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REVIEW OF METHODS FOR ASSESSING TRAFFIC CONDITIONS ON BASIC MOTORWAY AND EXPRESSWAY SECTIONS

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Abstract:

Motorways and expressways are the core of each country's road system. Road planning, design and management requires tools to ensure that roads have the right geometry, traffic layout and equipment. These include methods for capacity estimation and assessing traffic conditions. Because the paper focusses on the basic segments of motorways and expressways (sections located between interchanges and outside of their influence), its objective is to review and compare methods used worldwide and establish whether their assumptions or procedures could be used in Polish conditions. Four methods were selected for analysis: US, German, Swedish and Dutch. Theoretical and empirical comparisons were conducted, with the latter using data from sections of motorways and expressways in Poland collected in the RID-2B project. The results of the analyses showed important differences between the methods in terms of procedures for traffic conditions assessment, assumptions, base capacities, traffic conditions measures, factors or speed-flow models. Significant differences were also found when traffic parameter estimates made with particular methods were compared to real data from Polish roads. The results contributed to the development of Poland's new method, to be prepared as a result of the RID-2B project. It was concluded that none of the analysed methods can be directly adopted to Polish conditions. An important conclusion is the need to include Poland-specific motorway speed limits and procedure for determining free-flow speed, the basis for further analyses.

Keywords: *motorway, expressway, basic segments, capacity, traffic conditions*

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1. Introduction

Motorways and expressways (ME roads) are high standard roads which are the core of each country's road network. They are designed to handle large high speed traffic flows and ensure a high level of road safety, high driving comfort and low environmental impact. Decisions to build this type of roads 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 of the proposed solutions and assessing traffic conditions for forecasted traffic volumes. For this purpose, road traffic conditions assessment methods (RTCA methods) are used of which the best known is the US's HCM method (TRB, 2016). It gives concepts, guidelines and procedures to determine the capacity or assess traffic conditions on various types of roads, including ME roads. HCM is used in many countries, not just the US, although it is usually adapted to local conditions (GDDKiA, 1995; Luttinen and Innamaa, 2000). Other countries elaborate their own methods for determining the functionality of a planned road or assessing the operation of an existing road (FGSV, 2015; Nakamura, 1994; Ravinder et al., 2014; Rijkswaterstaat, 2015; Trafikverket, 2014; Zhou et al., 2016).

Poland has also faced the challenge of developing its own RTCA method for ME roads. In recent years the length of Poland's ME network has increased significantly, from a mere 600 km in 2002 to 3.7 thous. km in 2018. By 2025 the length of the ME network is to be 7.5 thous. km, which will ensure consistent, efficient and high quality interregional and international road connections in Poland. Given the increase, but also the amount of traffic carried by these roads (even over 100 thous. veh./24h) and the predicted growth, it is crucial to ensure appropriate traffic conditions on both existing and planned ME roads.

Despite its modest ME road network at that time, in 1995 Poland adopted formal guidelines on how to estimate capacity and assess traffic conditions on ME roads (Polish 1995 method) (GDDKiA, 1995), which was based on HCM 1985. Since then the ME network has increased twelvefold, the number of passenger cars has increased threefold, the average daily traffic volume has increased two and a half times, the vehicle fleet structure and the type structure of vehicle flows on the road have changed, yet the Polish 1995 method still applies, in a completely unchanged form. This problem was noticed by the General Directorate for National Roads and Motorways (GDDKiA) and in 2016, a consortium made up of the Cracow University of Technology, Gdansk University of Technology and Warsaw University of Technology began to work on the RID-2B project, aimed at updating the Polish 1995 method.

The first step towards developing a new Polish method for assessing traffic conditions on basic segments of ME roads (which are the sections of ME roads located between interchanges and outside of their influence) was to review existing RTCA methods used worldwide, with particular emphasis on the procedures, models, assumptions and parameters. The aim of the paper is to summarise the findings and to compare the methods using real data from ME roads in Poland. The following research (RQ) and practical (PQ) questions were posed:

- RQ1: Are there significant differences between RTCA methods used worldwide?
- RQ2: Are the results of the assessment of traffic conditions achieved by different RTCA methods comparable to each other?
- RQ3: What is the accuracy of traffic flow parameter estimates obtained with particular RTCA methods in relation to the real data from Polish roads?
- PQ1: Which of the analysed RTCA methods can be applied in Polish conditions?
- PQ2: What elements of the existing RTCA methods could be adopted in the new Polish RTCA method?
- PQ3: What should be the structure of the new Polish RTCA method?

2. Background

Road performance can be assessed from two perspectives: efficiency and prevailing traffic conditions. Road efficiency tells us how much traffic a given road section can carry. It is measured by capacity, defined as the maximum number of vehicles that may cross a given section of road or lane in an hour in prevailing roadway, traffic and control conditions (TRB, 2016). Traffic conditions are in turn a particularly important aspect for the road user, since they define the quality of travel, and in particular: the freedom to choose the desired speed, the freedom to manoeuvre, the level of traffic interruptions and travel comfort (Pamuła, 2016). Both concepts, capacity and traffic conditions, are interrelated - the traffic conditions that prevail on a given road at a given level of traffic volume strongly depend on its capacity. Therefore, in the traffic conditions assessment procedure for an existing or planned road, two main steps are distinguished: determination of capacity and assessment of traffic conditions on this road at a given traffic volume level, using measures and classification criteria. The most common measures of traffic conditions are the volume-to-capacity ratio or service flow rates (FGSV, 2015; Heikoop and Henkens, 2016; Zhou et al., 2016), traffic density (TRB, 2016) and measures used less often or used as auxiliary: probability of congestion occurrence (Geistefeldt, 2016; Heikoop and Henkens, 2016), speed related measures (Zhou et al., 2016) or travel time related measures (Heikoop and Henkens, 2016; Olszewski et al., 2018). The class of traffic conditions (level of service) is determined by comparing the actual values (measured or estimated) of selected traffic conditions measures with the threshold values of these measures, after reaching which the level (class) of traffic conditions changes. The simplest classification of road traffic conditions was initially used in Germany, where traffic conditions were divided into two classes: good (when the average speed v exceeds speed at capacity v_{opt}, $v > v_{opt}$) and bad (when $v < v_{opt}$). In the USA the division of traffic conditions into six classes (A-F) was introduced, called level of service (LOS). The LOS concept first appeared in the HCM published in 1965 (Roess and Prassas, 2014). Since then, classification and interpretation of traffic conditions using a 6-grade LOS scale has been adopted in many countries, i.e. Germany (FGSV, 2015), Scandinavian countries (Luttinen and Innamaa, 2000) (except Sweden), the Netherlands (Heikoop and Henkens, 2016) or China (Zhou et al., 2016). Particular countries, however, use different measures of traffic conditions or assume different threshold values of these measures for particular levels of service (see example in Table 1).

Table 1 shows that at a similar level of traffic flow rate or density, the level of service is assessed differently depending on the country. This results from the use of different methods to assess traffic conditions, and, in particular, different assumptions on how measures of traffic conditions are estimated and also different adopted road capacities depending on road class, speed limit or location. Table 2 shows the differences in base capacities of ME roads from country to country, for a four lane (2x2 lanes) rural motorway segment with a speed limit of 110 km/h. Base capacity should be understood as the capacity in conditions of a low heavy vehicles (HV) share, flat terrain, regular lane and right shoulder width.

Table 1. Comparison of LOS threshold values of selected traffic flow parameters adopted for the motorway traffic conditions assessment procedure in the USA and Germany – example of rural four lane motorway segment, speed limit 120 km/h (FGSV, 2015; TRB, 2016).

