INFLUENCE OF SELECTED ROAD PARAMETERS ON VELOCITY OF TWO-LANE, TWO-WAY HIGHWAY

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The paper presents the problem of relationship between velocity on two-lane, two-way highway and selected road parameters. Taking advantage of a number of analytic or empirically determined relationhips it can be evaluated which v_{85} velocity shall be guaranteed by the technical state of the given highway segment. Drawn along the road, the profile of velocity v_{85} (guaranteed by the technical state of the highway) enables to find the place where the decreased values of v_{85} occur or where sudden variations of this velocity occur in succeeding segments. The Author proposes to use the above analysis of the effect of individual highway parameters to asses the technical state of roads with regard to the guaranteed highway functional quality, i.e. v_{85} velocity [30, 31]. Analysis of technical state of highways with regard to velocity is needed and necessary, as writes St. Lenczewski in his foreword to [18]: "road accident statistics give the driver's error as one of the main causes analysis of accident locations proves their grouping on the definite, short segments of the highway. This phenomenon could mean that in certain definite places, sudden and unexpected to drivers, alterations and difficulties in traffic conditions take place and situations created by them lead to accidents, in which the highway plays an important part."

1. INTRODUCTION

Following the German design guidelines [3, 16], the term "reference velocity" v_m was introduced in Poland in the eighties (assumed as the quantile of velocity v_{85} of passenger vehicles in free flow traffic on wet pavement) and defined the basic relationships related to it. WPD [7] guidelines and now WT [4] in force, give the detailed definition of the value of reference velocity v_m assumed — depending on highway bendiness K in the form of the following function:

$$v_m = f(K). \tag{1.1}$$

In WT [4] a clause from WPD [7] was also retained, determining that the allowable variation of the reference velocity on successive road segments can amount to $|v_{85_{i+1}} - v_{85_i}| \leq 10$ km/h. The application of the above clause in WT [4] is recommended at the stage of building a new — or reconstructing existing highway, when assessing its flow fluidity. The assessment of highway fluidity refers only to the assessment of the succession of geometric parameters along the highway; no assessment is made in it of the succession of the variation of pavement operating properties.

In Poland — apart from the above assessment — a yearly evaluation of the technical state of pavement SOSN is carried out, i.e. the evaluation of the basic operating properties of the highway [5]. A similar system of evaluation of the pavement only is also used in Germany and in France [20, 32]. Technical state assessment restricted to operating properties of the pavement only can, however, bring in turn the result, that despite using specialized measuring instruments and application of expensive repair technologies, no expected effects shall be obtained after the repairs have been carried out. Highway manager e.g. plans to carry out repairs on rutted segment of the road on a horizontal arc of radius $R = 200$ m, only: the sole effect of this repair shall be the improvement of travel comfort, as the speed limit shall be still obligatory on this arc. On the other hand, after repairs carried out on a slippery segment of the highway situated on a longitudinal slope, traffic safety and road conditions shall be improved in the first place.

At the end of the nineties, the introduction of HDM-4 system [9] started in Poland. It is stating precisely the kind of highway maintenance in view of the economic effect of the planned road repair. In parallel with HDM system in Poland, the specification on economic effectiveness of highway investments [10], is in force, in which the design and travel velocities are the bases of cost and social advantage evaluation.

In Russia and in several ex-soviet republics a complex method of evaluation of the technical state of highways was developed by WASILIEW [36] and introduced in 1994. Velocity in this method is the basis of evaluation, but in course of evaluating it is presented in form of a number of coefficients[1], which — only after substitution of data and suitable calculations — result in velocity. This complex evaluation method of technical state of highway takes into account the influence of majority of road parameters on velocity, (i.e. geometrical parameters: roadway width B, shoulder width p, roadway width on bridges and overpass B_1, radius of horizontal arc R, longitudinal slope i_p and operating properties: pavement adhesion φ, longitudinal evenness S_c, load capacity of roadway u, allowable bridge loading), and also accident coefficient U_w and traffic parameters (i.e. traffic intensity Q, share of heavy vehicles p_c), are taken into account, but they do not include the influence of so important factor as road bendiness K, or rutting of pavement k. This complex method was developed in Russia in the eighties, it is therefore corresponding to the contemporary state of motor vehicles moving over Russian highways at that time.

[1] Considering wide difference in design velocities for roads of different classes, A. WASILIEW assumed the basic velocity $v^b = 120$ km/h and changed the reference velocity v_{85} into the coefficient of assuring the velocity Krs according tro the formula [36]:

$$Krs = \frac{v_{85}}{v^b} = \frac{v_{85}}{120}.$$

Every evaluated j-th parameter has a specified coefficient ensuring the velocity $Krs\,j$, E.g. influence on velocity in every characteristic i-th road segment: — roadway width is defined by Krs_i 1; — shoulder width and condition Krs_i 2; — traffic intensity and proportion of heavy vehicles Krs_i 3; — longitudinal slope Krs_i 4; horizontal arc radius and superelevation applied Krs_i 5; — longitudinal eveness Krs_i 6; — adhesion coefficient Krs_i 7; — roadway load capacity Krs_i 8; — allowable bridge loading Krs_i 9; — traffic safety Krs_i 10.

The analyses of traffic problems carried out hitherto prove that direct application of relationships of velocity to various highway parameters[2] established in other countries is impossible to apply without their verification on Polish roads [33] as these relationships depend closely on different highway traffic characteristics (dynamic characteristics of passenger cars and share of heavy vehicles) and — above all — on different traffic conditions connected with temperament and habits of drivers.

Research study on evaluation methods of the technical state of highways [5, 9, 20, 36, 37] carried out by the Author and presented in papers [22, 23, 24, 25, 27] proved that in evaluation of highway technical state it is important that:

First — what kind of roads are assessed — main highways or roads of lesser economic importance, as different types of vehicles travel on each of these roads,

Second — what should be directly the subject of evaluation and which end this evaluation should serve.

Summing up the above the Author defined the purpose of research carried out, i. e. the determination of velocity v_{85} guaranteed by the technical state of the highway for passenger cars and at wet state of the pavement. As the evaluation of the technical state of the highway should have the properties of the direct and inverse action; it should therefore determine the value of the velocity v_{85} quantile guaranteed by technical state of the highway (direct action) on one hand:

$$v_{85} = f(x_i), \tag{1.2}$$

where x_i — existing individual road parameters,
and on the other hand it should provide the answer which of the highway parameters x do not guarantee this velocity and by what amount (Δx) they should be corrected in order to guarantee the reference velocity v_m[3] (determined in [4]) by the technical state of the road (inverse action):

$$f(x \pm \Delta x) = v_m, \tag{1.3}$$

where x — existing parameter lowering the velocity v_{85}, Δx — adjustment of parameter x to guarantee the required reference, velocity v_m on the given segment of the road.

