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DEVELOPMENT OF THE NEW POLISH METHOD FOR CAPACITY ANALYSIS OF MOTORWAYS AND EXPRESSWAYS

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Abstract The paper presents development of the new Polish method for performing capacity analysis of basic segments of dual carriageway roads (motorways and expressways). The method is based on field traffic surveys conducted at 30 motorway and expressway sites (class A and S roads) in Poland. Traffic flows, composition and travel times were observed in 15-min intervals at each site using ANPR filming method. These data were used to calibrate a family of traffic speed-flow relationships for different roads, based on Van Aerde model. Free flow speed of traffic and road class are the basic parameters defining the speed-flow relationship and the value of capacity per lane in pcu/h. Traffic density was adopted as the measure of effectiveness for defining the level of service. The paper describes derivation of formulae for estimation of free flow speed for different types of roads as well as determination of equivalent factors for converting vehicles to passenger car units. The method allows us to determine capacity and the level of service based on existing or forecasted traffic flow.

Keywords: capacity analysis, motorways, expressways, Van Aerde model, free flow speed, level of service

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1. INTRODUCTION

Road capacity analysis is one of the most important tools used in traffic engineering. Generally speaking, it allows one to estimate the capacity (maximum traffic flow rate) of a given road and assess what traffic conditions will prevail on it at a given traffic flow. Capacity studies have a history of seventy years – the first edition of American Highway Capacity Manual (HCM) was published in 1950. Since that time there have been six new and expanded editions of the HCM as well as similar developments in many other countries.

Capacity analysis manual used so far in Poland [17] was published in 1995. The manual was based on 1985 edition of the US HCM and urgently required an update. This task was undertaken as part of the RID-2B research project entitled "Modern methods for calculating capacity and assessing traffic conditions for roads outside urban areas, including high-speed roads". The project was carried out by a consortium of three Polish universities: Cracow University of Technology, Warsaw University of Technology and Gdansk University of Technology and funded jointly by the General Directorate of National Roads and Motorways and the National Centre for Research and Development. The project resulted in a manual entitled "Methods for assessing traffic conditions and calculating capacity", the final version of which has not yet been published. The manual consists of three parts: the first one covers two-lane highways and temporary road signals at road works, the second concerns dual carriageway roads and road interchanges and the last one determination of the representative (design) traffic volume from surveys and traffic forecasts.

This paper presents part of the project's results, concerning the development of method for analysing traffic conditions on basic segments of dual-carriageway roads, namely: motorways and expressways. The method applies to uninterrupted traffic, i.e. traffic on road segments where there are no traffic signals, stop or give way signs, level rail-road crossings, etc. The basic segment shall be understood as a segment on which traffic is undisturbed by the manoeuvres of merging, diverging or weaving and its traffic conditions are the result of the presence of vehicles on the road, driving behaviour and interaction between vehicles. The paper focuses on the capacity of basic segments only and does not cover the method for analysing motorway interchanges and ramp areas.

2. BACKGROUND

Motorways and expressways are designed to handle large traffic flows at high speed and provide a high level of road safety, high driving comfort and low environmental impact. These roads are expensive to build and maintain, thus both planning, design and management must be well-thought-out and supported with technical and economic analyses. An important element of the analyses is to determine the functionality of the roads by estimating the capacity and assessing traffic conditions for existing or forecasted traffic volumes.

Over the years, significant research efforts have been directed towards development of capacity methodology in the United States as well as in many other countries. Most recently, in 2016, the 6th edition of the US Highway Capacity Manual (HCM) was published [19]. The methodology for capacity analysis has been developed in parallel in Germany, under the name HBS [2] and in many other countries, e.g. the Netherlands, Sweden, Japan and China [6, 9–11, 18, 20].

The HCM has a long history and builds on more than 70 years of road traffic research in the US [15], which makes it one of the most important publications regarding road traffic in the US and worldwide. While HCM serves as a guide for traffic analyses in the US, this capacity analysis methodology is also used in other countries, either in the original form or after adaptation to local conditions, characteristic of a particular country [9, 18].

Some of the HCM concepts have entered global traffic engineering practice permanently, such as level of service (LOS) concept for qualitative traffic conditions assessment and classification. In Europe, the leader in road traffic research is Germany. The German guide for capacity analyses – HBS, was first published in 2001 and most recently in 2015. It builds on empirical and simulation research conducted in Germany over the last decades [3, 4]. Comparably to the HCM, in the HBS traffic flow quality on road facilities is assessed using six LOS classes (A-F). However, the procedure for capacity analysis differs significantly from the HCM. For example, the HBS methodology provides discrete values of capacity and a set of speed-flow diagrams for roads of a given cross-section, gradient or road location, while in the HCM road and traffic characteristics are incorporated in the free-flow speed, capacity or speed-flow models. Thus, the HBS methodology does not require complicated calculations and, in practical use, analysis can be limited to reading graphs and tables.