Country	Level of service (LOS)				
	A	B	C	D	E
Volume-to-capacity ratio X [-]					
USA	0.34	0.55	0.73	0.88	1.00
Germany	0.30	0.55	0.75	0.90	1.00
Density k_0 [pc/km/lane]					
USA	7	11	16	22	28
Germany	4	8	12	17	23
Average speed of pc* v [km/h]					
USA	120	119	111	99	86
Germany	125	120	112	99	80
Service flow rate $q_{0,LOS}$ [pc/h/lane]					
USA	820	1310	1750	2110	2400
Germany	570	1045	1425	1710	1900

*pc – passenger cars

Table 2. Base capacity of a four lane rural motorway section with a speed limit of 110 km/h adopted in selected countries. Source: (FGSV, 2015; GDDKiA, 1995; Heikoop and Henkens, 2016; Luttinen and Innamaa, 2000; Nakamura, 1994; Ravinder et al., 2014; Trafikverket, 2014; TRB, 2016; Zhou et al., 2016)

Method	**Capacity [pc/h]**	**Method**	**Capacity [pc/h]**
United States	4,800	Poland	4,400
Germany	3,800*	Norway	4,000
Netherlands	4,300	Australia	3,600
Sweden	4,150*	Indonesia	4,600
Denmark	4,400	Japan	4,400
Finland	4,000	China	4,400

*Base capacity in pc/h estimated considering volume in veh./h and low HV share

Table 2 shows a high variation in adopted capacities from country to country. The lowest values are seen in Australia and Germany (3,600-3,800 pc/h) and the highest in the US (4,800 pc/h). It is clear that the difference in this case is even 1,000-1,200 pc/h (500-600 pc/h/lane). As stated by Wu (Wu, 2005) the difference in road capacity values between countries may result, among others, from different legal conditions and traffic rules. For example, in the USA it is common to stay in one lane and overtaking is allowed from any side, while in Germany there is a rule of driving on the right and overtaking only on the left. This may influence driver overtaking and lane selection behaviour, affecting lane distribution and road capacity (Wu, 2005). Similarly, the differences in how traffic rules are enforced may also significantly affect driver behaviour, and as a result, road capacity and traffic conditions.

Another reason for the differences in Table 2 is how traffic flow variability within the hour is treated. For example, in the US's HCM method the reference time period for the analysis is a 15-minute interval - that means that the given capacity corresponds to a maximum 15-minute traffic volume. While in the German HBS method the capacity is given as the maximum traffic volume corresponding to 1-hour time interval. For both values to be comparable, the peak hour factor PHF should be applied. For example, assuming $PHF = 0.95$ at the capacity flow, the hourly capacity value in the HCM is approx. 4560 pc/h. Similarly, the difference can be partly explained by how heavy vehicles are treated in the analyses and the adopted values of passenger car units (Srikanth and Mehar, 2017).

Understood as the capability of a road to carry traffic, the higher the capacity, the higher the volume that can be served. Thus, on similar roads in Germany, Poland or the US, at the same volume levels, drivers can have a different sense of freedom and driving quality. The RTCA method developed e.g. for the USA may not be applicable to ME roads in other countries and should be verified for specific country's conditions before use. This was proved by Pompigna and Rupi (Pompigna and Rupi, 2015), who found that the capacity estimated using the HCM method is even 30% higher than the actual capacity estimated based on empirical data from the A14 motorway in Italy. Thus, using the HCM for the case of Italian motorways may lead to an underestimation of traffic conditions assessment. Similar conclusions were drawn by Bertini et al. (Bertini et al., 2006), who compared the capacity obtained using HCM and HBS methods for the A9 motorway section in Germany. He found that the difference depending on the method used is even 20%. This can be a reason why countries work on their own methods or adapt existing ones to their specific conditions. This also justifies why the paper aims to compare RTCA methods and check how they apply to specific Polish conditions.

3. Methodology

In order to answer the questions, research was conducted to compare selected RTCA methods. The studies were divided into two segments:

- studies based on literature review and examination of existing RTCA methods (Chapter 4),
- analytical research using empirical data, based on a comparison of traffic condition assessments with selected RTCA methods and comparing estimated values of traffic condition measures with empirical data (Chapter 5).

The research covered those parts of RTCA methods which assess traffic conditions on basic segments of motorways (defined in Introduction). The methods can be applied to assess traffic conditions on basic segments of Polish motorways and expressways.

The objective of the theoretical research was to compare RTCA methods for their assumptions, input data, factors, input speed and capacity values. This helped to identify the advantages, disadvantages and gaps that would enable or hinder the use of the analysed methods in Poland. Four foreign methods were selected for the analysis: the US's HCM, Germany's HBS, Sweden's SHCM and the Netherlands' DHCM. The choice of methods was dictated by their originality and availability; as a result, the detailed analysis did not include methods that are a direct adaptation of another method (e.g. HCM) or Asian methods, the manuals of which would be difficult to find and use.

The objective of the analytical research was to compare the selected RTCA methods (HCM, HBS, SHCM, DHCM) using empirical data from Polish ME roads.

3.1. Data

The analyses use data from traffic measurements carried out within the RID-2B project (RID, 2016).

These included ME road segments selected in a four-stage procedure looking at the technical feasibility of conducting measurements and road and traffic parameters, i.e. cross-section, speed limit, vicinity of interchanges, annual average daily traffic, traffic flow composition or road location.
The measurements were carried out with ANPR (automatic number-plate recognition) and MioVision Scout devices for a minimum period of 24 hours, from May to October 2017. Data were obtained such as the speed of individual vehicles and the number of vehicles registered by the measuring devices, with classification by type (passenger car, light truck, heavy truck, bus, etc.). The data was aggregated into 15-minute intervals. Traffic flow and average speed of vehicles (aggregated into two classes: passenger cars, heavy vehicles) data was obtained for each interval. For further analyses, data was extracted only for daytime hours (5:00-21:00) to avoid the impact of lack of natural lighting on the speed of vehicles. Similarly, based on the analyses of video files, intervals involving road incidents and adverse weather conditions were excluded.
A collective summary of the survey sites is presented in Table 3. It presents survey site location (urban/rural), road cross-section (2x2 lanes, 2x3 lanes) and the speed limit (90-140 km/h). The total number of measurement hours amounted to 540 h. Figure 1 presents speed-flow charts for empirical data collected at the survey sites.

Table 3. A collective summary of the survey sites

Cross-section	Speed limit [km/h]	Road location		Total
		rural	urban	
Four lane (2x2 lanes)	100	0	2	2
	110	2	0	2
	120	0	4	4
	140	4	4	8
Six lane (2x3 lanes)	90	0	2	2
	120	0	4	4
	140	0	8	8
Total		6	24	30

For each of the survey sites, the necessary data were compiled such as the number of lanes, width of lanes and shoulders, speed limits, and interchange density. All analysed sections were situated on flat terrain. In each survey site the free-flow speed was determined as the average speed of passenger cars in low traffic conditions (<1,000 veh/h/lane) and the peak hour factor *PHF*, as the ratio of one hour traffic flow to four times the maximum traffic volume in the busiest 15 minutes of this hour.

3.2. Analyses based on empirical data

For each survey site and 15-minute interval, the measures of traffic conditions were calculated using the selected RTCA methods: average speed of passenger cars and volume-to-capacity ratio. Since the analysed RTCA methods apply to free-flow traffic conditions only (when $v > v_{opt}$), the intervals in which the speed fell below 80 km/h were excluded from the analysis. Due to the aggregation of traffic volumes into 15-minute intervals, capacity in the case of HBS, DHCM, SHCM (which are based on a 1-hour interval analysis) was reduced to 15-minute values using the PHF factor.
Descriptive goodness-of-fit measures were used to assess the accuracy of speed estimation produced by individual RTCA methods. These measures are commonly used to evaluate fit and compare nonlinear models. In each case the lower the value, the better the speed estimate in relation to empirical data. The analysed goodness-of-fit measures included:

- Mean Squared Error (MSE) – the average squared difference between the actual and estimated values,