In order to reach the above objective the Author formulated the following work tasks:

- definition and choice of main highway parameters characterizing its technical state,

[2] In road operation, road parameters are divided into:

- permanent parameters — parameters that do not change during operation of the road — unless the road is modernized (the Author included here: roadway width B, lane width b, road bendiness K, arc of horizontal radius R together with turning angle γ, longitudinal slope i_p etc, — as a rule these are parameters connected with road geometry),
- variable parameters — changing during road operation e.g. transverse and longitudinal evenness, pavement roughness — i. e. operational properties of pavement.

[3] In this paper, the reference velocity specified in § 13 WT [4] depending on highway class, roadway width and ts bendiness K shall be named — *the required reference velocity* and denoted v_m.

• development of methodology of test segment choice with aim of obtaining comparable and one-parameter relationships of velocity v_{85} quantile of the analysed highway parameters $v_{85} = f(x)$;

• dependence analysis of velocity v_{85} on the chosen road parameters regarding their suitability to the evaluation of technical state of the highway.

The Author is presenting in this paper the results of investigations carried out in relation to some chosen highway parameters.

2. GENERAL ASSUMPTIONS ON INVESTIGATIONS CARRIED OUT

Analysing the relationships presented in [3, 8, 16][4], the Author assumed that in view of the operational value of the highway it will be ineffective — when evaluating the technical state of the road — to lump all the considered parameters into one equation, because in this case no assessment could be made of need or the necessity of repair required by one road parameter (lowering velocity v_{85} over the given segment). In this case a local lowering of v_{85} can be only stated without the possibility to explain the cause of this variation. The above assumption was the result of many combinations of matrix calculus analyses computed according to Eq. (2.1) [30] taking into consideration highway parameters analysed by the Author in wet state of pavement:

$$\left.\begin{aligned} &a_1B_1 + a_2b_1 + a_3p_1 + a_4l_{b1} + a_5l_{k1} + a_6K_1 + a_6R_1 + a_8\gamma_1 + a_9i_{p_1} + a_{10}l_{z1} + a_{11}k_1 \\ &\qquad + a_{12}IRI_1 + a_{13}S_1 = v_{85\,1} \\ &a_1B_2 + a_2b_2 + a_3p_2 + a_4l_{b2} + a_5l_{k2} + a_6K_2 + a_6R_2 + a_8\gamma_2 + a_9i_{p_2} + a_{10}l_{z2} + a_{11}k_2 \\ &\qquad + a_{12}IRI_2 + a_{13}S_2 = v_{85\,2} \\ &\qquad\qquad \cdots\cdots\cdots\cdots \\ &a_1B_i + a_2b_i + a_3p_i + a_4l_{bi} + a_5l_{ki} + a_6K_i + a_6R_i + a_8\gamma_i + a_9i_{p_i} + a_{10}l_{zi} + a_{11}k_i \\ &\qquad + a_{12}IRI_i + a_{13}S_i = v_{85\,i} \end{aligned}\right\}, \tag{2.1}$$

where a_j — individual constant matrix coefficients, $j = 1, 2, \ldots, 13$; i — number of hectometre segments analysed; B_i — roadway width in the analysed segment i, [m], b_i — traffic lane width over the analysed segment i, [m], p_i — shoulder width in the analysed segment i, [m], l_{bi} — puddle width on shoulder in the analysed segment i, [m], l_{ki} — puddle width on roadway in the analysed segment i, [m], K_i — highway bendiness over the examined segment i, [°/km], R_i — horizontal arc radius over the analysed segment i, [m], γ_i — turning angle of road, [°], i_{pi} — longitudinal slope of highway over the analysed segment i, [%], l_{zi} — stopping sight distance over the analysed segment i, [m], k_i — rut depth over the

[4] The basic relationships analysed in [3] were the formulae (6.10) – (6.14) quoted from the British design guidelines [8] and the formulae given in Tables 6–8 quoted from the German design guidelines [16].

analysed segment i, [mm], IRI_i — longitudinal evenness index over the analysed segment i, [mm/m], S_i — pavement roughness over the analysed segment i, [-]; $v_{85\,i}$ — passenger cars velocity quantile in free flow traffic and wet pavement over the analysed segment i, [km/h].

Input base of data used in matrix calculations was taken from [17], defining the operational properties of pavement: longitudinal evenness, rut depth and surface roughness; remaining data i.e. velocity v_{85} quantile and the values of remaining highway parameters were obtained from the field investigations by the Author.

As the successive stage of analysis, taking into consideration the influence of several parameters on velocity v_{85} quantile, the Author examined the results of mathematical analysis carried out by A. WASILIEW within the technical state of complex highway evaluation method developed by himself [35, 36]. A. WASILIEW assumed three mathematical models, analysing their usefulness in evaluation of highway technical state from the point of view of their useful value [35, 36]:

• *First model* assumed the adoption of the resulting velocity guarantee coefficient $Krs_i^{\text{resulting}}$ on the i-th segment as the product of individual partial coefficients Krs_ij, taking the theoretical assumption that all the analysed highway parameters influence together on velocity quantile v_{85}:

$$Krs_i^{\text{resulting}} = Krs_i1 \cdot Krs_i2 \cdot Krs_i3 \cdot \ldots \cdot Krs_i10, \tag{2.2}$$

• *Second model* assumed the adoption of the resulting velocity guarantee coefficient $Krs_i^{\text{resulting}}$ on the i-th segment as the minimum value of all coefficients Krs_ij. In this case the theoretical assumption was that one or several of the analysed highway parameters exert greatest influence on velocity quantile v_{85}:

$$Krs_i^{\text{resulting}} = \min\{Krs_i1 \cdot Krs_i2 \cdot Krs_i3 \cdot \ldots \cdot Krs_i10\}. \tag{2.3}$$

• *Third model* assumed the adoption of the resulting velocity guarantee coefficient $Krs_i^{\text{resulting}}$ on the i-th segment as the expansion of the general function of the resulting coefficient in Taylor series. In this model, the theoretical assumption was that all of the analysed highway parameters display a common, complex influence on velocity quantile v_{85}, some highway parameters show in addition the mutual double or treble interaction:

$$Krs_i^{\text{resulting}} = f(Krs_i1 \cdot Krs_i2 \cdot Krs_i3 \cdot \ldots \cdot Krs_i10) \tag{2.4}$$

$$= \prod_{j=1}^{n} Krs_ij_{k,t,z} + \sum_{k,t}^{m} \beta_{k,t}(1 - Krs_ij_k) \cdot (1 - Krs_ij_t)$$

$$+ \sum_{k,t,z}^{w} \gamma_{k,t,z}(1 - Krs_ij_k) \cdot (1 - Krs_ij_t) \cdot (1 - Krs_ij_z),$$

where k, t, z — indices of corresponding velocity guarantee coefficients Krs at double or treble mutual interactions, $\beta_{k,t}$, $\gamma_{k,t,z}$ — coefficients of corresponding double or treble mutual interactions, $Krs_i j_k$, $Krs_i j_t$, $Krs_i j_z$ — velocity guarantee coefficients of two or three mutually bounded parameters, m, w — size of the corresponding two or three mutually bounded parameters, n — total number of velocity guarantee coefficients.