In comparison with the US or Germany, Polish research experience on capacity regarding motorways and expressways is rather poor and limited to the most recent years. Despite the fact that the first local studies were conducted in the late 1980s [7], until 2016 the HCM methodology had been officially recommended for the use in traffic analyses. The guide on how to estimate road capacity and assess traffic conditions published in 1995 [17], was practically a Polish translation of HCM 1985, with only slight modifications of the original. The latest studies [12, 13, 16] have shown that neither the HCM nor any other methodology can be directly applied for the traffic analyses of road facilities in Poland and that the Polish methodology needs to be developed based on own studies.

3. TRAFFIC SURVEYS ON DUAL CARRIAGEWAY ROADS

In Poland, dual carriageway roads belong to three functional classes which are the following: motorways (A class), expressways (S class) and high-speed trunk roads (GP class). Field surveys were carried out using ANPR and Mio Vision Scout cameras at 30 road survey sites between March and October 2017 on class A and S dual carriageway roads. Survey test sites were selected using a four-stage procedure which covered the following selection criteria: road class, cross-section (number and width of lanes, shoulder presence), speed limit and traffic flow. Practical issues like the physical possibility of conducting video surveys were also considered.

The selected survey sites comprised: 20 motorway and 10 expressway segments. Each road segment had a speed limit in the range of 90-140 km/h, 16 of the sites analysed were segments with a cross-section of 2x2 lanes, the remaining 14 were segments with 2x3 lanes. Table 1 shows the breakdown of survey sites by their characteristics.

Table 1. Characteristics of traffic survey sites

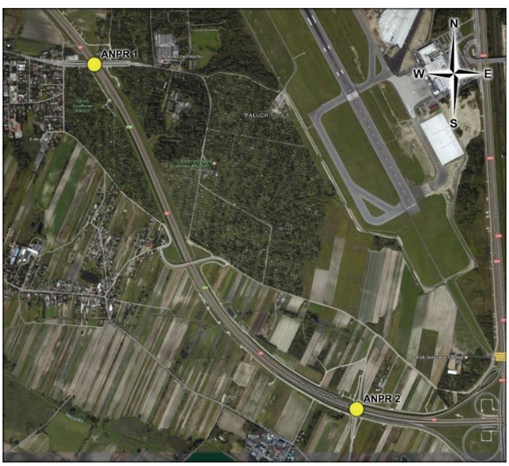
Cross section	Speed limit [km/h]	Area type	Number of segments	Number of survey hours [h]	Segment length [m]			Average ramp density [ramp/km]	Average slope [%]
					min	max	average		
2x2	100	m	2	27	4119	4119	4119	0.65	1.87
	110	r	2	28	4095	4095	4095	0.30	0.65
	120	m	4	59	2437	4587	3512	0.58	0.78
	140	r	4	70	2156	4559	3358	0.10	1.02
	140	m	4	61	2439	3185	2812	0.63	0.52
2x3*	90	m	2	18	942	942	942	1.10	1.14
	120	m	4	51	2435	4947	3691	1.30	0.87
	140	m	8	112	1953	3462	2532	0.63	1.02

m – metropolitan, r- rural

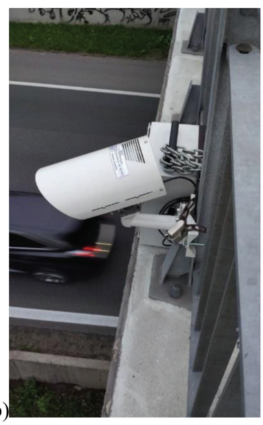
*) In Poland, there are currently no motorway/expressway segments with 2x3 lanes in rural areas or with a 100 km/h speed limit.

Observations of traffic flow and traffic speed at each surveyed road segment were carried out using ANPR MAV Rapier 50IQ cameras (Fig. 1b) and MioVision Scout equipment. Length of the surveyed road segments varied, depending mostly on the possibility to install cameras, and ranged from 940 m (S8 expressway) to 4950 m (S86 expressway). The average segment length was 3070 m. All the survey sites were located in flat terrain. The total number of hours of observations was 426 (245 on 2x2 cross section and 181 on 2x3). Mean entry and exit ramp density was 0.98 per km of road.

During the surveys traffic data were collected at each survey site in 15-minute intervals: traffic volumes of passenger cars and heavy vehicles as well as passage times of individual vehicles. From passage times, average speed of traffic stream was determined in 15-min intervals. For each interval, traffic flow rate and the proportion of heavy vehicles were calculated. These data were eventually used to determine the free flow speed of each road and to estimate the capacity of roadway segments according to their class, free flow speed and number of lanes.



a)



b)

Fig. 1. Example of a survey site: (a) location of ANPR cameras at segment end points along S2 expressway (b) ANPR camera installed at an overhead bridge.

Traffic data were recorded for a total of 1700 15-minute survey intervals. The minimum observed traffic flow rate was 320 veh/h and the maximum 6232 veh/h (Table 2). Proportion of heavy vehicles ranged from 0% to 57,8% (high proportion occurs during early morning hours). Average traffic speeds ranged from 17 km/h to 143 km/h.