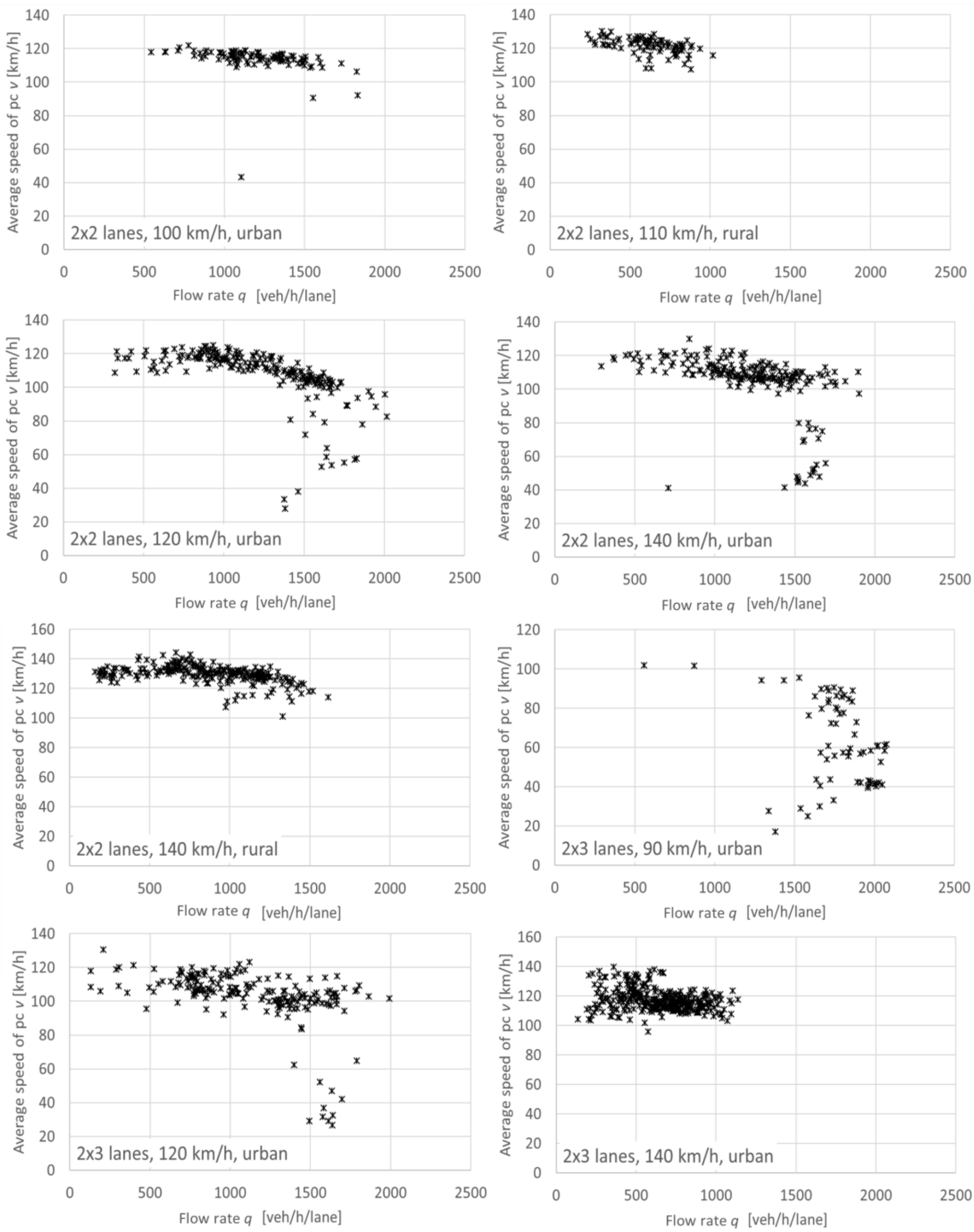
$$MSE = \frac{1}{T}\sqrt{\sum_{t=1}^{T}\left(y_t - y_t\right)^2} \quad (1)$$

- Root Mean Squared Error (RMSE) – indicates how the average actual values of the analysed variable deviate from the estimated values of this variable; expresses the average estimation error in the units of variable of interest,

$$RMSE = \sqrt{\frac{1}{T}\sum_{t=1}^{T}\left(y_t - y_t\right)^2} \quad (2)$$

- Mean Absolute Percentage Error (MAPE) – indicates the average size of estimation errors of the analysed variable in relation to its actual values,

$$MAPE = \frac{1}{T}\sum_{t=1}^{T}\left|\frac{y_t - y_t}{y_t}\right| \cdot 100\% \quad (3)$$



ig. 1. Speed-flow charts presenting empirical data from survey sites

- Mean Error (ME) – the average difference between the observed and estimated value of the analysed variable,

$$ME = \frac{1}{T}\sum_{t=1}^{T}\left(y_t - y_t\right) \qquad (4)$$

- Mean Percentage Error (MPE) – indicates what percentage of the actual value of the analysed variable is the estimation error.

$$MPE = \frac{1}{T}\sum_{t=1}^{T}\frac{\left(y_t - y_t\right)}{y_t}\cdot 100\% \qquad (5)$$

where:
T – number of observations,
y_t – observed value of the analysed variable,
$\hat{y}_t$ – value of the analysed variable estimated using the model.

T-test was used to assess whether the difference between empirical and estimated mean speeds is statistically significant. The significance level was set at $\alpha = 0.05$ and $p < 0.05$ was considered to be statistically significant. The tests were conducted for different levels of flow rate, taking into account the speed limit and the number of lanes.
Not all RTCA methods use the LOS concept, therefore the assessment of traffic conditions by individual RTCA methods was carried out for the volume-to-capacity ratio X, values of which were determined for each survey site and for each time interval with the use of the four analysed methods. The results were analysed by comparing their distributions in 6 X classes (Table 4). The results of the analyses are presented in Chapter 5.

Table 4. The classes of traffic conditions adopted for analyses

Traffic regime	The class of traffic conditions	Volume-to-capacity ratio ***X***
Free-flow	I	≤ 0.3
	II	≤ 0.55
	III	≤ 0.75
	IV	≤ 0.9
	V	≤ 1.0
Congested	VI	>1.0

4. Comparison of RTCA methods

4.1. General review of RTCA methods

The history of RTCA methods for assessing traffic conditions on ME roads dates back to 1950, when the first version of the US Highway Capacity Manual (HCM) was published (Roess and Prassas, 2014). The manual was followed by subsequent versions in 1965, 1985 (further updated in 1992, 1994 and 1997) and 2000, 2010, 2016, in which both the definition of capacity, measures of traffic condition assessment and the format of the method itself changed. To date, the HCM is one of the most important sources of engineering knowledge on transport and road traffic in the US and around the world. The development of American guidelines was an impulse for many countries to carry out their own research and attempt to formulate their own methods. For example, in selected European countries (Germany, Sweden, the Netherlands) original methods are used that are based on national research. Other countries such as Canada, Australia, Poland, Finland, Norway and Denmark use procedures and models from the HCM adapted to local conditions.
In Germany, the impulse to create their own method was sparked by the publication of the second version of the HCM in 1965, however, it was not until 2001 that a national method was published for the first time (Boltze, 2006; Geistefeldt, 2016). In 2015, the latest second version of the German HBS method was published (FGSV, 2015). The German method, despite several similarities (e.g. the use of LOS), significantly departs from the HCM, with the models based on empirical studies and simulations conducted in Germany during the previous 20 years.
The Dutch have been conducting regular annual monitoring of traffic conditions on motorways since 1968 using the HCM method (Heikoop and Henkens, 2016). The first attempts at creating their own method were made in the 1990s, as a result of which the Dutch HCM was published in 1999, followed by subsequent editions in 2002, 2011 and 2015 (in force). The method is based on empirical capacity studies and simulations carried out using the FOSIM model. Similarly to the German and American methods, it uses the LOS on the A-F scale to classify traffic conditions, but the procedure itself differs significantly from the procedures used in the HCM or HBS methods.

Sweden also developed its own method. The Swedish SHCM was first published in 1977 and then updated in the 1990s (Bergh et al., 2016), while the latest guidelines were published in 2014 (Trafikverket, 2014). Swedes do not use the LOS. At the road design stage, the use of capacity calculations is to ensure that the newly designed road, for a design hour is characterised by a maximum average speed of 10 km/h below the speed limit, the maximum of a 5-minute time loss and the volume-to-capacity ratio of not more than 0.5 (Luttinen and Innamaa, 2000).
RTCA methods are also used in Asian countries. A project was implemented in India (2012-2017) aimed at developing their own capacity analysis guidelines Indo-HCM (Ravinder et al., 2014). Indonesia has its own method (Irawan et al., 2009) which takes account of the high proportion of two-wheeled vehicles in the country. China, which over the past several years has become a global power in terms of motorway and expressway length, began traffic studies in 2000, and intensified work on CHCM – a Chinese method of calculating capacity in 2012 (Zhou et al., 2016). The method adopts six levels of service (A-F), determined on the basis of volume-to-capacity ratio and the difference between average speed and free-flow speed as an additional indicator, which takes into account the composition of traffic. Japan, which had previously used the HCM, in 1984 published their own method, based on research conducted in the country, without using the LOS to assess traffic conditions.
Individual RTCA methods vary in terms of procedure, models, assumptions or factors that may impact speed or capacity. In particular:

- different base capacities are adopted in the RTCA methods (Table 2),
- the methods are based on a 1-hour or 15-minute interval of traffic conditions analysis,
- calculations are made for a lane (e.g. HCM) or cross-section (HBS, Dutch and Swedish methods),
- the procedure uses the traffic flow rate expressed in pc/h (e.g. HCM, China, the Netherlands) or veh./h (e.g. HBS, Sweden),
- most methods use the LOS concept, except for Sweden, the Netherlands and Japan,
- the LOS is usually determined on the basis of density (HCM, Poland) or volume-to-capacity ratio (HBS, China, the Netherlands), the less often used criteria include: congestion probability (the Netherlands) or a decrease in the average speed relative to free-flow speed (China),
- the influence of other factors on free-flow speed and capacity (e.g. lane width, weather conditions, road class) is taken into account,
- the methods require detailed calculations (HCM) or reading particular measures from tables and graphs (Germany, Sweden).

