffic speed and volume. For the traffic volume of $Q \cong 0$, ϕ should obviously adopt the value of 1 in case when $k \cong 0$, and the value of 0 when $k \cong k_{max}$ (i.e. in case of traffic jam). Fig. 1 illustrates the proportion of the vehicles moving freely in traffic flow recorded by the authors in five roundabouts.

Regression and correlation analyses for the obtained results were carried out using the samples comprising only passenger and delivery cars. The analyses demonstrated that the best fit with empirical data is obtained by introduction of splines. Data analysis allowed for identification of three ranges of traffic volume in roundabout lane, with the form of ϕ function similar to a uniform model. For each range it is possible to describe in detail the proportion of vehicles which move freely in a roadway of a small roundabout by means of a suitably adjusted

Table 1. Values of parameters in R. Akçelik's model for evaluation of the proportion of vehicles which move freely (Akçelik 2007; Tanyel, Yayla 2003)

Number of lanes	For traffic flow in mainline of the intersection without traffic light			For traffic flow in roundabout		
	t_p	b	ϕ	t_p	b	ϕ
1	1.5	0.6	$\phi = e^{-0.9\frac{Q}{3600}}$	2.0	2.5	$\phi = e^{-5.0\frac{Q}{3600}}$
2	0.5	0.5	$\phi = e^{-0.25\frac{Q}{3600}}$	1.0	2.5	$\phi = e^{-3.0\frac{Q}{3600}}$
> 2	0.5	0.8	$\phi = e^{-0.4\frac{Q}{3600}}$	0.8	2.5	$\phi = e^{-2.5\frac{Q}{3600}}$

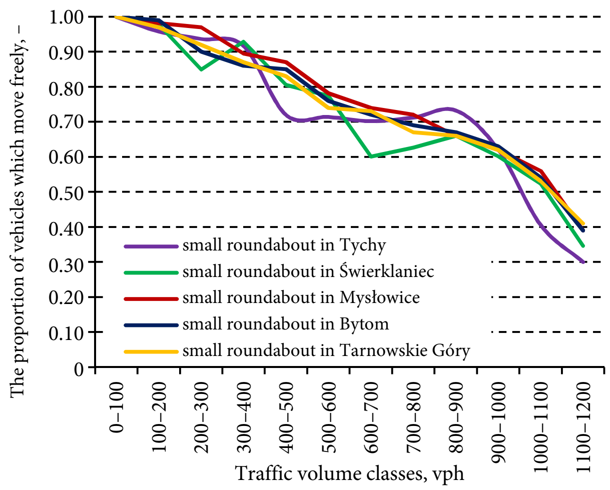

Fig. 1. Proportions of vehicles which move freely in five small roundabouts in the analysed classes of traffic volume units

single model function. For low-volume traffic ($0 < Q \leq 220$, vph), the proportion of vehicles which move freely on a roadway in a small roundabout is on average equal to one, with a relatively slight downward tendency with an increase in traffic volume (Fig. 2). All the vehicles move then under conditions of free traffic. In this range of traffic volume, application of several types of functions which would allow for description of the proportion of vehicles which move freely was analysed. Among all the analysed types of functions (e.g. linear function, polynomial function of second and third degree, exponential function, logarithmic function, power functions and other function with curvilinear shape), the best match was observed for square function (polynomial function of second degree). An increase in traffic volume over $Q = 220$ vph is accompanied by a substantial decline in proportion of vehicles moving freely which results mainly from limitation of freedom of moving and limitation of opportunities of choosing driving speeds by the drivers. This results in partial interaction of vehicles between each other. It was empirically confirmed that this phenomenon takes place under conditions of traffic volume in circular roadway within the range of: $220 < Q \leq 950$ vph. Finally, it was demonstrated that in this basic range of traffic volume, the proportion of vehicles which move freely depending on traffic volume is best described by logarithmic function ($R^2 = 0.89$).