As can be seen from Table 2 (number of survey intervals), most of the observations were eventually made in metropolitan areas. The reason for this was the need to capture the full range of traffic flows, including congested flow conditions. At the present time in Poland, such conditions occur very rarely outside of metropolitan areas.

Table 2. Characteristics of traffic data

Cross section	Speed limit [km/h]	Area type	Number of survey intervals	Traffic flow [veh/h]			Heavy vehicles [%]			Speed [km/h]		
				min	max	average	min	max	average	min	max	average
2x2	100	metropolitan	106	1084	3660	2396	5.4	18.3	11.0	43.1	117.2	108.8
	110	rural	109	468	2032	1291	13	51.8	26.8	97.3	121.2	109.3
	120	metropolitan	236	644	4032	2507	4.7	57.8	16.7	27.8	116.0	101.3
	140	rural	280	320	3228	1743	0.0	30.6	5.4	97.8	143.1	126.7
	140	metropolitan	244	584	3804	2475	1.8	49.1	14.1	40.6	129.5	99.5
2x3	90	metropolitan	71	1676	6232	5297	2.5	24.1	8.6	17.0	97.9	62.6
	120	metropolitan	204	392	5976	3355	1.4	26.3	7.9	21.2	124.3	101.6
	140	metropolitan	446	404	3408	1909	6.5	54.5	20.6	93.4	139.6	111.0

4. TRAFFIC FLOW MODELING

4.1 Speed-flow-density models

The basic relationship used in road capacity analysis is traffic speed-flow-density (q-v-k) relationship [5]. In order to select a mathematical model that reflects changes in traffic conditions depending on traffic flow level on basic segments of dual carriageway roads in Poland, data from the permanent count station located on the Tri-City Bypass expressway (S6 km 326) were used. Heavy traffic flow observed there means that the road is already operating near its capacity, which is particularly evident during peak hours. This gives one the ability to observe different traffic states (free flow, steady flow, forced flow) and to model them using the q-v-k relationship.

Data from the S6 expressway, aggregated to intervals of 5-min, contained information on traffic flow, heavy vehicles and average speed. Using passenger car equivalent factors for heavy vehicles (section 4.2), the equivalent traffic flow was determined. Using these data, a few selected known q-v-k models were calibrated. Each model was examined with regard to fit to data and correctness of the estimated boundary parameters with reference to their expected ranges.

The Van Aerde model [1] was selected for further research (Figure 2) as it had a good fit to empirical data and was correctly reproducing the different traffic states. An application software SPD_CAL was used, created by the model developers [14]. It enables to calibrate four parameters: free-speed, speed-at-capacity, capacity, and jam density. Calibration is performed by algorithm which starts with an initial set of parameters and computes the error function for this initial solution by projecting each observation on the three-dimensional functional form. The algorithm then proceeds by iteratively varying the values of the free-speed, speed-at-capacity, capacity, and jam density using a heuristic hill-climbing technique to select the optimum parameters that minimize the sum of squared orthogonal errors. Van Aerde model was also used in the German HBS method [2].

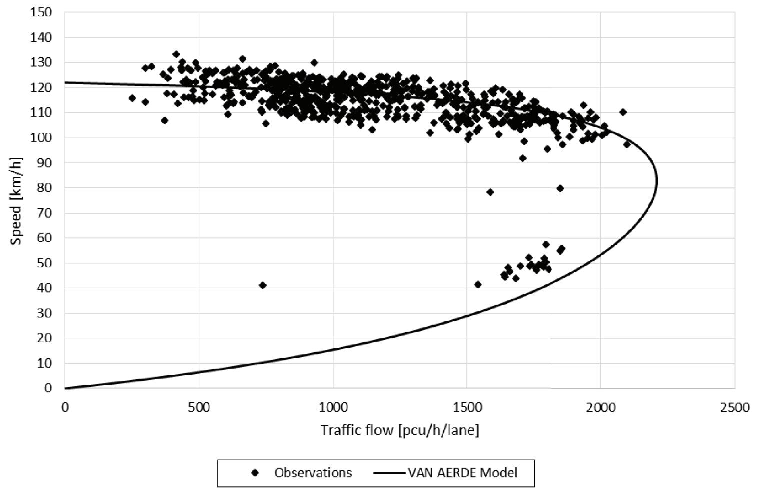


Fig. 2. Calibration of the Van Aerde model for motorways

The selected Van Aerde model was subsequently adapted to data from traffic surveys carried out by the RID-2B project team which was aimed to capture traffic on roads with different road and traffic conditions. For constructing the models, data aggregated for 15-min intervals and traffic flows converted into passenger car units per lane Q [pcu/h/lane] were used.