Further in the paper a more detailed analysis and comparison of approaches for motorways were made for the methods: the US's HCM, Germany's HBS, the Netherlands' DHCM and Swedens's SHCM. They are original methods, based on own studies, rather than directly adopting elements of other methods. The instructions for assessing traffic conditions are available (in their respective languages).

4.2. The US's HCM

The HCM 6 method assumes that traffic conditions are mostly influenced by: the number of lanes, the width of the lane and obstacle-free right shoulder, ramp density, fluctuations of traffic in the design hour, HV share and the longitudinal gradient of the road section and its length. The HCM also allows for the inclusion of the impact of weather, incidents and driver familiarity with the route in the additional procedure.
The starting point is the determination (measurement or estimation) of free-flow speed (FFS). This is the speed that occurs under low traffic volume conditions at which there is no interaction between the vehicles. In formula (6), the impact of the relevant factors is considered: right-side lateral clearance (f_{RLC}), lane width (f_{LW}) and ramp density on the analysed segment (f_{ID}), reducing the base free-flow speed ($FFS_0 \mathrm{v}_{\mathrm{sw}_0}$) due to restrictions. The value of FFS_0 is assumed by default as 120 km/h and the method itself applies to FFS in the range of 90 – 120 km/h.

$$FFS = FFS_0 - f_{LW} - f_{RLC} - a \cdot f_{ID}^{b} \tag{6}$$

where: a, b – coefficients of the equation (given in HCM; for speed expressed in mi/h: a=3.22, b=0.84).

Analysing the sensitivity of the model (6) it can be stated that:

- lane width below 3.65 m reduces FFS by 3.1-10.6 km/h (the highest reduction for a ≤ 3 m-wide lane),
- right-side lateral clearance less than 1.8 m reduces FFS by 0-6 km/h (the highest reduction when ≤ 0.6 m),
- each increase in the averaged (10 km) total ramp density per 1.6 km-road by 2 ramps causes a reduction of FFS by approx. 8 km/h.

In the HCM method the base capacity C_0 is given and varies, depending on FFS, in the range of 2,250 – 2,400 pc/h/lane. The flow rate q_0 (in pc/h/lane) is determined from the formula (7) by dividing the demand volume Q expressed in veh./h by the number of lanes (n) and the coefficients taking into account: the impact of irregular traffic distribution in the hour (PHF), the HV share and longitudinal gradient (f_{HV}). At the same time: the greater the traffic variability within the hour, the smaller the PHF; the greater the HV share and the greater the longitudinal gradient, the lower the f_{HV} value. Thus, along with the increase in traffic variability, HV share or gradient, the flow rate q_0 increases.

$$q_0 = \frac{Q}{PHF \cdot n \cdot f_{HV}} \tag{7}$$

By relating the obtained value of q_0 to C_0, it is already possible at this stage to assess the traffic conditions, i.e. to determine whether the cross-sectional capacity has been exceeded (when $q_0/C_0 \geq 1$). In this case, the procedure ends with the assignment of traffic conditions corresponding to LOS F. Or, the method allows for further calculations, i.e. determining the average travel speed v, and the existing LOS, the measure of which is the traffic density k_0 (as the ratio of q_0 to v).

The average speed of passenger cars v at the observed traffic volume is determined from the HCM model (8). The model assumes that the speed v is constant and equals FFS until the break point flow rate $q_{0,BP}$ is exceeded, when the speed begins to decrease in accordance with the formula (8). The $q_{0,BP}$ will be in the range of 1,000 – 1,800 pc/h/lane, depending on FFS. For the flow rate in the range of $q_{0,BP} < q_0 < C_0$ the average speed depends on: FFS, C_0, $q_{0,BP}$ and the $k_{0,opt}$ density occurring at the flow rate equal to the capacity.

$$\begin{aligned} v &= FFS && \text{when } q_0 \leq q_{0,BP} \\ v &= FFS - \frac{\left(\left(FFS - \frac{C_0}{k_{0,opt}}\right) \cdot (q_0 - q_{0,BP})^2\right)}{(C_0 - q_{0,BP})^2}, && \text{when } q_{0,BP} \leq q_0 \leq C_0 \end{aligned} \tag{8}$$

The curves determined based on the model (8) for different values of FFS are presented in Figure 2. From the curves the average speed at a given flow rate and capacity can be read.

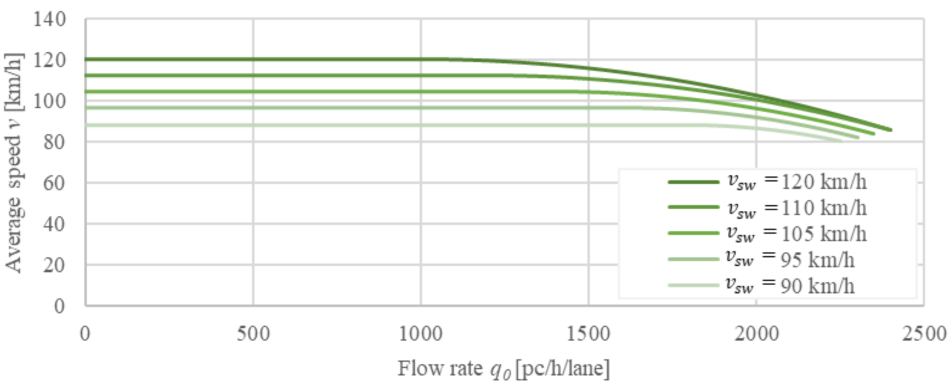


Fig. 2. Speed-flow relationship in HCM for free-flow speed levels

4.3. Germany's HBS

The HBS method provides for the impact of the following factors on traffic conditions: location of the section, number of lanes, longitudinal gradient, and length of the gradient section, HV share and the speed limit. The HBS is closely related to the German motorway design guidelines (FGSV, 2011). The method significantly deviates from the HCM, primarily due to the use of 1-hour analysis interval, different traffic flow rate units (veh./h instead of pc/h) and reference (cross-section, not one lane), the factors and the model used.

The procedure consists of four steps: (1) gathering data, (2) determining capacity, (3) assessing traffic conditions - assigning the LOS, (4) calculating average speed. The HBS does not require complex calculations, which makes it a "pen & paper" method. The capacity is read from the table considering location of the road, number of lanes, speed limit, HV share and longitudinal gradient. The road capacity C varies in the range of 3,200 – 4,000 veh./h on four lane (2x2 lanes) motorways and 4,600 – 5,800 veh./h on six-lane (2x3 lanes) motorways (the given values correspond to the total capacity of a roadway in one direction of traffic). The capacity C is directly compared with the traffic flow q to determine the volume-to-capacity ratio $X = q/C$. Based on this measure, traffic conditions are assessed by assigning the appropriate level of traffic conditions LOS. If X does not exceed 1, it is possible to determine the average speed from the $v(q)$ graphs prepared for over 270 combinations of factors. These curves were developed using the Van Aerde model (Van Aerde and Rakha, 1995), whose parameters were determined empirically and are included in the HBS method, in the section dedicated to motorways (Geistefeldt, 2016). Another way to determine the average speed for the given parameters, which change depending on the HV share, road location, gradient and speed limit, is the application of the model (9):

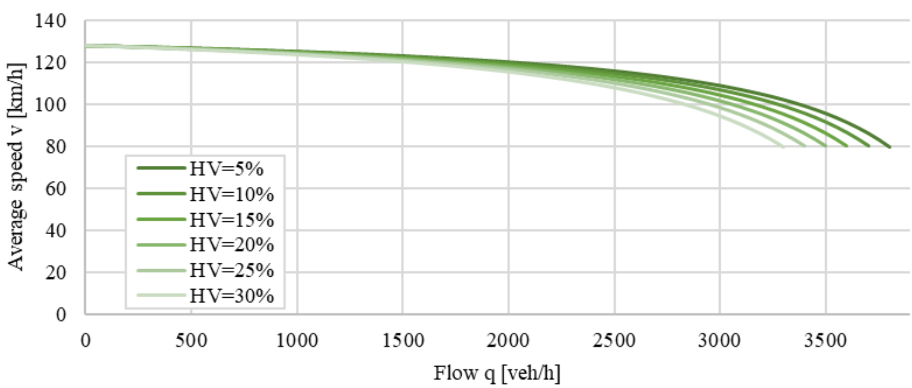
$$v(q) = \frac{v_0}{1 + \frac{v_0}{L_0 \cdot (C_0 - q)}} \tag{9}$$

where: v_0, C_0, L_0 are model parameters given in the HBS.