The analysis of three models described in [35, 36], carried out from the point of view of result inequalities obtained from measurements and calculated on the basis of the three models presented above, proved that the first model produced the differences between the calculated and measured results within 40–50%. Calculations carried out using second model produced results close to results of measurements — the expected value of discrepancy of results was 0.045, and standard deviation of this discrepancy amounted to 0.06. Calculations carried out using third model brought the results closest to those obtained in the real measurements. The expected value of result discrepancy was 0.004 and their standard deviation — 0.057. The second model, however, when compared to the third has an essential superiority consisting in basic simplicity of analysis and easy accessibility to analysed data.

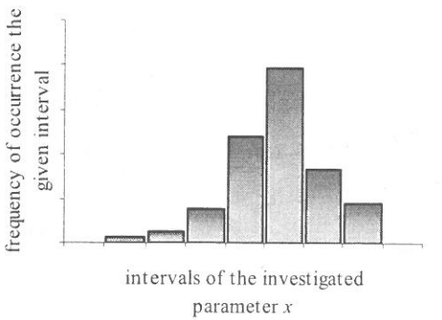
Basing on the above, the Author assumed that she will use the second model (2.4) for the proposed evaluation of the technical state of highways. It consists in searching for the road parameter causing the greatest lowering of velocity v_{85} quantile in the analysed segment, i. e. consisting in finding the cause of the local deterioration of the technical state of the highway. As the method pertains to the technical state evaluation of roads situated outside the towns or fragments of these roads, every change of velocity v_{85} quantile above the allowable value Δv_{85} = 10 km/h on successive road segments along the road or local lowering of v_{85} is indicating that the technical state of the road does not assure the travel at the reference velocity v_m defined in WT [4].

Considering the above the Author proposed to apply one of the Total Quality Management methods — heuristic quality control method. The foundations of this method have been published by K. Ishikawa in his book "TQM — The Japanese Way" in 1962, formulating seven necessary quality inspection elements applied in analyses in order to find the cause of the examined of result (Fig. 1) [1]: 1 — Pareto analysis[5]; 2 — various elements of the statistical analysis of the "causes" i.e. parameters x (Fig. 1a); 3 — various elements of the statistical analysis of the assessed "effects" i.e. parameters y (Figs. 1b and 1c); 4 — inspection diagrams (Fig. 1f); 5 — dependence diagrams $y = f(x)$ (Fig. 1 d); 6 — parameter stratification (i.e. division of parameters or discrimination according to various criteria — (Fig. 1d); 7 — "fish" diagram[6] (so called diagram of "searching for the cause of the definite effect" (Fig. 1e).

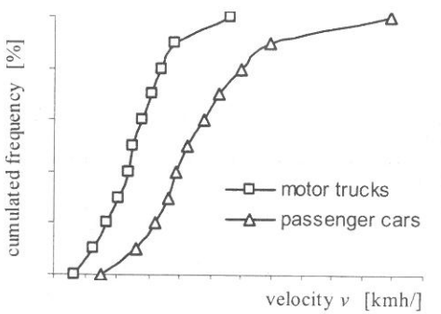
[5] Pareto analysis consists in determination of importance of considered parameters. To this end, the Pareto-Lorentz diagram is assisting the verification of importance of the analysed parameters, as according to investigations quoted in [1], in most cases 20% of causes is decisive in forming 80% of effects.

[6] According to J. Sikorski of Polish Academy of Sciences [www.ibspan.waw.pl/~sikorski/tqm/wyk], "... "fish" diagram serves to investigate the causes of faulty progress or effects accompanying the defects of products, allows to accumulate and systematize the knowledge enabling the study of potential causes of occurrence of the given problem. On the basis of expert knowledge it leads to systematizing the potential causes and to mulate working hypotheses on subject-cause and effect connection. It is preceding methodical data collection and analysis, which should lead to the discovery of real causes..."

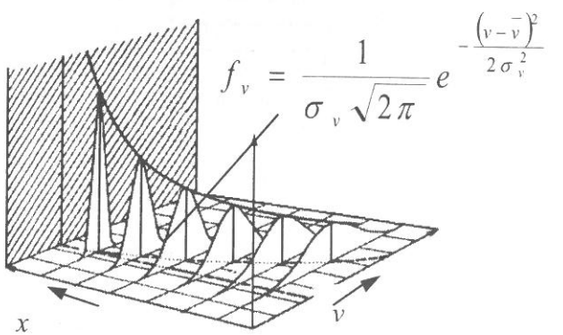
a) bar chart: distribution of investigated parameter x



b) cumulative distribution function of velocity v

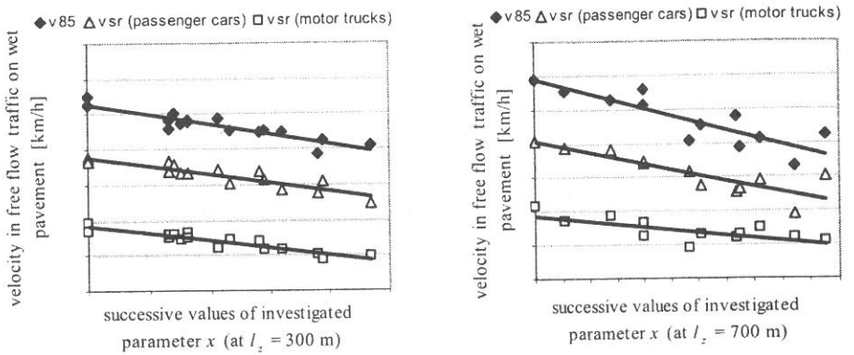


c) parameter variability of normal distribution of velocity v as the result of value variation of the analysed parameter x

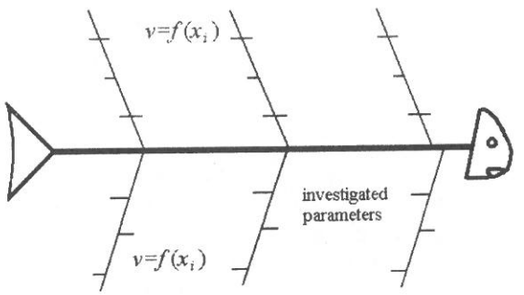


[Fig. 1]

d) stratification of velocity and the investigated parameter x (e.g. different sight distance l_z)



e) "fish" diagram



f) inspection diagram along the road

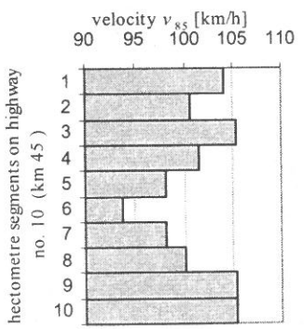


Fig. 1. Individual quality control elements in the heuristic quality control method (Author's interpretation on example of highway parameters).
Rys. 1. Poszczególne elementy kontroli jakości w heurystycznej metodzie analizy jakości (interpretacja autorki na przykładach parametrów drogowych)

The detailed description of application of individual elements of this method in evaluation of the technical state of roads was presented in [31] by the Author.