Analyses were carried out to group survey sites with similar road-traffic conditions. The optimum division was achieved by grouping the sites according to the free flow speed and the type of area (rural/metropolitan). As a result of this grouping, 6 groups of survey sites were obtained. The Van Aerde model was then calibrated for each group using the SPD_CAL software [14].

4.2. Passenger car equivalent factors for heavy vehicles

Equivalent factors for heavy vehicles (defined as heavy goods vehicles with a total mass of >3,5 t and buses) E_c were determined by calibrating the speed-density relationship of Van Aerde model using empirical data and SPD_CAL software. Potential E_c equivalent factor values were assumed to be in the range of 1.6 to 2.6, with a step of 0.1. Modelling was carried out separately for roads with 2x2 lanes and 2x3 lanes. The best fit was achieved for 2x2 roads at E_c = 2.4 and for 2x3 roads at E_c = 1.6.

The values of equivalent factors for passenger cars for roads with gradients steeper than 2% (upgrades) were developed on the basis of the HBS manual [2]. This was done because national surveys took place almost exclusively on roads in flat areas. The final pcu equivalent factor values are shown in Tab. 3. The effect of longitudinal grades on driving dynamics of passenger cars is expressed by E_s values. The values of equivalents for heavy vehicles, E_c, depend on the road class, the number of lanes in the cross-section and the flow-to-capacity ratio of the road, X.

Studies found a greater impact of heavy vehicles on the traffic stream speed for 2x2-lane roads than for 2x3-lane roads, which is reflected in higher E_c values for such sections. Heavy vehicles also have a greater dynamic impact on other vehicles under light traffic, while this impact decreases as traffic flow approaches capacity. Consequently, Table 3 shows higher E_c values for the low and medium traffic range (flow-to-capacity ratio $X < 0.75$) and lower for heavy traffic ($X \geq 0.75$).

Table 3. Pcu equivalent factors E_s and E_c

Vehicle type	Road class, cross-section type	Flow-to-capacity ratio X	Longitudinal grade (upgrade)			
			≤2%	3%	4%	5%
cars, E_s	all	all	1.00	1.07	1.20	1.33
heavy vehicles, E_c (trucks, buses)	A+S, 2 x 3 lanes, 2 x 4 lanes	<0.75	1.94	2.12	2.38	2.73
		0.75 – 1	1.60	1.75	1.96	2.25
	A+S, 2 x 2 lanes	<0.75	2.40	2.54	2.77	3.02
		0.75 – 1	2.10	2.22	2.43	2.64

4.3. Peak hour factor

The basic interval used in LOS estimation is one hour. In case of such a relatively long analysis period, we should take into account variability of traffic within the hour, which can be reflected by peak hour factor, k_{15}. This factor is defined as the ratio of the average traffic flow rate during the hour to the maximum flow rate during the peak 15 minutes.

Relationship between k_{15} and traffic flow rate was investigated using data from basic dual carriageway road segments (see section 3) as well as data from ramp and weaving areas which were also surveyed during the same research project. Altogether traffic flows were observed at 115 survey sites during 2844 15-min intervals. Peak hour factors were calculated for all these intervals by adding up 4 subsequent 15-min periods to find the hourly volume. The calculated k_{15} values were averaged for every 10 veh/h traffic flow interval. The results for metropolitan areas are shown in Fig. 3.

Using the combined traffic surveys carried out on class A and S roads, the following relationships between the k_{15} factor and representative traffic flow have been determined:

- when traffic flow $Q_m \le 1000$ veh/h:

$$k_{15} = \begin{cases} 0.87 & \text{for metropolitan areas} \\ 0.90 & \text{for rural areas} \end{cases} \tag{4.1}$$

- for metropolitan areas when $Q_m > 1000$ veh/h (Fig. 3):

$$k_{15} = 0.482 + 0.063 \cdot \ln\left(\frac{Q_m}{n}\right) \qquad R^2 = 0.70 \tag{4.2}$$

- for rural areas when $Q_m > 1000$ veh/h:

$$k_{15} = 0.725 + 0.029 \cdot \ln\left(\frac{Q_m}{n}\right) \qquad R^2 = 0.22 \tag{4.3}$$

where:
Q_m - representative traffic flow [veh/h], n - number of lanes [-].