Figure 3 shows an example of v(q) curve graphs for a rural section of a motorway, with a speed limit of 120 km/h, flat terrain and 2 lanes, with varying percentages of HV share.

4.4. Sweden's SHCM

The procedure in SHCM distinguishes two classes of motorways, depending on the percentage of sections with visibility over 500 m and type of terrain. Class 1 is technically superior to class 2. The procedure includes the following steps: (1) gathering input data, (2) selecting from the manual a table referring to a given cross-section, speed limit, road class and location, (3) reading the values of capacity and average speed of vehicles from the table, taking their class into account. The base capacity is defined for a cross-section. The model (10) helps to determine the (irregular) distribution of traffic into lanes.



ig. 3. Speed-flow relationship in the HBS for four lane, rural, flat ME section with speed limit of 120 km/h

Traffic flow is expressed in veh./h, with the possibility of conversion into pc/h. The method does not use the LOS concept.

$$q_{RL} = \mathrm{a} \cdot (1 - e^{-\mathrm{b} \cdot q}) \quad (10)$$

where: q_{RL} – traffic flow in the right lane, a, b – model parameters (5).

The Swedish method, like the HBS, does not require complex calculations but involves reading the data from the appropriate tables – an example is shown in Table 5.

Table 5. Example for a four lane rural motorway, class 1, speed limit 110 km/h in Swedish HCM (Trafikverket, 2014)

Break point	Flow* [veh./h]	Average speed [km/h]		
		PC	HV	HV with trailer
0	0	109.0	92.0	85.5
1	1944	109.0	92.0	85.5
2	3456	101.5	85.9	79.9
3	4320	69.5	69.5	69.5
4	5184	10.0	10.0	10.0

* The given values correspond to the total flow on a roadway in one direction of traffic.

The average speeds and break point traffic flows depending on the cross-section, speed limit and road class were determined empirically. Table 5 should be understood as follows: in point 0, vehicles travel at free-flow speed; after exceeding point 1 the traffic flow begins to affect the speed of the vehicles; after exceeding point 2 this effect intensifies; in point 3 road capacity is achieved, while point 4 represents theoretical traffic flow equal to 1.2 times capacity, used in economic analyses. These relationships can also be presented in a graph as broken lines with break point values specified in the tables (Figure 4).

4.5. The Netherland's DHCM

In the Dutch method traffic conditions are assessed using two indicators: volume-to-capacity ratio and congestion probability, i.e. the maximum probability of a driver coming across congestion (in the Netherlands this is defined as the state of motorway traffic when the speed drops below 50 km/h).

Capacity (in pc/h) is defined for the so-called typical sections of motorway, i.e. sections with a speed limit of 100 or 120 km/h, 15% of HV share, with no obstacles or roadside elements to distract drivers, flat terrain (<2.5%), good quality surface, equipped with a traffic management system, where measurements are taken in good weather conditions and in daylight. In this case, the capacity depends on the number of lanes only. For a four lane motorway the capacity is 4300 pc/h, in the case of a six lane motorway it is 6200 pc/h (the given values correspond to the total capacity of a roadway in one direction of traffic).

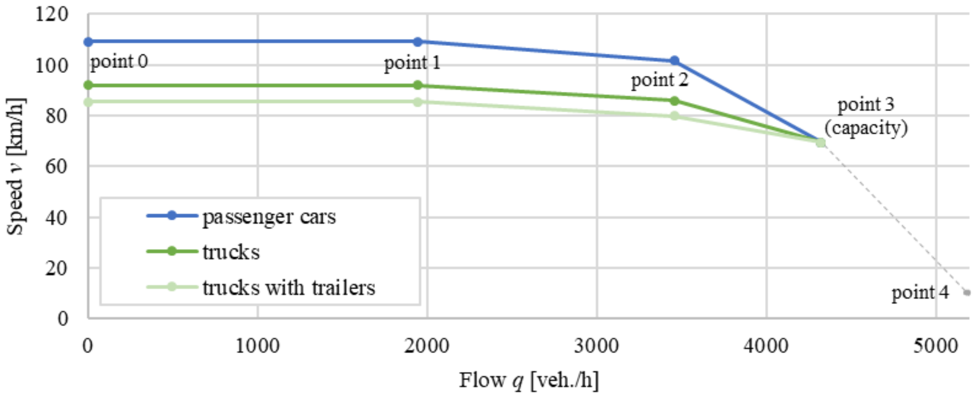


Fig. 4. Speed-flow relationship in SHCM for a four lane rural motorway, class 1, section with a speed limit of 110 km/h

The obtained capacity is adjusted for the impact of:
- weather conditions (adjustment factor equals: 1.00 for good weather conditions, 0.95 for light precipitation and 0.90 for heavy precipitation),
- lighting conditions (adjustment factor equals: 1.00 for daylight, 0.97 for lit roads, 0.95 for unlit roads).

The research conducted for the purposes of the Dutch HCM showed no impact on the capacity of lane width, right-side lateral clearance, presence of emergency lanes and speed limits. As a result, these factors are not taken into account in the analysis.

The last step in the procedure is to assess traffic conditions. The method does not use the classification of traffic conditions according to LOS. Traffic conditions are assigned to one of the five classes based on the volume-to-capacity ratio X and the corresponding congestion probability (Table 6).

Table 6. Traffic conditions assessment indicators used in the Dutch HCM

X	Congestion probability [%]
< 0.3	0
0.3 – 0.8	< 1
0.8 – 0.9	< 20
0.9 – 1.0	20 - 100
> 1.0	100

4.6. General comparison

A comparison of the selected RTCA methods in terms of the data they require, the initial parameters or factors considered in the analysis (Table 7), shows that the methods are highly varied, both in terms of the initial values, procedures, and the factors reflecting real road and traffic conditions. The HCM is particularly complex as it has the most complicated procedure and considers the highest number of factors.

Table 7. Comparison of selected RTCA methods

Characteristics	**HCM**	**HBS**	**SHCM**	**DHCM**
Required data and factors considered	volume, HV share, driver population, free-flow speed, number of lanes, lane width, right-side lateral clearance, ramp density, terrain profile, peak hour factor, weather conditions	volume, HV share, location (rural/urban), speed limit, number of lanes, terrain profile	volume, HV share, location (rural/urban), speed limit, number of lanes, road class	volume, HV share, number of lanes, weather conditions, lighting conditions
LOS concept	yes, A-F	yes, A-F	no	no
Traffic conditions assessment criteria	density, speed, volume-to-capacity, service flow rates	q/C ratio, speed	speed, service flow rates	q/C ratio, congestion probability
v(q) model	HCM	Van Aerde	Polyline	none
Reference	one lane	cross-section	cross-section	cross-section
Base traffic flow unit	pc/h/lane	veh./h	veh./h	pc/h
Analysed time period	15 min. with the highest volume within peak hour or 30-50th hour	1h, 50th hour	1h, 30th hour	1h, working day annual average
Number of procedure steps	6	4	3	3
Base capacity* of four lane road** (pc/h)	4,500 - 4,800	3,700 - 3,800	4,020 - 4,460	4,300
Base capacity* of six lane road** (pc/h)	6,750 - 7,200	5,300 - 5,400	5,400 - 6,000	6,200
Input speed (km/h)	free-flow speed, 90-120	speed limit: 80, 100, 120, no limit	speed limit: 70-120	speed limit: 100, 120

* Estimated for a very low HV share

** The given values correspond to the total flow on a roadway in one direction of traffic

There are also differences in the assumed base capacities – these values differ by up to 1,000 pc/h for four lane and 1,800 pc/h for six lane motorways. The range of input speeds in the analysis may constrain the use of the methods in other countries. For example, in the case of the HBS, DHCM and SHCM, traffic conditions may be assessed for specified speed limits only (e.g. 100 km/h, 120 km/h); in the HCM, roads with FFS higher than 120 km/h are not assessed for traffic conditions. That is the case with Polish motorways, where the speed limit is 140 km/h, as a result FFS will most likely be higher than 120 km/h. In this case, none of the methods allows for the assessment of traffic conditions or the correct estimation of the average speed of traffic flow. Although some of the methods are not based on the LOS concept, each may determine the volume-to-capacity ratio X which is the basis for comparing traffic conditions estimated with different methods. A significant difference occurs when permissible or free-flow speed are treated as the initial speed. In the case of the HCM, the starting point is the determination of free-flow speed, which is then introduced as a variable into the v(q) model. The v(q) curve will consequently originate exactly from the determined free-flow speed. In the case of a different approach used in the HBS and SHCM, where curves are determined separately for roads with similar roadway and traffic conditions, it is assumed that, on roads with the same cross-section, class, location (type of area), speed limit and similar traffic composition, drivers behave similarly. The question arises whether this behaviour will be similar in a country different from the one for which the method was developed. Chapter 2 suggests that in each country there are some differences e.g. in the traffic rules, traffic management or traffic rules enforcement, therefore, driver behaviour differs as well. This difference may be reflected e.g. in the average speed of traffic flow.