In case of congestion, after exceeding the traffic volume of 950 vph, the most of vehicles move in a motorcade, maintaining minimal headways. The value of proportion of vehicles which move freely (ϕ) declines rapidly with an increase in traffic volume (Q). Under these conditions of traffic, among all the studied functions, the best match is observed for the root curve obtained as a result of transformation of parabola equation in a canonical form. The relationship which describes the proportion of vehicles which move freely in traffic flow should be additionally limited to the case of traffic flows with traffic density equal to optimal density, i.e. similar to the flow under conditions of optimal traffic capacity. It can be expected that when the flow exhibits traffic density greater than optimal, the analysed proportion of vehicles declines quite rapidly to zero with an increase in traffic density (Fig. 2). As a result, under conditions similar to traffic capacity of the circular roadway, i.e. when $Q \approx 1110$ vph, the proportion of vehicles which move freely amounts to ca. $\phi \approx 0.35[-]$. Therefore, the final description of the dependency of the proportion of vehicles which move freely on a roadway of small roundabout on traffic volume is given by Eq (15).

For polynomial dependency of the proportion of vehicles which move freely on traffic volume in a roadway in small roundabout non-linear correlation coefficient was 0.97. Mean standard deviation for the proportion of vehicles which move freely on a roadway of small roundabout from theoretical values calculated from the evaluated regression function amounted to 0.02 (2%) which confirms very low divergence of the values calculated by means of the polynomial function from empirical data. The coefficient of residual variability amounted to 0.0, which means that standard deviation of residual component amounts to 4% of mean value of proportion of vehicles which move freely on a roadway of small roundabout. For logarithmic dependency of the proportion of vehicles which move freely on traffic volume in a roadway of small roundabout, the authors obtained the coefficient of non-linear correlation equal to 0.95. Mean standard deviation of empirical values of the proportion of vehicles which move freely on a roadway of small roundabout on theoretical values calculated from the evaluated function of non-linear regression amounted to 0.04 (4%) which confirms very low divergence of the values calculated by the logarithmic function from empirical values. The coefficient of residual variability

$$\phi = \begin{cases} -0.000001Q^2 + 0.00005Q + 1 & \text{for } 0 \text{ vph} \leq Q \leq 220 \text{ vph} \\ -0.2277Ln(Q) + 2.1839 & \text{for } 220 \text{ vph} < Q \leq 950 \text{ vph} \\ 0.35 + \sqrt{\dfrac{Q-1110}{-2195}} & \text{for } 950 \text{ vph} < Q \leq 110 \text{ vph} \wedge Q < C \\ 0.35 & \text{for } Q = C \end{cases} \quad (15)$$

where C – traffic capacity in a lane of a roundabout, vph.

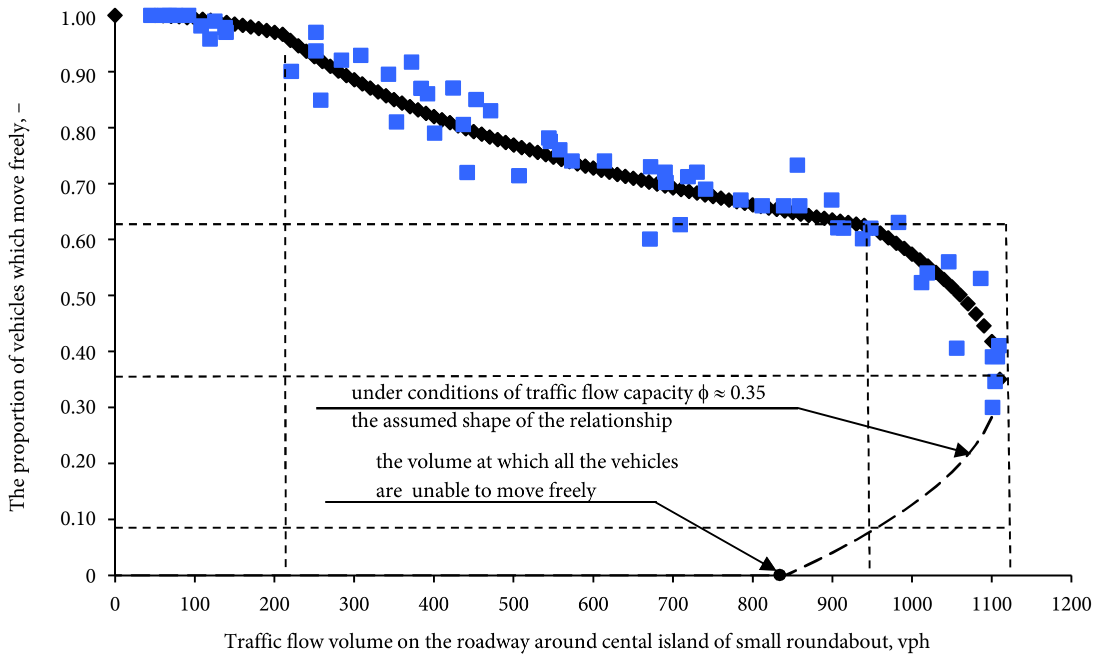

Fig. 2. The dependency of the proportion of vehicles which move freely on the small roundabout on traffic volume