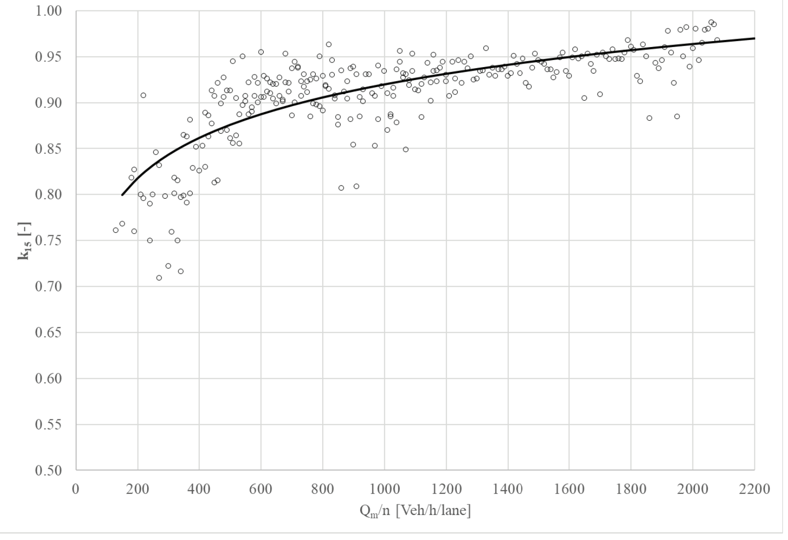


Fig. 3. Relationship between k_{15} and Q_m for metropolitan areas

4.4. Free flow speed

For each of the survey sites, the free flow speed has been determined as the average speed of passenger cars at traffic flow rates lower than 1000 pcu/h/lane. HCM recommends a similar approach for determining the basic free flow speed of traffic [19]. The free flow speed has been determined separately for each direction of traffic as well as for the whole road cross-section. Probe vehicle data were also used as an additional source of data on free flow speeds [13].

Correlation analyses were conducted to check dependency of free flow speed on road location, geometry and characteristics. It was found that free flow speed is correlated with speed limit (r = 0.48) and ramp density (r = –0.74). In addition, the free flow speed depends strongly on the type of area (metropolitan or rural). On the other hand, there was no significant correlation with factors such as the number of lanes, shoulder width or longitudinal gradient. Based on these observations, models were built to estimate the free flow speed when it is not possible to measure it directly. Factors affecting the free flow speed are: road location, speed limit and ramp density (exit and entry points at interchanges). The relationships obtained are as follows, for motorways:

$$V_{sw} = 82.2 - 10.7 g_{wz} + 7.7\delta_z + 0.334\, V_d \tag{4.4}$$

and for expressways:

$$V_{sw} = 83.5 - 10.7 g_{wz} + 7.7\delta_z + 0.334\, V_d \tag{4.5}$$

where:
V_{sw} – free flow speed [km/h], g_{wz} – ramp density [1/km], δ_z – area index ($\delta_z = 0$ for metropolitan area, $\delta_z =$ 1 rural area), V_d – speed limit [km/h].

The model is characterized by a very good fit to empirical data on free flow speed: $R^2 = 0.726$ with n = 76 observations. Variables describing location of the road (δ_z), speed limit (V_d), and ramp density (g_{wz}) are statistically significant at 0.001.

5. CAPACITY ANALYSIS METHOD

5.1. Method assumptions

Before formulating the new Polish method of assessing traffic conditions and calculating capacity of dual carriageway roads, a number of assumptions had to be made regarding the definition of capacity, traffic flow units, the analysis period and the type of speed-flow-density relationship. The most important choices to be made were presented in a previous paper [12]. The decisions were based on the comparison of HCM and HBS methods and literature studies, as well as preliminary analyses using the empirical data collected in Poland [16].

As a result of these analyses, the following assumptions were made:

- Passenger car units were adopted as the basic units for expressing traffic flow and density, as in the HCM method. An alternative approach known from HBS method of using real vehicles and the percentage of heavy vehicles is impractical as it would require too many combinations of models.
- The basic period of analysis of traffic conditions is 15 minutes, as in the HCM method. Speed-flow modelling was also performed using 15-min intervals for averaging the density and speed of traffic. Using 15-min intervals ensures that the observed variability of traffic conditions within the hour is reflected in the method. In addition, the adoption of hourly periods would significantly reduce the variability and number of empirical data samples.
- Capacity will be defined for one traffic lane (as in the HCM method) and not for the whole cross-section of the road (as in the HBS method). This solution will make it possible to analyse traffic conditions on 2x4-lane roads (such cross-sections are allowed for in the new design guidelines [8]). The differentiation of the traffic flow characteristics between 2x2 and 2x3-lane cross-sections was taken into account through different values of passenger car equivalent factors for heavy vehicles for these two types of road cross-section.
- Density of traffic expressed in passenger car units per km per lane was adopted as the basic criterion for LOS for dual carriageways, including motorways and expressways, as in both the HCM and HBS methods.
- For dual carriageway roads of all classes, the traditional division into 6 levels of service of traffic (LOS) is assumed, designated by letters A (best) to F (worst). Table 4 shows the maximum traffic density for each LOS – exceeding each of these values means a decrease in LOS by one level. For comparison, LOS criteria used in the HCM and HBS methods [16] are also shown.

Table 4. LOS criteria for dual carriageway roads

Level of service	Maximum traffic density		
	New Polish method	HCM	HBS
LOS [i]	[pcu/km/lane]	[pcu/km/lane]	[pc/km/lane]
A	6.5	7	4
B	11.0	11	8
C	16.0	16	12
D	21.0	22	17
E	26.5	28	23
F	> 26.5	> 28	> 23

5.2. Equivalent traffic flow rate

The equivalent traffic flow rate, Q_o , is the flow rate of traffic during the peak 15 minutes in an hour, converted to hourly flow and expressed in passenger car units per lane. This flow represents the traffic loading on the road in a standard way, taking into account traffic composition, hourly traffic variability and the impact of longitudinal gradients.