5. Empirical comparison

Fig. 5 shows the distribution of the estimated volume-to-capacity ratio returned by the HCM, HBS, SHCM and DHCM methods for the analysed survey sites. Sections with a speed limit of 140 km/h were excluded from the comparison because, as demonstrated in Chapter 4, none of the methods analysed provide for the possibility of assessing traffic conditions for roads with a speed limit of 140 km/h or free-flow speed over 120 km/h. Based on the results presented in Figure 5 it follows that:

- the vast majority of estimated values of volume-to-capacity ratio by HCM, HBS, DHCM methods are in the range of $0.3 - 0.75$; in the case of SHCM most often $0 - 0.75$,
- when $X \leq 0.9$ similar results of traffic condition assessment are returned by HCM, HBS and DHCM methods,
- in the case of SHCM there are significant differences from other methods, traffic conditions are more often classified as better in relation to other methods,
- there are practically no situations in which the road capacity has been exceeded on the analysed survey sites.

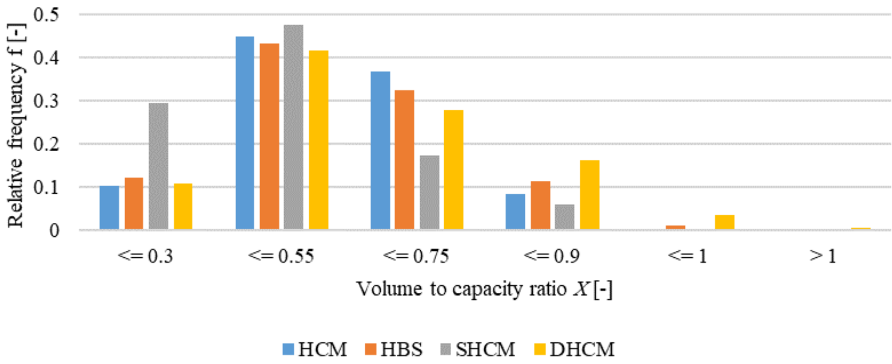


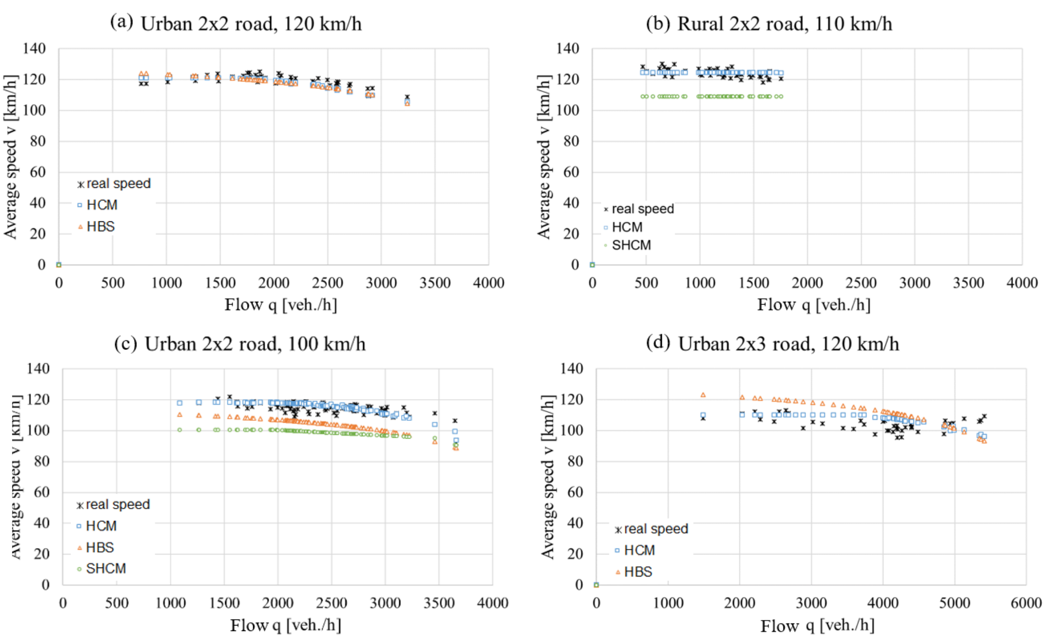
Fig. 5. Distribution of volume-to-capacity ratio

Analyses were conducted in order to compare the observed speeds of passenger cars with RTCA method estimates. For each data point (15-min. time interval at a particular survey site) the speed was estimated using HCM, HBS and SHCM methods (calculations were not made for DHCM as it does not provide a procedure for average speed estimation). Formulas given in Chapter 3 were used to assess the accuracy of estimated speeds against the real data. The results are given in table 8. It was found that the smallest errors in speed estimation occur for the HCM method, while the largest errors in speed estimation are returned by the SHCM. For the HCM method, the estimated speed deviates by 3.8 km/h on average from the actual value (RMSE error), while in the HBS the deviation is more than 2 times greater and in the SHCM more than 4 times greater.

Similar conclusions can be drawn comparing the speed values estimated using the methods on the v(q) graphs (Figure 6). Based on the results of the speed comparison, it can be observed that for both four lane (2x2 lanes) and six lane (2x3 lanes) roads with a speed limit of 100 km/h, 110 km/h and 120 km/h, visually the best fit is the HCM method. Where the SHCM applies (100 km/h and 110 km/h speed limits), the speed is evidently underestimated. The HBS method (applicable to speed limits of 100 and 120 km/h) gives good results when the actual average speed in the conditions of low traffic (up to 1000 veh/h/lane) does not differ significantly from free-flow speed (Figure 6a). If there is a significant difference between the two speeds (e.g. Figure 6c,d), the speed estimate by the HBS is less accurate than by the HCM. Given that the initial speed parameter in HCM is free-flow speed, and in the other two methods the relationships are derived for the given speed limit, for the data from Polish ME roads much better results are obtained when the relationship is derived for the given free-flow speed rather than the speed limit.

Table 8. Comparison of the observed and estimated mean speeds - results

Measure of error	Speed estimation method		
	HCM	HBS	SHCM
MSE [km^2/h^2]	14.2	70.6	204.3
RMSE [km/h]	3.8	8.4	14.3
MAPE [%]	2.7	6.2	11.7
ME [km/h]	-0.3	2.7	13.5
MPE [%]	-0.5	2.2	11.6



ig. 6. Estimation of v(q) relationship for selected cross-sections of ME roads in Poland

In order to assess whether the difference between observed and estimated speeds is statistically significant, t-tests for equity of means were conducted. The tests compared observed vs. estimated mean speeds for roads with similar characteristics (cross-section, speed limit, location) at given traffic flow levels (table 9). Table 10 presents the results of t-tests for HCM, HBS and SHCM method.

The results in table 10 indicate that there is a statistically significant difference ($p < 0.05$) between the observed mean speed and the mean speed estimated with the use of HBS or SHCM method, regardless of the volume level. In case of HCM, almost in all cases it was impossible to state that the means are significantly different.