In order to find the cause resulting in local lowering of the velocity v_{85} quantile, the parameters characterising the technical state of the highway should be chosen and their influence on v_{85} velocity determined. Preceding this, measurements of each analysed parameter x and instantaneous velocities should be carried out on segments chosen for the investigations. Such a broad spectrum of investigations required the acceptance of several basic principles [11, 21, 34, 36]. Namely, hectometre segments selected for the measurement of instantaneous velocities in case of each analysed parameter should be chosen in the manner assuring only the variability of the investigated parameter x; the remaining highway parameters on selected segments should have equal or very similar values. Only such investigation methodology of segment choice gave the bases to determine one-parameter dependence of v_{85} velocity quantile upon the analysed highway parameter x.

Following the principle that only the investigated parameter can be variable, it was also necessary to take into account that travelling conditions are different in the rain and in dry weather. For this reason, in the presented investigations it was assumed that they are carried

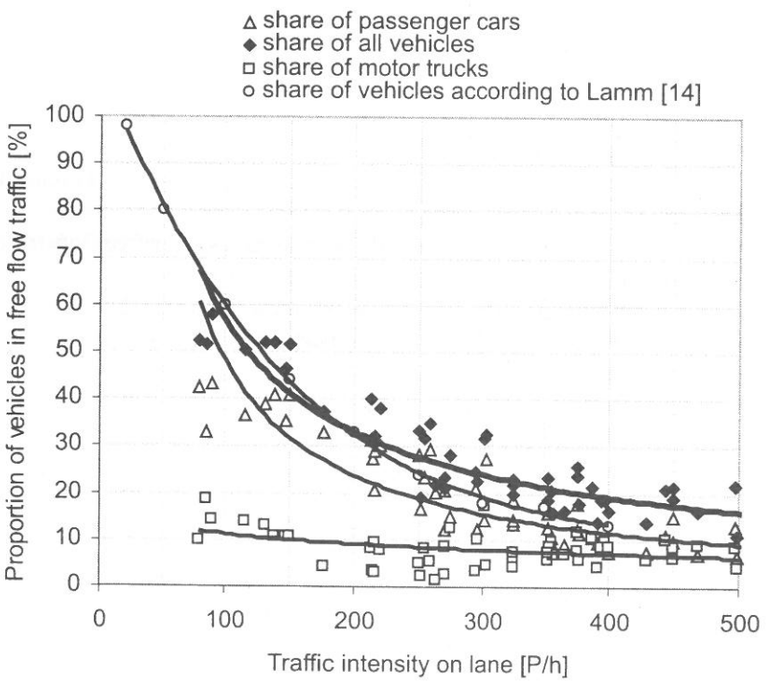


Fig. 2. Dependence of vehicle shares in free flow traffic on traffic intensity.
Rys. 2. Zależność udziału pojazdów w ruchu swobodnym od natężenia ruchu

out in wet state of pavement. Besides, it was assumed that the investigations of instantaneous velocities shall be carried out during rain of medium intensity, avoiding in this way the influence of extreme atmospheric conditions[7] on lowering of the v_{85} velocity quantile and worse visibility on the highway.

The following assumption was to take the measurement of passenger car velocity in free flow traffic only. As in the bases of technical evaluation of highways it was assumed that for every selected parameter x the relationship $v_{85} = f(x)$, shall be defined, passenger cars only in free flow traffic could be taken into consideration, because only in the case of free flow traffic it can be assumed that highway parameters and not traffic flow parameters are influencing the driver. Driving in free flow traffic, the driver can at any moment readjust the velocity of his car to actual road conditions and not to traffic conditions and nothing except the analysed parameter shall shall influence him. Following the research results by R. Lamm [3, 14] and the results of own investigations [27], the Author assumed (Fig. 2) that the share of vehicles in free flow traffic amounts to about 20% for traffic intensity $Q_w > 400$ P/h/lane. As on analysed highways the share of hours with traffic intensity of $Q_w > 400$ P/h/lane was negligible, only the vehicles in free flow traffic were chosen. The instantaneous velocity measurements were taken only at traffic intensity $Q = 100 \div 300$ P/h/lane.

Having measured on the highway the instantaneous velocities of vehicles in free flow traffic, the quantile of v_{85} velocity and mean values of vehicle group velocities: passenger cars v_{sr}^{o} and goods vehicles v_{sr}^{c} in free flow traffic for each measured hectometer segment could be determined. The choice of the velocity distribution parameters mentioned above was taken considering their general characteristics, namely [3, 9, 14, 37]:

- velocity v_{85} quantile of passenger cars in free flow traffic is always connected with determination of traffic safety conditions,
- mean velocities of passenger cars v_{sr}^{o} and goods vehicles v_{sr}^{c} in free flow traffic serve for economic calculations.

Furthermore, when preparing the bases of evaluation of technical state of highways, their separation was assumed according to their importance and velocities possible to attain when travelling on them.

All investigations were carried out on national highways with bituminous pavement, in West-Pomeranian district. In total, the velocities were measured on 150 highway segments carrying out about 40 thousand instantaneous velocity measurements (of which about 30 thousand pertained to passenger cars only).

3. INVESTIGATION METHODOLOGY

The first element of the heuristic method in the qualitative analysis of the technical state of highways evaluation method evolved, was Pareto analysis, i. e. indication of the group of

[7] The extreme meteorological conditions occur in course of heavy rains and cloud bursts. In this case the main cause of lowering of velocity and deterioration of visibility are meteorological conditions and not highway parameters.

most important technical state parameters of highways, affecting the velocity [31]. The drivers, who are direct users of the highway are receiving via their senses only a part from all highway parameters [3, 18, 26, 28]. The majority of these parameters is not connected between them. E.g. state of pavement drainage or ditch clogging has no direct influence on the driver, travelling on the highway who does not pay attention to the state of its drainage. But overgrown grass in ditches will not drain water; after some time it will become stationary, forming slough, washing the subsoil out and lowering the carrying capacity of soil at highway shoulder. External loads due to vehicle wheels will — after some time — weaken the structure of the pavement which will lose its carrying capacity. Carrying capacity is closely connected with longitudinal evenness, which, in turn — by deformation and wave length of surface irregularities — induces vehicle vibrations and is thus limiting the velocity which would be possible to attain [26, 28]. Carrying out similar analyses for every highway parameter, their mutual relationships were analysed within the framework of investigations. This allowed to determine the number of most important highway parameters directly influencing the velocity [31].