(5.1) $$Q_o = \frac{Q_m}{n \cdot k_{15}} E_w$$

where:

Q_o - equivalent traffic flow [pcu/h/lane], Q_m - representative traffic flow [veh/h], E_w - weighted passenger car equivalent factor [pcu/veh], n - number of lanes [-], k_{15} - peak hour factor [-].

The weighted passenger car equivalent factor for the traffic stream is given by the formula:

(5.2) $$E_w = E_s(1 - u_c) + E_c \cdot u_c$$

where:

E_s - passenger car equivalent factor for passenger cars on upgrades [pcu/veh], E_c – passenger car equivalent factor for heavy vehicles [pcu/veh], u_c – proportion of heavy vehicles in traffic [-].

Values of pcu equivalent factors E_c and E_s are given in Table 3.

5.3. Capacity

Based on the models developed, the capacity of motorways and expressways has been determined, depending on the free flow speed of the road. Table 5 shows the basic capacity values for roads of different classes, expressed in passenger car units per hour per lane. The optimum speed is also shown, that is the speed at traffic flow equal to capacity. Basic capacity values are given by the following equations – for motorways:

(5.3) $$C_o = 1600 + 5 \cdot V_{SW}$$

and for expressways:

(5.4) $$C_o = 1550 + 5 \cdot V_{SW}$$

where:

C_o – basic capacity [pcu/h/lane], V_{SW} – free flow speed [km/h].

Table 5. Values of basic capacity for motorways and expressways

Free flow speed V_{sw}	Motorways		Expressways	
	Capacity C_o	Optimum speed V_{op}	Capacity C_o	Optimum speed V_{op}
km/h	pcu/h/lane	km/h	pcu/h/lane	km/h
130	2250	85	-	-
120	2200	83	2150	80
110	2150	81	2100	78
100	2100	79	2050	76
90	2050	77	2000	74

The basic capacity is expressed in passenger car units per lane. In order to obtain the capacity of the entire cross-section in vehicles per hour, the values in Table 5 must be multiplied by the number of lanes and divided by E_w - weighted average passenger car equivalent factor, corresponding to the actual traffic composition (Eq. 5.2).

5.4. Level of service

Taking into account the pre-assumed parameter ranges, curves based on Van Aerde model have been calibrated to represent the relationship between the average traffic speed and the traffic flow rate. These curves and the values of capacity of class A and S roads (Table 5) form the basis for the method of assessing traffic conditions of basic road segments. Figures 4 and 5 show families of speed-flow curves - for motorways and expressways, respectively.

Based on the selected chart and the previously calculated equivalent traffic flow Q_o (Eq. 5.1), the speed of traffic V_e can be determined. If the free flow speed for the given road segment differs from the nearest curve by more than 1 km/h, we can use interpolation between the nearest two curves. The density of traffic is given by the formula known as the "fundamental traffic relationship". Density is equal to the traffic flow rate divided by the speed:

$$k_o = \frac{Q_o}{V_e} \tag{5.5}$$

The prevailing level of service of traffic is determined by comparing the density calculated from Eq. (5.5) with the maximum densities for each LOS given in Table 4.