amounted to 0.05 which means that standard deviation of residual component amounts to 5% of mean value of the proportion of vehicles which move freely on a roadway of small roundabout.

Analysis of regression and correlation were complemented with two statistical tests (for polynomial function and logarithmic function). Tests of significance for correlation coefficients were performed in order to verify whether the correlation between the proportion of vehicles which move freely on a roadway of small roundabout (ϕ) and traffic volume in circular roadway (Q) differs significantly from zero (i.e. it exists). It was found in both analysed cases that, at the level of significance of $\alpha = 0.05$, the correlation exists between the proportion of vehicles which move freely (ϕ) and traffic volume (Q).

The quality of adaptation of root function to the empirical data which describes the dependency of the proportion of vehicles which move freely on traffic volume on a roadway of small roundabout in the third range of variability Q was assessed based on the evaluation of absolute errors δ_C (%) for individual measurements using the following dependency:

$$\delta_C = \left| \frac{\hat{\phi}_M^i - \phi_E^i}{\phi_E^i} \right| 100\,, \%, \tag{16}$$

where δ_C – absolute error, %; $\hat{\phi}_M^i$ – i proportion of vehicles which move freely determined from the model; ϕ_E^i – i empirical proportion of vehicles which move freely.

The level of the relative errors were determined from the relationship

$$\mu_C = \hat{\phi}_M^i - \phi_E^i [-], \tag{17}$$

where μ_C – relative error.

The total from the module of residuals was determined based on the following formula:

$$\psi = \sum_{i=1}^{n} \left| \hat{\phi}_M^i - \phi_E^i \right| [-]. \tag{18}$$

The results obtained from verification confirm good conformance of the obtained model with actual road and traffic conditions which are observed in small single-lane roundabouts. Mean level of absolute error was 2.76%. Mean relative error was barely 0.01 [–]. The obtained conformance confirms the opportunities for using the model in practical applications.

4. Effect of the proportion of trucks and buses in traffic flow volume on $\phi(Q)$ function

Another stage of analyses involved the assessment of the effect of the proportion of trucks and buses in traffic flow on $\phi(Q)$ dependency. In order to achieve this, the analysis was carried out for two cases of flow mixed in terms of type-related structure. Consequently, apart from passenger cars, the flow also contained trucks and buses. In the first case, the proportion of trucks and buses in traffic flow did not exceed 14%, whereas, this value in the second case ranged from 18% to 22%. Analogically, the proportion of vehicles which move freely on a roadway of roundabout as a function of traffic volume was described using spline composed of three parts. The obtained relationship for the mixed flow with the proportion of trucks and buses in traffic flow up to 14% is given by Eq (19) (Fig. 3).

Furthermore, the relationship which describes the proportion of vehicles which move freely in the mixed

$$\phi = \begin{cases} -0.000002Q^2 + 0.000033Q + 1 & \text{for } 0 \text{ vph} \le Q \le 180 \text{ vph} \\ -0.2245Ln(Q) + 2.1105 & \text{for } 180 \text{ vph} < Q \le 900 \text{ vph} \\ 0.41 + \sqrt{\dfrac{Q-1000}{-3460}} & \text{for } 900 \text{ vph} < Q \le 1000 \text{ vph} \wedge Q < C \\ 0.41 & \text{for } Q = C \end{cases} \quad (19)$$

$$\phi = \begin{cases} -0.000004Q^2 + 0.000151Q + 1 & \text{for } 0 \text{ vph} \le Q \le 150 \text{ vph} \\ -0.2161Ln(Q) + 2.0146 & \text{for } 150 \text{ vph} < Q \le 810 \text{ vph} \\ 0.45 + \sqrt{\dfrac{Q-900}{-6250}} & \text{for } 810 \text{ vph} < Q \le 900 \text{ vph} \wedge Q < C \\ 0.45 & \text{for } Q = C \end{cases} \quad (20)$$