To the most important highway parameters influencing the velocity, and necessary to assess the technical state of highways the Author reckoned: bendiness of the road K, width of roadway B, longitudinal slope i, traffic lane width b, shoulder width p, horizontal radius R with angle of turn γ and superelevation i_o, stopping sight distance l_z, roughness of pavement S, longitudinal evenness (expressed by *IRI* index), rut depth k, puddle width on shoulder l_b or roadway sides l_k.

Having chosen road parameters the Author determined the real range of their values and frequencies, taking advantage of data base [17] (results of SOSN investigations from years 1995–2002 concerning rut depth k, pavement roughness S — rendered accessible by GDDKiA Department of Szczecin) or carrying by own means the necessary measurements of individual parameters on highways. Detailed analyses were carried — in all — on 160 km of national highways. Considering discrepancies occurring sometimes in the results measured by SOSN and the real state of roadway rutting, the Author carried out checking investigations of rut depths, using purposely developed special measurement methodology (described in [29]). These investigations were carried mainly with the aim of choosing such test segments where the rut had fairly even depth along the entire investigated segment.

Width measurements of: roadway B, traffic lane b, shoulder p, puddle on roadway l_k, and on soil shoulder l_b were carried out in 11 cross sections on every hectometer segment (what — in practically all investigated cases — exceeded three times the statistically required number of measurements for significance level of $\alpha = 0.05$). Taking measurements of parameters mentioned above in 11 cross-sections was due to the measurement methodology and way of calculating the possible depths of water in ruts as well as puddle widths[8].

[8] To calculate the possible water depths in ruts and puddle widths in course of rain of various duration t and intensity q, the Author developed a special *Computer program calculating puddle parameters on highway shoulder or on the roadway for the given duration and intensity of rain*, Archive KDMiMB WBiA PS, Szczecin 1999.

Longitudinal slopes of investigated segments were determined on the basis of geodesic levelling of: roadway axis, both roadway edges, and axes of both traffic lanes. The theodolite was used to determine the turning angle of route.

As one of the investigated parameters was the stopping sight distance l_z to enable stopping (a parameter closely connected with pavement roughness S); it was determined in investigations for each road segment at the place of hectometer post (i.e. every time when entering the investigated hectometer segment) at the level of driver's eyes.

Statistical analysis of measurement results was made for every analysed parameter. On this basis; mean values were determined for a given highway parameter and corresponding quantiles. In addition, for all measured road parameters cumulative distribution functions were carried out to eliminate segments with values of given parameters varying over the length of analysed segment (e.g. shoulder widths, depths of outer ruts etc.).

Having determined the variability ranges of the chosen highway parameters, the measurements started of instantaneous velocities in free flow traffic. In the field of statistical investigation methods of highway traffic conditions in Poland — automatic of semi-automatic measurement techniques were not until recently used, due mainly to the lack of suitable equipment [33]. At first, in the years 1996–1998, in order to proceed with the investigations program, the Author utilized so called "simple measuring techniques" [3] — stop-watches with microwave senders, dictaphones or TV cameras. Since the above measuring techniques are characteristic by appreciable investigation costs and labour-consuming data processing, the Author together with the employees of the Electronic Establishment "MART" undertook the construction of electronic device for velocity measurement and generic structure of traffic, using infra-red radiation[9] (Fig. 3) [2]. From 1998 this device was used in field investigations.

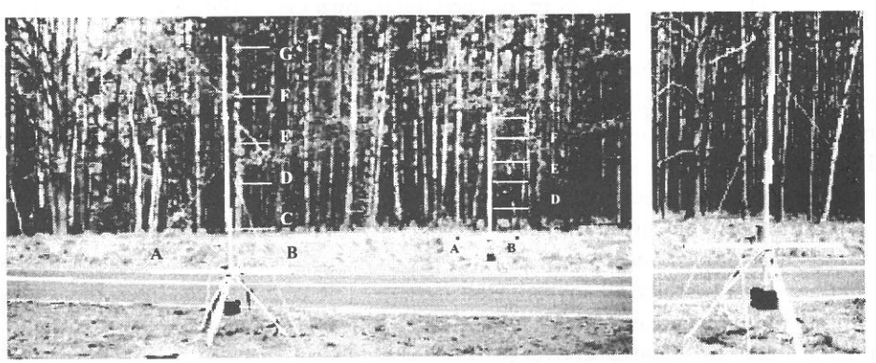


Fig. 3. Measuring devices installed during investigations: sensors A, B — for measurement of velocity and width of vehicles; sensors C, D, E, F and G — for measuring the height of vehicles.
Rys. 3. Urządzenie pomiarowe zastosowane w badaniach: czujniki A, B — służą do pomiaru prędkości i długości pojazdu, czujniki C, D, E, F i G — służą do pomiaru wysokości pojazdu

[9] The description of functioning and of measurement taking is included in *Technical Documentation* of the device for traffic velocity and generic structure of vehicles — prepared by Electronic Establishment "MART" in Szczecin, financed within the framework of apparatus investment KBN Decision N1829/IA/108/96.

Table 1

Setting-up of basic parameters obtained from preliminary velocity measurements.
Zestawienie podstawowych parametrów uzyskanych z wstępnych pomiarów prędkości

	Passenger cars			Motor trucks		
	Passenger cars	Minibus and delivery vans	Overall passenger cars	Motor trucks without trailers	Truck tractors with semitrailers and motor with trailers	Overall goods vehicles
	1	2	3	4	5	6
Standard deviation of sampley σ	20.4	8.3	19.8	9.1	11.6	11.5
Minimum size of sample at confidence level 0.90	47	12	48	17	22	23
Minimum size of sample at confidence level 0.95	67	17	68	24	31	33
Preliminary measurement of sample size	**137**	**37**	**179**	**30**	**30**	**60**

Measurements of instantaneous velocities were made on a 100 m segment for two groups of vehicles: *passenger vehicles* (including passenger cars, delivery vans and minibuses) and *motor trucks* (which included lorries without trailers, truck-tractors with semitrailers and motor trucks with trailers).