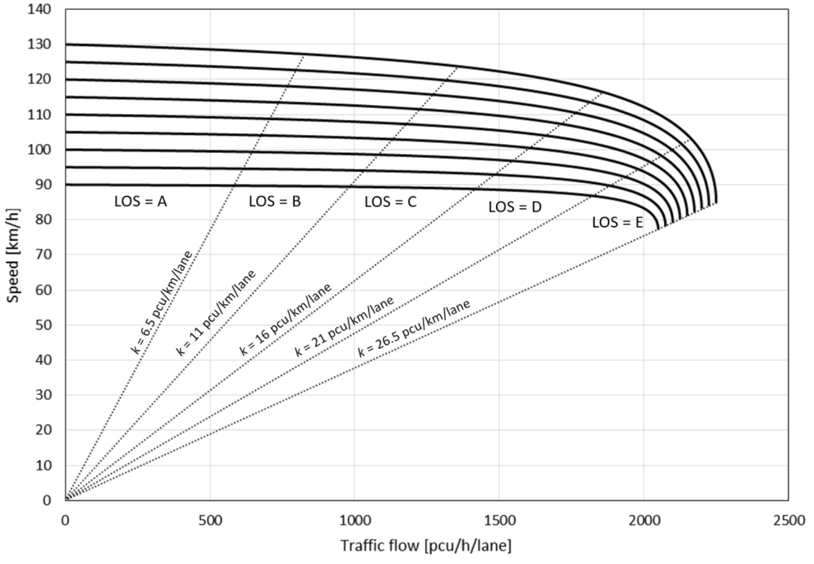


Fig. 4. Traffic speed-flow relationships for motorways

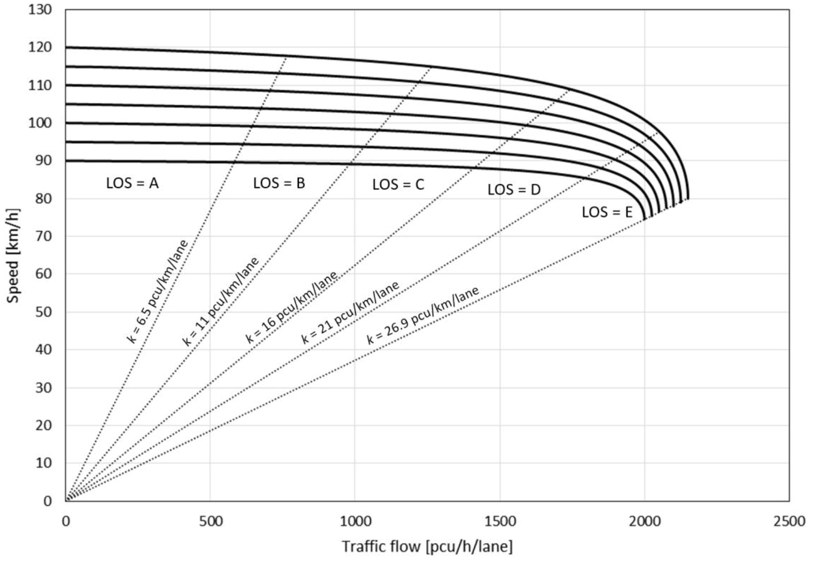


Fig. 5. Traffic speed-flow relationships for expressways

5.5. Steps in the capacity analysis procedure

The procedure of capacity analysis can be applied both to segments of existing dual carriageway roads as well as proposed roads. It consists of the following steps:

1) For each road segment and each direction, assemble the input data: road class, number of lanes, area type (metropolitan, rural), ramp density, longitudinal grade, speed limit, representative traffic flow, traffic composition, peak hour factor.
2) Calculate the free flow speed for each road segment and each direction (see section 4.4). For existing roads, it is recommended to measure the free flow speed in the field.
3) Based on the free flow speed V_{sw} and road class, determine capacity and optimum speed.
4) Based on the free flow speed V_{sw} and road class, choose the appropriate speed-flow curve.
5) Determine equivalent traffic flow Q_o in pcu per hour per lane.
6) Using the curve from step 4, estimate the traffic speed V_e, corresponding to the value of equivalent traffic flow Q_o (pcu/h/lane).
7) Find the traffic density in pcu/km.
8) Determine the Level of Service based on traffic density.

6. SUMMARY AND CONCLUSIONS

The new capacity analysis method presented applies to basic segments of motorways and expressways. It was developed on the basis of field surveys carried out on 30 segments of class A and S roads. Observed traffic flow rates and speeds in 15-minute intervals were used to calibrate free flow speed models as well as traffic speed-flow relationships for roads of different types. In the adopted model, the free flow speed depends on the speed limit, the type of area (metropolitan, rural) and the ramp density. The Van Aerde model was adopted to represent the speed-flow relationship, which was calibrated based on traffic survey results. In the resulting family of models, the basic capacity of the road depends on the road class (motorway, expressway) and the free flow speed of the road segment. The method allows one to determine the level of service for a given road under either observed or forecast traffic flow rate. Based on local and foreign experience, threshold values of traffic density (in passenger car units per km) have been assumed as criteria for determining the Level of Service. The critical traffic density corresponding to capacity is equal to 26.5 pcu/h/lane for all types of dual carriageway roads.

For determination of the Level of Service, traffic flow has to be converted to equivalent flow rate, expressed in pcu/h/lane. This flow rate takes into account traffic composition and fluctuations of traffic during one hour. Passenger car equivalent factors were determined by an iterative method, using Polish and German experience. Formulae for the calculation of peak hour factor were estimated from surveys based on representative traffic flow rate and area type.

In summary, we can conclude that the proposed new capacity analysis methodology, based on field traffic surveys conducted in Poland, will allow for a more accurate and systematic estimation of capacity and assessment of traffic conditions on basic segments of motorways and expressways. As the speed-flow models were calibrated based mostly on observations in metropolitan areas, they are expected to produce more accurate results for these areas. In future research, it would be advisable to validate the models for rural areas, as more suitable speed-flow data become available.