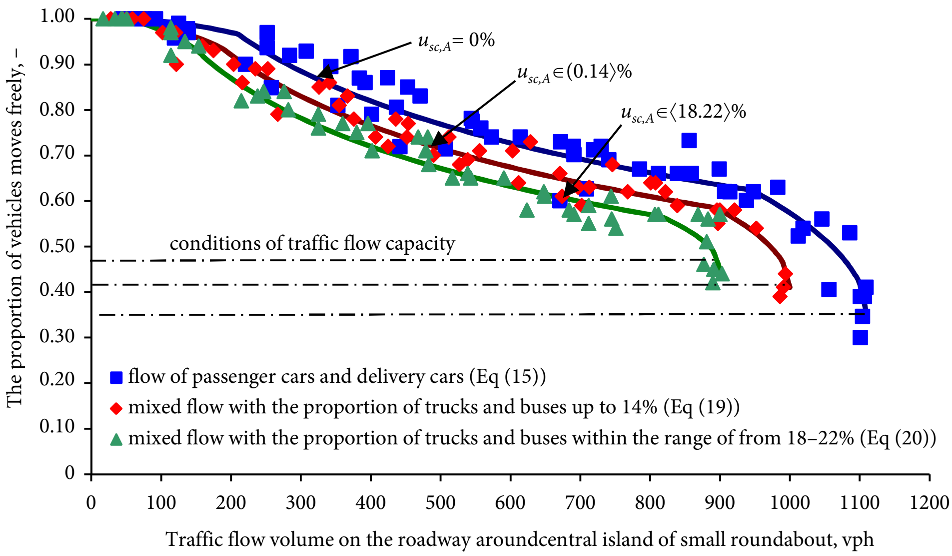

Fig. 3. Comparison of the proportion of vehicles which move freely in a uniform flow in terms of composition (only passenger and delivery cars) and mixed (with the proportion of trucks and buses up to 14% and with the proportion of trucks and buses ranging from 18–22%)

flow where the proportion of trucks and buses ranges from 18% to 22% is given by Eq (20) (Fig. 3).

In consideration of the results of the analyses presented in Fig. 3, one can note that even insignificant proportion of trucks and buses in traffic flow causes substantial decline in the number of vehicles which move freely in individual classes of traffic volume. For the value of traffic volume of 300 vph, for example, the proportion of trucks and buses in traffic flow up to 14% causes as much as 7% decline in the value of ϕ in relation to the flow without heavy vehicles and as much as 12.5% decline in the case of the flow with trucks and buses from 18% to 22%. These discrepancies tend to rise with an increase in traffic volume. For traffic volume of 900 vph, for $u_{sc,A} = 0\,\% \rightarrow \phi(Q) = 0.63$ [–], for $u_{sc,A} \in \langle 0.14 \rangle \rightarrow \phi(Q) = 0.58$ [–], and for $u_{sc,A} \in \langle 18.22 \rangle \rightarrow \phi(Q) = 0.45$ [–]. This means that a decline in mixed flows amounts, respectively, to 8% and as much as 29%.

Unfavourable effect of the presence of trucks and buses on the proportion of vehicles which move freely in traffic flow can be explained quite easily. With insignificant traffic volumes which correspond to free traffic conditions, all the vehicles in the flow are able to move at any speed. Under these conditions, the presence of a particular insignificant number of trucks and buses in traffic flow does not cause a substantial decline in the proportion of vehicles which move freely. Increase in traffic volume, and, in consequence, traffic flow density, leads to more frequent "meeting" of trucks (which move much slower and take much more space in a traffic lane) with faster passenger and delivery cars, which, in practice, causes more intensive decline in the proportion of vehicles which move under conditions of free traffic. In consequence, increase in traffic volume and density will be accompanied by continuous decline in the speed and freedom of traffic for even higher number of vehicles. Consequently, the transition from free state to partially non-free state will cause changes in the character of the relationships between traffic volume and the proportion of vehicles which move freely, and the effect of trucks and buses on the conditions in traffic flow will become more apparent. Under conditions of the traffic close to the traffic capacity of a circular roadway in roundabout, the effect of trucks and buses on the proportion of vehicles which move freely is the most substantial (Fig. 3).