Before starting field investigations, preliminary measurements were carried out (Table 1) in order to determine the minimum sample size at two significance levels $\alpha = 0.1$ and $\alpha = 0.05$. Maximum velocity evaluation error was equal to about 5 km/h, at accuracy level evaluation of mean value for passenger vehicles $\mu = 0.05$ and for motor trucks $\mu = 0.07$.

On the basis of preliminary results (Table 1) it was assumed that the minimum size of sample for passenger vehicles shall be 120 and for motor trucks — 60, (at the minimum sample size equal to 30 vehicles in individual groups: delivery vans and minibuses, lorries without trailers, motor trucks with trailers and truck-tractors with semitrailers).

To assure uniform traffic intensity on the highway while taking the instantaneous velocity measurements in free flow traffic, preliminary traffic intensity measurements were carried out during 24 hours on several highway stretches. The analysis of gathered results proved that lowest variations of traffic intensity occur between 11 a.m. and 5 p.m. Besides, analysis of traffic distribution during weekdays based on data [6] proved that investigations should be carried from Tuesdays to Thursdays. Such assumptions allowed to predict — within possibilities — the approximate traffic intensity during the entire duration of measurements.

4. THE INFLUENCE OF SELECTED HIGHWAY PARAMETERS ON VELOCITY

Within the analyses carried on variable parameters influencing velocity, the influence of pavement roughness and rut depth were investigated.

The investigations of influence of pavement roughness S[10] on v_{85} velocity quantile were carried out during the period of past several years. As the only formulae published in publications [3, 19] taking into account relationship of velocity and friction coefficient μ refer to the determination of visibility distance to enable stopping, the roughness coefficient in these formulae is defined for smooth tyres, while the measured velocities in those investigations always referred to vehicles with threaded tyres, the Author decided to rely on empirical relationships. The results obtained in the investigations are shown in Fig. 4.

Analysis of these results proved that within the dependence of v_{85} velocity quantile on pavement roughness S, the stratification of data with relation to stopping sight distance l_z should be taken into account in addition.

As in the final stage of the technical state evaluation of highways, these relationships shall be depending on roughness measured within the annual control by SOSN, the Author proposes to express the empirical equations inserted below, in relation to pavement roughness S as well (and not on friction coefficient μ). Taking into account that all equations obtained as the result of regression are linear functions (4.1), the relevant coefficients of obtained equations are presented in tabular form (Table 2).

[10] Pavement roughness S is characterizing non-skid properties; in SOSN measurements $S = \mu \cdot 100$ (p. 62 in [5]).

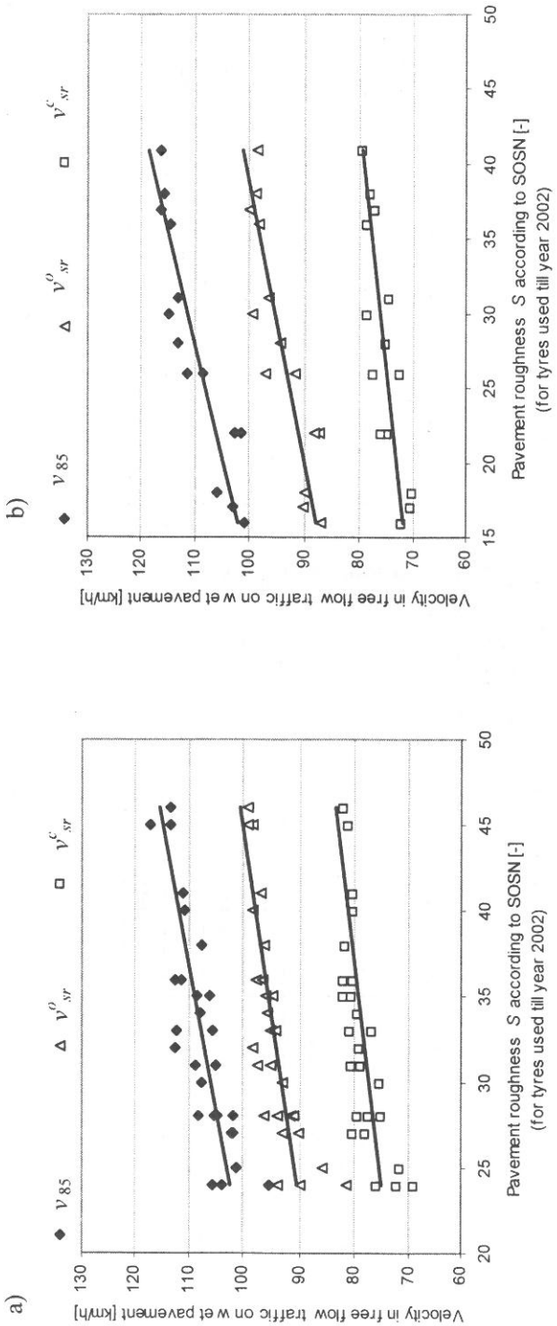


Fig. 4. Dependence of velocity in free flow traffic on pavement of roughness S: a) relationship $v = f(S)$ at stopping sight distance l_z = 100-300 m, b) relationship $v = f(S)$ at stopping sight distance l_z= 500-700 m.

Rys. 4. Zależność prędkości w ruchu swobodnym od szorstkości nawierzchni S: a) zależność $v = f(S)$ przy odległości widoczności na zatrzymanie l_z = 100-300 m, b) zależność $v = f(S)$ przy odległości widoczności na zatrzymanie l_z = 500-700 m

Table 2

Setting-up of coefficient values of linear equation (4.1)
(roughness S is determined for tyres used till year 2002).
Zestawienie wartości współczynników równania liniowego (4.1)
(szorstkość S określona dla opony stosowanej do 2002 r.)

Parameters of velocity distribution in free flow traffic	Stopping sight distance l_z = 100–300 m		correlation coefficient	Stopping sight distance l_z = 500–700 m		correlation coefficient
	coefficients			coefficients		
	a	b		a	b	
v_{85}	0.59	88	**0.81**	0.66	92	**0.91**
v^o_{sr}	0.47	79	**0.76**	0.52	80	**0.88**
v^c_{sr}	0.39	66	**0.74**	0.31	67	**0.82**
	range of $S = 24 \div 46$			range of $S = 16 \div 41$		