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LIST OF FIGURES AND TABLES:

OPRACOWANIE NOWEJ POLSKIEJ METODY ANALIZY PRZEPUSTOWOŚCI ODCINKÓW AUTOSTRAD I DRÓG EKSPRESOWYCH

Słowa kluczowe: analiza przepustowości, autostrady, drogi ekspresowe, model Van Aerde, prędkość swobodna, poziom swobody ruchu

STRESZCZENIE:

Referat przedstawia badania, które doprowadziły do powstania nowej polskiej metody analizy przepustowości odcinków międzywęzłowych autostrad i dróg ekspresowych. Metoda została opracowana w ramach projektu badawczego RID-I-50

pt. „Nowoczesne metody obliczanie przepustowości i oceny warunków ruchu dla dróg poza aglomeracjami miejskimi, w tym dla dróg szybkiego ruchu". Celem projektu była nowelizacja polskiej metody oceny warunków ruchu i szacowania przepustowości dla dróg o ruchu nieprzerywanym. Projekt był współfinansowany przez Generalną Dyrekcję Dróg Krajowych i Autostrad oraz Narodowe Centrum Badań i Rozwoju w ramach programu Rozwój Innowacji Drogowych. Projekt został zrealizowany przez konsorcjum trzech uczelni: Politechniki Krakowskiej, Politechniki Gdańskiej i Politechniki Warszawskiej.

Opisana w artykule część projektu dotyczy dróg o klasie funkcjonalnej A (autostrady) i S (drogi ekspresowe). Obie klasy to drogi dwujezdniowe o ograniczonym dostępie. Metoda powstała na podstawie badań terenowych na 30 odcinkach tych dróg. Podczas pomiarów ruch był filmowany na obu końcach odcinka pomiarowego a przy pomocy metody automatycznej identyfikacji numerów rejestracyjnych ANPR określano czas przejazdu odcinka przez poszczególne pojazdy. Dla każdego interwału 15-minutowego określano natężenie i strukturę ruchu oraz średnią prędkość.

Opracowana nowa metoda uwzględnia związki występujące pomiędzy fundamentalnymi zmiennymi charakteryzującymi ruch (natężenie, prędkość, gęstość) na poszczególnych poziomach swobody ruchu. Pomierzone natężenia ruchu oraz prędkości wykorzystano do kalibracji zależności natężenie-prędkość dla różnych typów dróg na podstawie modelu teoretycznego Van Aerde. Uzyskane zależności pokazano na rys. 4 dla autostrad oraz rys. 5 dla dróg ekspresowych. Na podstawie modeli można wyznaczyć przepustowości odcinków dróg w zależności od klasy drogi (A lub S) oraz prędkości w ruchu swobodnym. Przepustowość wynosi od 2000 do 2150 E/h/pas dla dróg ekspresowych oraz od 2050 do 2250 E/h/pas dla autostrad (Tabela 5). Poza modelami natężenie-prędkość, w ramach projektu opracowano równanie do szacowania prędkości swobodnej na danej drodze w zależności od klasy drogi, typu obszaru (aglomeracja, poza aglomeracją), prędkości dopuszczalnej oraz gęstości wjazdów i wyjazdów (równania 5.1 i 5.2).

Wyznaczenie poziomu swobody ruchu wymaga przedstawienia natężenia ruchu w postaci natężenia obliczeniowego, w pojazdach umownych na godzinę na pas. Natężenie obliczeniowe uwzględnia udział pojazdów ciężkich, współczynniki przeliczeniowe na pojazdy umowne oraz współczynnik nierównomierności godzinowej k_{15}. Wartości współczynników przeliczeniowych pojazdów ciężkich na pojazdy umowne wyznaczono stosując procedurę iteracyjną z wykorzystaniem doświadczeń polskich i niemieckich. Do zastosowania przyjęto wartości, które pozwoliły najlepiej dopasować modele Van Aerde do danych empirycznych (Tabela 3). Współczynniki przeliczeniowe zależą od liczby pasów na jezdni, pochylenia podłużnego drogi oraz stopnia obciążenia drogi. Dane empiryczne z pomiarów ruchu wykorzystano także do kalibracji zależności współczynnika nierówności godzinowej od natężenia ruchu i typu obszaru.

Metoda pozwala na wyznaczenie poziomu swobody ruchu (PSR) panującego na odcinku drogi dwujezdniowej dla zmierzonego lub prognozowanego miarodajnego natężenia ruchu. Na podstawie doświadczenia krajowego i międzynarodowego, przyjęto gęstość ruchu (w pojazdach umownych na km na pas) jako miarę efektywności dla zdefiniowania poziomów swobody ruchu dla dróg dwujezdniowych. Maksymalne gęstości dla poszczególnych poziomów PSR podaje Tabela 4. Wartość 26,5 E/km/pas jest to gęstość krytyczna, odpowiadająca natężeniom ruchu równym przepustowości dla wszystkich typów dróg dwujezdniowych.

W podsumowaniu należy zauważyć, że proponowana nowa metodyka analizy przepustowości dla odcinków dróg dwujezdniowych jest oparta na danych empirycznych zebranych podczas pomiarów ruchu w Polsce. Dzięki temu metoda lepiej oddaje lokalne warunki ruchu i pozwala na bardziej dokładne i systematyczne obliczanie przepustowości jak również ocenianie warunków ruchu na polskich autostradach i drogach ekspresowych.

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