Table 9. Mean speeds observed at survey sites and estimated using RTCA methods

Road characteristics	Flow *q* [veh/h/lane]	Mean speed *v* [km/h]			
		Observed	HCM estimate	HBS estimate	SHCM estimate
2x2 lanes, 100 km/h, urban	<1000	118.0 ± 2.0	118.2 ± 0.3	109.0 ± 0.8	100.5 ± 0.0
	1000-1500	115.0 ± 2.8	117.6 ± 0.7	105.2 ± 1.6	99.2 ± 0.9
	1500-2000	112.4 ± 2.6	113.5 ± 2.5	99.4 ± 3.0	96.6 ± 1.3
	total	114.5 ± 3.8	116.5 ± 2.7	104.1 ± 3.9	98.8 ± 1.6
2x2 lanes, 110 km/h, rural	<1000	121.5 ± 4.6	121.4 ± 4.3	n.a.	109.0 ± 0.0
	1000-1500	117.6 ± 4.4	116.6 ± 3.1	n.a.	109.0 ± 0.1
	total	121.0 ± 5.0	120.3 ± 4.5	n.a.	109.0 ± 0.0
2x2 lanes, 120 km/h, urban	<1000	116.9 ± 4.5	117.0 ± 3.4	122.3 ± 1.1	n.a.
	1000-1500	116.9 ± 4.0	116.1 ± 3.4	117.9 ± 2.0	n.a.
	1500-2000	105.3 ± 6.5	109.3 ± 3.1	107.8 ± 4.3	n.a.
	total	110.8 ± 8.4	112.5 ± 5.3	113.2 ± 7.5	n.a.
2x3 lanes, 120 km/h, urban	<1000	115.2 ± 8.5	112.0 ± 4.9	124.7 ± 0.5	n.a.
	1000-1500	110.3 ± 6.0	110.3 ± 5.7	120.8 ± 0.9	n.a.
	1500-2000	106.4 ± 8.1	106.9 ± 8.1	115.8 ± 2.3	n.a.
	≥2000	101.3 ± 6.0	102.5 ± 6.6	106.4 ± 5.4	n.a.
	total	106.6 ± 7.9	107.0 ± 7.5	115.2 ± 7.0	n.a.

Table 10. T-test for equity of mean results

Road characteristics	Flow *q* [veh/h/lane]	n	T-test results					
			HCM		HBS		SHCM	
			t	p-value	t	p-value	t	p-value
2x2 lanes, 100 km/h, urban	<1000	13	-0.38	0.707	14.90	<0.001	31.08	<0.001
	1000-1500	65	-7.19	<0.001	24.36	<0.001	42.90	<0.001
	1500-2000	25	-1.55	0.133	16.45	<0.001	26.78	<0.001
	total	103	-4.36	<0.001	19.42	<0.001	38.64	<0.001
2x2 lanes, 110 km/h, rural	<1000	64	0.23	0.816	n.a.	n.a.	21.77	<0.001
	1000-1500	30	1.00	0.327	n.a.	n.a.	10.74	<0.001
	total	94	1.08	0.284	n.a.	n.a.	25.13	<0.001
2x2 lanes, 120 km/h, urban	<1000	28	-0.14	0.889	-6.21	<0.001	n.a.	n.a.
	1000-1500	79	1.41	0.161	-1.98	0.052	n.a.	n.a.
	1500-2000	107	-5.62	<0.001	-3.32	0.001	n.a.	n.a.
	total	214	-2.62	0.009	-3.21	0.002	n.a.	n.a.
2x3 lanes, 120 km/h, urban	<1000	9	0.98	0.355	-3.31	0.011	n.a.	n.a.
	1000-1500	68	-0.02	0.983	-14.30	<0.001	n.a.	n.a.
	1500-2000	58	-0.34	0.736	-8.55	<0.001	n.a.	n.a.
	≥2000	57	-1.05	0.300	-4.75	<0.001	n.a.	n.a.
	total	192	-0.44	0.658	-11.26	<0.001	n.a.	n.a.

6. Discussion

The review and comparative analysis of RTCA methods were designed to answer the research and practical questions posed at the beginning. The discussion below presents the extent to which responses to these questions are conclusive.

RQ1: Are there significant differences between RTCA methods used worldwide? It has been proven that there are significant differences between the methods in the analytical procedure, the initial values assumed and factors changing traffic conditions or road capacity, or the applied speed-flow v(q) relationship models. This confirms the conclusions of the literature review (Bertini et al., 2006; Luttinen and Innamaa, 2000; Pompigna and Rupi, 2015). The HBS method is relatively simple to use and does not require complicated calculations or a lot of data, unlike the HCM method, for example. Nevertheless, it is based on predefined v(q) curves for given roadway and traffic conditions, i.e. on the assumption that drivers behave similarly on roads with similar geometrical characteristics and with a similar traffic structure. Whereas in the HCM, roadway and traffic conditions are introduced as variables into the v(q) model, and the average speed is determined by the free-flow speed, not by the speed limit, as is in the case of HBS. A completely different approach is promoted by Swedes who, for predefined road and traffic conditions, provide critical volume and speed values in 4 classes of traffic conditions, thus departing from the LOS concept. The Dutch, in turn, only give the capacity for the characteristic road and traffic conditions regardless of the speed limit or free-flow speed. Moreover, the assumptions of RTCA methods are different, such as the time intervals used in the analyses, the reference system (lane or roadway) or the units used (traffic flow expressed in pc/h or veh/h).

RQ2: Are the results of the assessment of traffic conditions achieved by different RTCA methods comparable to each other? Chapter 5 analyses the measures of traffic conditions (speed, q/C ratio) estimated with the analysed RTCA methods for data from ME roads in Poland. The volume-to-capacity ratio X is determined by the capacity value which (as shown in Chapter 2) varies depending on the method used and thus volume-to-capacity ratio will depend on the capacity adopted. The higher the capacity, the better the traffic conditions at the same volume. For empirical data from ME roads in Poland, the distribution of the volume-to-capacity ratio estimated by the HCM, HBS, DHCM methods is similar. Compared to the other methods, the SHCM stands out significantly with a substantial variability of distribution of estimated X values. Similarly, when analysing the differences in the average speed estimated using each individual method, variations between them can be observed. In particular, calculations by the SHCM method result in evidently lower speeds compared to the observed data. The speed estimate closest to the empirical data is returned by the HCM method, which was additionally confirmed by t-test results. Analysing the results presented in Figure 6, it can be observed that the difference between methods may increase depending on the analysed survey site and driver behaviour (e.g. common speeding which is not anticipated in the HBS or SHCM method, in the HCM method may be already taken into account by using v_{sw}).

RQ3: What is the accuracy of traffic flow parameter estimates obtained by particular RTCA methods in relation to the real data from Polish roads? Chapter 5 shows that the lowest errors in estimating the average speed of passenger cars are obtained using the HCM method. The deviation of the estimate from the real speed is on average 4 km/h, so a relatively high accuracy of estimation is obtained. It is crucial to consider the real free-flow speed, so that the estimated speed is closest to the actual measured speed.

PQ1: Which of the analysed RTCA methods can be applied to Polish conditions? Theoretically, Polish road and traffic conditions are closer to European than to American conditions (Wu, 2005) which, however, is not to indicate the feasibility of any of the European methods in Poland. Based on the literature review (Bertini et al., 2006; Heikoop and Henkens, 2016; Luttinen and Innamaa, 2000; Pompigna and Rupi, 2015), it was suggested that due to differences between countries (traffic rules, restrictions, enforcement, driver behaviour), none of the methods should be used in Poland directly without adaptation. Further research is needed, to verify, among others, the initial base capacity or applied adjustment factor values, which have not yet been covered by this paper. The methods come with a limitation which is the inability to assess traffic conditions on Polish motorways with a speed limit of 140 km/h making Polish research into this necessary. None of the methods were able to assess traffic conditions based on empirical data for sections with such a speed limit, as a result of which these sections were actually omitted in the comparison.

PQ2: What elements of the existing RTCA methods could be adopted in the new Polish RTCA method? According to the authors' studies one of the basic assumptions of the Polish RTCA method should be based on free-flow speed and development of v(q) models that will take this variable into account. A wider free-flow speed range should be included to allow for analysis on roads with speeds of 140 km/h where free-flow speed is likely to be higher than 120 km/h. However, national research is needed to determine the capacity and identify factors which affect it and to answer the question: what is the capacity of Poland's ME roads and what factors should be considered in the analysis. Similarly, deciding on the reference system to be used (lane vs. cross-section) or flow rate units (pc/h vs. veh./h), requires conducting research and detailed analysis of data from basic sections of ME roads in Poland. All decisions regarding the shape and assumptions of the Polish method should be supported by detailed research. Simulation methods can also support this research but the need to calibrate the tools used for Polish conditions should be considered.