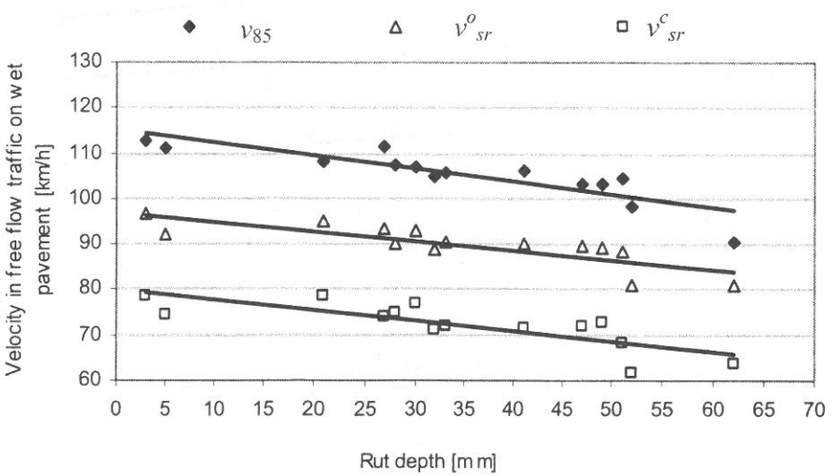
$$v = a \cdot S + b \qquad [\text{km/h}], \tag{4.1}$$

where v — three parameters of velocity distribution in free flow traffic and in wet state of pavement i.e.: v_{85} — passenger cars velocity quantile, [km/h], v^o_{sr} — mean velocity of passenger cars, [km/h], v^c_{sr} — mean velocity of motor trucks, [km/h], S — pavement roughness defined for test tyre, smooth and grooved, [-], a, b — corresponding coefficients of linear function given in Table 2.

For each of the three analysed dependencies of velocity on pavement roughness, ($v_{85} = f(S)$, $v^o_{sr} = f(S)$, $v^c_{sr} = f(S)$) a check was carried out whether this relationship is statistically significant using three tests for correlation significance (*Student, Guilford and Pearson tests*) [34]. All of them confirmed the significance of the analysed correlations.

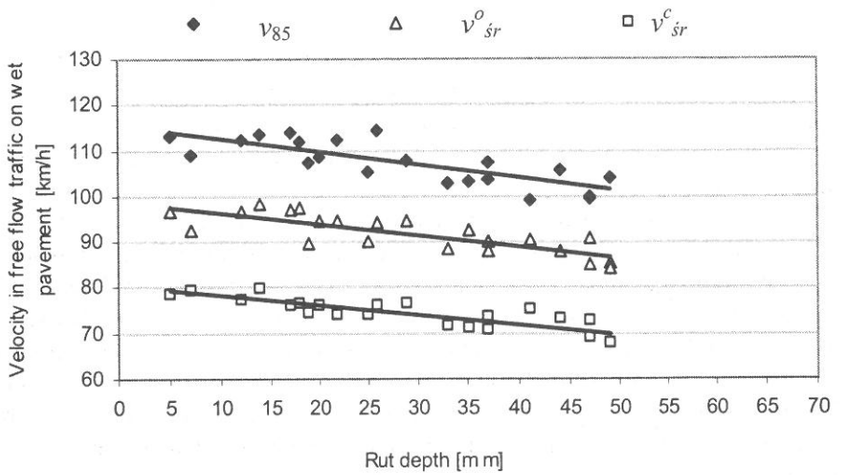
Concerning the investigation of rut depth on velocity, it should be stressed that a very important factor was the determination of water depth in the ruts during the rain. This problem was discussed by the Author in detail in [29]. Starting the investigation on rut depth influence on v_{85} quantile, the variation range of this parameter, occurring most frequently on national highways was determined in the first place, on the basis of data [17]. Next, several dozen of segments were chosen for measurements, which were divided into three groups depending on the stopping sight distance l_z occurring on them, in a similar way as in the case of investigation of roughness on velocity (Fig. 5). Investigation results were subjected to statistical analysis, applying to each analysed relationship — as in the previous case, apart from the calculation of correlation coefficient — three correlation significance tests. All three tests confirmed the correlation significance of the analysed data. In all analysed cases linear regression methods were used (4.2). Suitable coefficients of dependent equations obtained for each of the data groups as well as correlation coefficients calculated using the classical formula are presented in tabular form (Table 3).

a)



[Fig. 5]

b)



c)

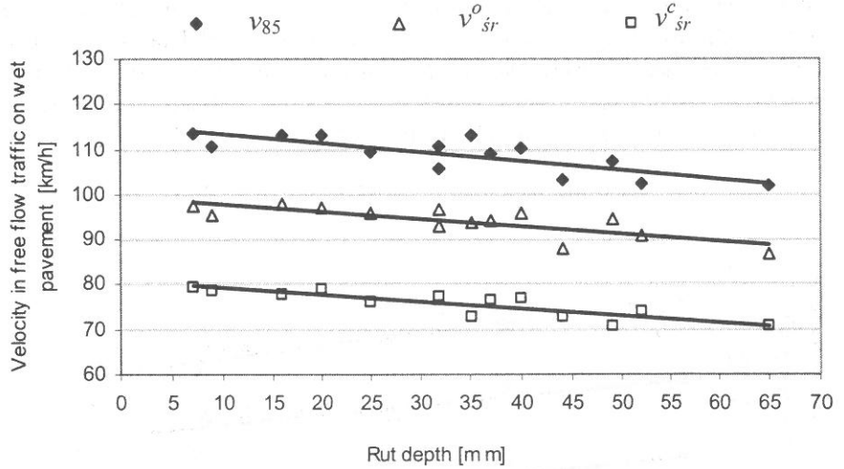


Fig. 5. Dependence of velocity in free flow traffic on rut depth k: a) relationship $v = f(k)$ at stopping sight distance l_z = 170–200 m, b) relationship $v = f(k)$ at stopping sight distance l_z = 300–450 m, c) relationship $v = f(k)$ at stopping sight distance l_z = 700–800 m.

Rys. 5. Zależność prędkości w ruchu swobodnym od głębokości koleiny k: a) zależność $v = f(k)$ przy odległości widoczności na zatrzymanie l_z = 170–200 m, b) zależność $v = f(k)$ przy odległości widoczności na zatrzymanie l_z = 300–450 m, c) zależność $v = f(k)$ przy odległości widoczności na zatrzymanie l_z = 700–800 m

Table 3

Setting-up of coefficient values of linear equation (4.2) (for different stopping sight distance).
Zestawienie wartości współczynników równania liniowego (4.2) (dla różnych odległości widoczności na zatrzymanie)

Parameters of velocity distribution in free flow traffic	l_z = 170–200 m		correlation coefficient	l_z = 300–450 m		correlation coefficient	l_z = 700–800 m		correlation coefficient
	coefficients			coefficients			coefficients		
	a	b		a	b		a	b	
v_{85}	−0.28	115	0.86	−0.29	115	0.80	−0.20	115	0.79
$v^{o}_{śr}$	−0.21	97	0.81	−0.23	98	0.78	−0.16	99	0.80
$v^{c}_{śr}$	−0.22	80	0.79	−0.20	80	0.84	−0.15	81	0.85
	in scope $k = 0 \div 60$ [mm]			in scope $k = 0 \div 50$ [mm]			in scope $k = 0 \div 65$ [mm]		

(4.2) $$v = a \cdot k + b \qquad [\text{km/h}],$$

where v — three parameters of velocity distribution in free flow traffic and in wet state of pavement i.e.: v_{85} — passenger cars velocity quantile, [km/h], v_{sr}^{o} — mean velocity of passenger cars, [km/h], v_{sr}^{c} — mean velocity of motor trucks, [km/h], k — rut depth, [mm], a, b — corresponding coefficients of linear function given in Table 3.