Under conditions similar to traffic capacity in circular roadway, the following values of ϕ were obtained:

- $\phi \approx 0.35$ – for the flow of exclusively passenger and delivery cars ($Q_{max} \approx 1110$ vph);
- $\phi \approx 0.41$ – for the mixed flow with the proportion of trucks and buses up to 14% ($Q_{max} \approx 1000$ vph);
- $\phi \approx 0.45$ – for the mixed flow with the proportion of trucks and buses from 18% to 22% ($Q_{max} \approx 900$ vph).

For all the analysed function, the parameters of assessment of their accuracy were determined similarly to the functions which described the traffic flow without proportion of heavy vehicles. The values of the obtained parameters confirm good match of the adopted functions to empirical data. Similarly to the previous case, the regression and correlation analyses were complemented with statistical tests, which, at the level of significance of $\alpha = 0,05$ in all cases, confirmed correlations between the variables.

5. Comparison of the models proposed in this study with previous models that illustrated the proportion of vehicles which move freely in traffic flow

Fig. 4 presents a comparison of the models discussed in Chapter 2 (assuming $t_p = 1.8$ s) with the models developed by previous authors (Eqs (15), (19), (20)). This comparison allows for drawing the following conclusions.

1. High divergence in the profiles of the analysed functions. This divergence is observed especially under conditions of traffic volumes which are close to traffic capacity. For example, for $Q \approx 1200$ vph for two extreme function profiles (calculated with O. Hagring's model and R. Ackelik's model from aaSIDRA Intersection software) this divergence reaches as much as 60%.

2. Relatively high conformance of the profile of the function $\phi(Q)$ with the models developed by the authors of this study is observed for the Tanner's model (Eq (6)) and partially (for $Q > 300$ vph) for Hagring's model (Eq (8)).

3. Many of the previous models raise some doubts about their adequateness:

- O. Hagring's (Eqs (7)–(8)), Troutbeck's (Eq (9)) and R. Akçelik's (Eq (10)) models do not meet the basic boundary condition, i.e. these functions adopt the value of $\phi(Q) << 1$ for $Q = 0$ (with $k = 0$) but they should adopt the value of 1.0;
- S. Tanyel's & N. Yayl's model (Eq (12)) assumes that in flow with traffic volume up to ca. 440 vph all the vehicles move freely what is at variance with actual traffic observations;
- for traffic volumes near traffic capacity, none of the models (except for the models obtained in