PQ3: What should be the structure of the new Polish RTCA method? Based on the analysis of RTCA methods (FGSV, 2015; GDDKiA, 1995; Rijkswaterstaat, 2015; Trafikverket, 2014; TRB, 2016), it was concluded that work on the Polish RTCA method should include at least the following stages:

1. Defining the area and scope of analysis. At this stage, the scope of the method and its limitations should be defined, i.e. the road and traffic conditions the method applies to.
2. Determining road capacity depending on road and traffic conditions. At this stage, it is necessary to determine, based on empirical data, road capacity depending on e.g. road class, free-flow speed, location. This is a key stage in the procedure.
3. Selecting the traffic conditions assessment measures. At this stage it should be clear which measures of traffic conditions can be estimated using the method. The choice of measures will largely be determined by the data available for the development of the method.
4. Developing a method for estimating selected measures of traffic conditions. Additionally, it should be assumed how the individual measures of the method will be determined (e.g. using analytical models, from the chart, from the defined values).
5. Adopting a method of classification of traffic conditions and determination of threshold values of measures assumed for classification. At this stage, it is necessary to determine which measure of traffic conditions will be the basic measure for their classification and to set its threshold values, beyond which a visible deterioration of traffic conditions occurs.
6. Developing a procedure for traffic conditions assessment (traffic conditions evaluation and classification procedures). At this stage, it is necessary to define the next steps to be taken by the end user which will enable a gradual determination of road capacity and assessment of traffic conditions on the road.

The classification of traffic conditions with the LOS in the Polish RTCA method could also be used to determine the class of traffic conditions acceptability. To this end, it is necessary to introduce classes of acceptability for the levels of service, which indicate what is an acceptable or tolerable value of LOS for the road of a given class and of given traffic conditions. Until now in Poland it was recommended that the level of service should not exceed level C in rural areas and D in urban agglomerations for ME roads (temporarily levels D and E are tolerated).

7. Conclusions

The paper presents a comparison of RTCA methods for assessing traffic conditions used in various countries, with particular attention paid to the procedures, models, assumptions and parameters. It also evaluated how the methods reflect the actual traffic conditions in Poland. The research helps to formulate the following conclusions:

1. Comparisons of traffic conditions on motorways and expressways in Poland indicate that there are quite significant differences between the methods adopted for analysis.

2. The Polish method developed in 1995 (as a direct adaptation of the HCM method) needs to be changed due to the change in geometric parameters and quality of expressways and motorways, speed limits, changes in the quality of the vehicle fleet and in driver behaviour, etc.
3. Due to significant differences between the results of the estimated parameters and empirical data, none of the analysed methods can be directly adopted to Polish conditions.
4. The analyses and comparisons of selected methods for assessing traffic conditions helped to formulate important elements for the Polish method, its structure and methodology.
5. An important conclusion is the need to include in the method Poland-specific speed limits on motorways and the procedure for determining free-flow speed, which should be the basis for further analyses.

The results of the research and analyses will be used in the qualification work and under the RID-2B project for the development of a new Polish RTCA method.

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References

[1] VAN AERDE, M. & RAKHA, H., 1995. *Multivariate calibration of single regime speed-flow-density relationships*. Proceedings of the 6th International VNIS Conference, IEEE, 334–341. DOI: 10.1109/VNIS.1995.518858

[2] BERGH, T., NORDQVIST, K., STRÖMGREN, P., DAVIDSSON, F., BÅNG, K.L. & CARLSSON, A., 2016. *Capacity Issues in Sweden - Applications and Research*. Transportation Research Procedia, 15, 36–50. DOI: 10.1016/j.trpro.2016.06.004

[3] BERTINI, R.L., BOICE, S. & BOGENBERGER, K., 2006. *Comparison of Key Freeway Capacity Parameters on North American Freeways with German Autobahns Equipped with a Variable Speed Limit System*. Proceedings of the 5th International Symposium on Highway Capacity and Quality of Service, 279–287.

[4] BOLTZE, M., 2006. *Recent Developments in Germany Related to Highway Capacity and Quality of Service*. Proceedings of the 5th International Symposium on Highway Capacity and Quality of Service, 23–39.

[5] FGSV, 2011. Guidelines for the Design of Motorways: RAA. Cologne: FGSV Verlag GmbH.

[6] FGSV, 2015. Handbuch Für Die Bemessung von Straßenverkehrsanlagen (German Highway Capacity Manual). Cologne: FGSV Verlag GmbH.

[7] GDDKiA, 1995. *Instrukcja obliczania przepustowości dróg I i II klasy technicznej (Polish Highway Capacity Manual)*. Warsaw: GDDKiA.

[8] GEISTEFELDT, J., 2016. *Assessment of basic freeway segments in the German Highway Capacity Manual HBS 2015 and beyond*. Transportation Research Procedia, 15, 417–425. DOI: 10.1016/j.trpro.2016.06.035

[9] HEIKOOP, H. & HENKENS, N., 2016. *Recent Developments and History of the Dutch HCM*. Transportation Research Procedia, 15, 51–62. DOI: 10.1016/j.trpro.2016.06.005

[10] IRAWAN, M.Z., SUMI, T. & MUNAWAR, A., 2009. *Implementation of the 1997 Indonesian Highway Capacity Manual (MKJI) Volume Delay Function*. Journal of the Eastern Asia Society for Transportation Studies, 8, 350–360. DOI: 10.11175/easts.8.350

[11] JAMROZ, K., KRYSTEK, R., CIELECKI, A., KEMPA, J., SANDECKI, T., SOSIN, J., SZCZURASZEK, T., et al., 1986. *Aktualizacja Wytycznych Obliczania Przepustowości Dróg Zamiejskich (Polish guidelines on rural roads capacity estimation)*. Gdansk-Warsaw-Bydgoszcz.

[12] LUTTINEN, R.T. & INNAMAA, S., 2000. *Nordic Highway Capacity. Uninterrupted Flow Facilities in Denmark, Finland, Norway, and Sweden*. Helsinki: Finnra.

[13] NAKAMURA, M., 1994. *Research and application of highway capacity in Japan*. Second International Symposium on Highway Capacity, 103–112.

[14] OLSZEWSKI, P., DYBICZ, T., JAMROZ, K., KUSTRA, W. & ROMANOWSKA, A., 2018. *Assessing highway travel time reliability using Probe Vehicle Data*. Transportation Research Record, 2672(15), 118–130. DOI: 10.1177/0361198118796716

[15] PAMUŁA, T., 2016. *Classification of road traffic conditions based on texture features of traffic images using neural networks*. Scientific Journal of Silesian University of Technology. Series Transport, 92, 101–109. DOI: 10.20858/sjsutst.2016.92.10

[16] POMPIGNA, A. & RUPI, F., 2015. *Differences between HCM procedures and fundamental diagram calibration for operational LOS assessment on Italian freeways*. Transportation Research Procedia, 5, 103–118. DOI: 10.1016/j.trpro.2015.01.016

[17] RAVINDER, K., VELMURUGAN, S. & GANGOPADHYAY, S., 2014. *India's Highway Capacity Manual Project: Developing a national guide to address unique traffic conditions*. TR News, 295, 17–22.

[18] RID, 2016. *Modern Methods of Calculating the Road Capacity and Assessment of Traffic Conditions of Roads Outside Municipal Agglomerations, Including Expressways (RID-2B Project)*. Cracow-Warsaw-Gdansk.

[19] RIJKSWATERSTAAT, 2015. *Capaciteitswaarden Infrastructuur Autosnelwegen (Dutch Highway Capacity Manual)*. Utrecht: Rijkswaterstaat.

[20] ROESS, R.P. & PRASSAS, E.S., 2014. *The Highway Capacity Manual: A Conceptual and Research History*. Cham: Springer. DOI: 10.1007/978-3-319-05786-6

[21] SRIKANTH, S. & MEHAR, A., 2017. *A modified approach for estimation of Passenger Car Units on intercity divided multilane highways*, Archives of Transport, 42(2), 65–74. DOI: 10.5604/01.3001.0010.0528.

[22] TRAFIKVERKET, 2014. *TRVMB Kapacitet Och Framkomlighetseffekter (Swedish Highway Capacity Manual)*. Borlänge: Trafikverket.

[23] TRB, 2016. *Highway Capacity Manual*. Washington D.C.: Transportation Research Board.

[24] WU, N., 2005. *Impact of traffic regulation on lane flow-distribution and capacity of motorways*. Proceedings of the 5th International Conference of Transportation Professionals, Xian, China.

[25] ZHOU, R., ZHONG, L., ZHAO, N., FANG, J., CHAI, H., ZHOU, J., LI, W., et al., 2016. *The Development and Practice of China Highway Capacity Research*. Transportation Research Procedia, 15, 14–25. DOI: 10.1016/j.trpro.2016.06.002