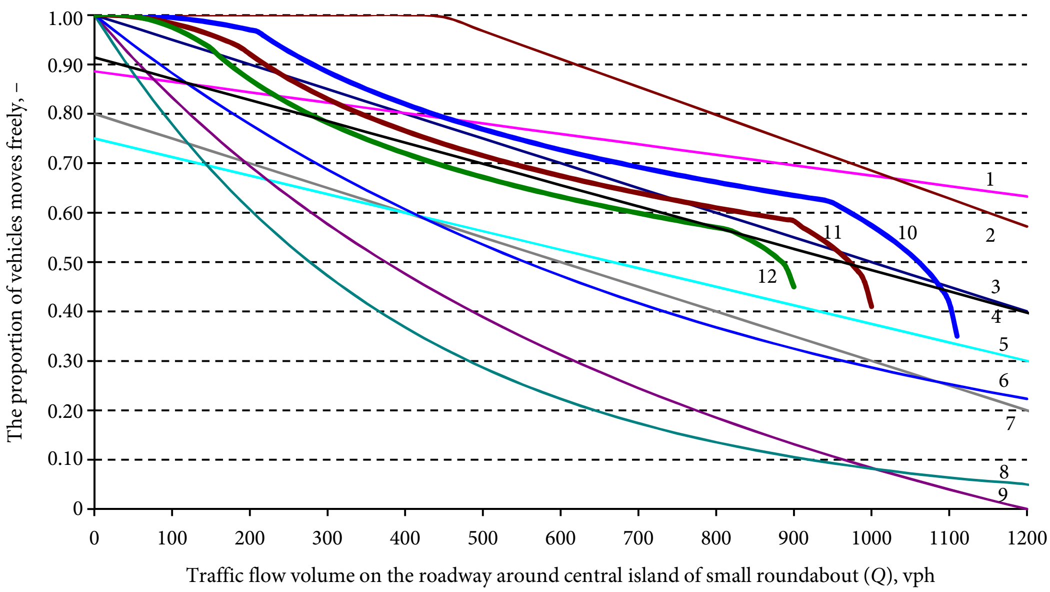

Fig. 4. Function of the proportion of vehicles which move freely depending of traffic flow according to different models, where 1 – O. Hagring's model (Eq (7)); 2 – S. Tanyel's & N. Yayl's model (Eq (12)); 3 – J. Tanner's model (Eq (6)); 4 – O. Hagring's model (Eq (8)); 5 – R. Akçelik's model (Eq (10)); 6 – R. Akçelik's model (Eq (14)); 7 – R. Troutbeck's model (Eq (9)); 8 – W. Brilon's model (Eq (13)); 9 – R. Akçelik's model (Eq (11)); 10 – authors' model (Eq (15)); 11 – authors' model (Eq (19)); 12 – model obtained in this study (Eq (20))

this study) meets the conditions which result from the fundamental principle of traffic flow (Wardrop's principle). For this conditions, the extreme of the function $\phi(Q)$ should exist in point $Q = C$;

– none of the models (except for the models obtained in this study) took into consideration the effect of heavy vehicles (trucks and buses) on the value of ϕ , although, according to the study this effect is very significant.

6. Conclusions

1. The adequateness of the description of traffic in all the intersections where traffic is not controlled by means of traffic lights is strongly dependent on the adopted model of the proportion of vehicles which move freely in traffic flow. The accuracy of this model determines the accuracy of the traffic volume and traffic conditions in these intersections.

2. A number of previous models which described the proportion of vehicles which move freely in traffic flow raise doubt and do not meet fundamental boundary conditions; they are at variance with fundamental Wardrop's principle of flow, exhibit function profile which is difficult to justify and do not take into consideration an important factor of the proportion of heavy vehicles (trucks and buses in traffic flow).

3. It was found based on the results of the analyses that the proportion of the vehicles which move freely in traffic flow depending on traffic volume is best characterized by means of spline function composed of three components which include quasi-free, uniform and non-uniform traffic.

4. The relationships which describe the proportion of vehicles which move freely in circular roadways in small single-lane roundabouts were obtained for the flow of light vehicles, for the mixed flow with the proportion of heavy vehicles up to 14% and for the mixed flow with the proportion of heavy vehicles ranging from 18% to 22%.

5. With small values of traffic volumes and low traffic densities, almost all the vehicles in the flow move freely. With the increase in traffic volume up to the value of max level ($Q = C$) the number of vehicles moving freely decreases. As results from the findings obtained in this study, under conditions of max volume, there are from 34% to 45% of them depending on the proportion of heavy vehicles (trucks and buses). With higher proportion of heavy vehicles, the proportion of vehicles which move freely in traffic flow declines. The traffic volume decreases over the level of $Q = C$, i.e. further increase in traffic flow density (as results from fundamental Wardrop's principle of traffic flow) and the number of vehicles which move freely will also decline rapidly. Their proportion in traffic flow is likely to disappear at the traffic flow density of $k_{opt} < k < k_{\max}$ (where $k_{\max}$ – max traffic flow density under traffic jam conditions, k_{opt} – traffic flow density under conditions of traffic flow capacity, i.e. at $Q = C$). The capacity value was determined taking into account the model relations between traffic volume, traffic speed and traffic flow density which are results of the fundamental Wardrop's traffic flow principle.

6. Increase in the presence of heavy vehicles in traffic flow on roundabout causes considerable decline in the number of vehicles which move freely. Compared to the traffic flow which was composed of exclusively passenger and delivery cars, the traffic flow with proportion of trucks up to 14% caused an average 8% decline in the proportion of vehicles which move freely in traffic flow. The mixed traffic flow with the proportion of trucks ranging from 18% to 22% causes a decline to ca. 12%.

7. The models of $\phi(Q)$ proposed by the authors of this study exhibit high quality of their adjustment to empirical data. They also take into consideration the proportion of heavy vehicles in traffic flow. Therefore, they can be successfully used in development of the methods of calculation of traffic capacity in small roundabouts with higher accuracy compared to previous methods.

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Received 22 August 2011; accepted 21 March 2012