With reference to constant parameters the Author carried out the investigation of the effect of road bendiness K, roadway width B, traffic lane width b, ground shoulder width p and puddle width l_b on road shoulder l_k. As in the discussed investigations the stopping sight l_z was the stratifying parameter, separate investigations of the effect of this parameter on velocity have not been carried out. The obtained empirical dependencies of velocity on roadway width B and traffic lane width b, shoulder width p, and puddle width l_b on road shoulder l_k have been published by the Author in [26, 28, 31].

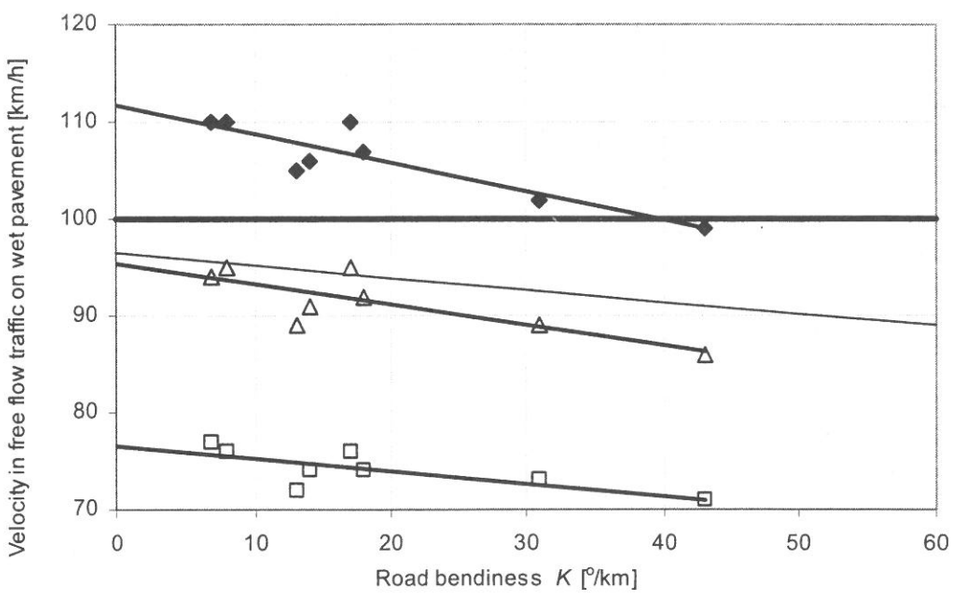


Fig. 6. Compare results velocity in free flow traffic recived from researchs with value pubshed in [4 and 7] for road bendiness in scope $0 < K \leq 40$ [°/km]; ▬ dependence after [4]; ── dependence after [7]; ♦ $\overline{v_{85}}$; Δ $\overline{v_{sr}^{o}}$; □ $\overline{v_{sr}^{c}}$.

Rys. 6. Porównanie wyników prędkości w ruchu swobodnym otrzymanych z badań z wartościami opublikowanymi w [4 i 7] dla krętości drogi w zakresie $0 < K \leq 40$ [°/km]

In this paper the dependencies of v_{85} velocity quantile on highway bendiness K shall be presented. This dependency was published in [3, 7] in the form of several curves for different roadway widths B within the highway bendiness range $0°/\text{km} \leq K \leq 360°/\text{km}$. Instructions WT [4] in force now, give the concrete values of reference velocity v_m depending on highway bendiness in the range $0°/\text{km} \leq K \leq 240°/\text{km}$. As mentioned above, all investigations of instantaneous velocities discussed in this paper pertained to highways placed in lowlands. To verify them it was decided to compare the v_{85} velocity quantiles, obtained in investigations with reference velocity v_m published in [4, 7] (Fig. 6). To this end, on 160 km of investigated highways their bendiness K was determined and the set of v_{85} velocity quantiles, obtained during site measurements, was assigned to each of the eight bendiness values on investigated roads. The data set obtained was non-uniform, as for each of the eight bendiness values a different number of investigated segments (several to more than a dozen) was obtained. When determining the relationship $v_{85} = f(K)$ it was therefore decided for each of the investigated highway bendiness K to assume arithmetic mean of $\overline{v_{85}}$ velocity quantiles defined on investigated segments assigned to the given bendiness. Similar method of analysis is recommended in [34] in cases of analysis of non-uniform input data.

Data non-uniformity consisted in this case on different rutting ($18 \text{ mm} \leq k \leq 35 \text{ mm}$) in some investigated segments, different stopping sight distance l_z ($250 \text{ m} \leq l_z \leq 500 \text{ m}$) in others; different was also the shoulder width p ($1.0 \text{ m} \leq p \leq 1.8 \text{ m}$). All the segments, however, were situated on level, straight in plan, highway intervals which also had similar roadway width — about 7 m — and pavement roughness ($33 \leq S^{11} \leq 40$).

Similar calculations of values of arithmetic mean of velocities were carried out for each of the eight cases of bendiness K with reference also to the mean velocities of passenger cars and motor trucks in free flow traffic (Fig. 6) to confirm the differences in magnitudes of the arithmetic mean values obtained, $\overline{v_{sr}^{o}}$ i $\overline{v_{sr}^{c}}$ from the required reference velocity value v_m. Detailed analysis of the data obtained proves that for the bendiness in the range $0°/\text{km} \leq K \leq 20°/\text{km}$, the arithmetic mean values of $\overline{v_{85}}$ velocity quantiles are much exceeding the values of v_m published in [14, 36], and arithmetic means of passenger cars velocities $\overline{v_{sr}^{o}}$ are only slightly smaller.

As the proposed evaluation of technical state of highways is based mainly on real velocities, the Author proposes in connection with this to introduce higher reference velocities v_m for bendiness $0°/\text{km} \leq K \leq 40°/\text{km}$) (Fig. 7). Introduction of higher required reference velocities v_m for the above bendiness range K will allow to choose for repairs those segments, where the value of the required velocity v_m is not guaranteed by the technical state of highway because of slippery pavement or rutting. From the analysis of the measurement data follows that on these segments e.g. v_{85} velocity quantile amounts now to $v_{85} = 110$ km/h or $v_{85} = 107$ km/h.

[11] Pavement roughness is defined for the test tyre, smooth, grooved.

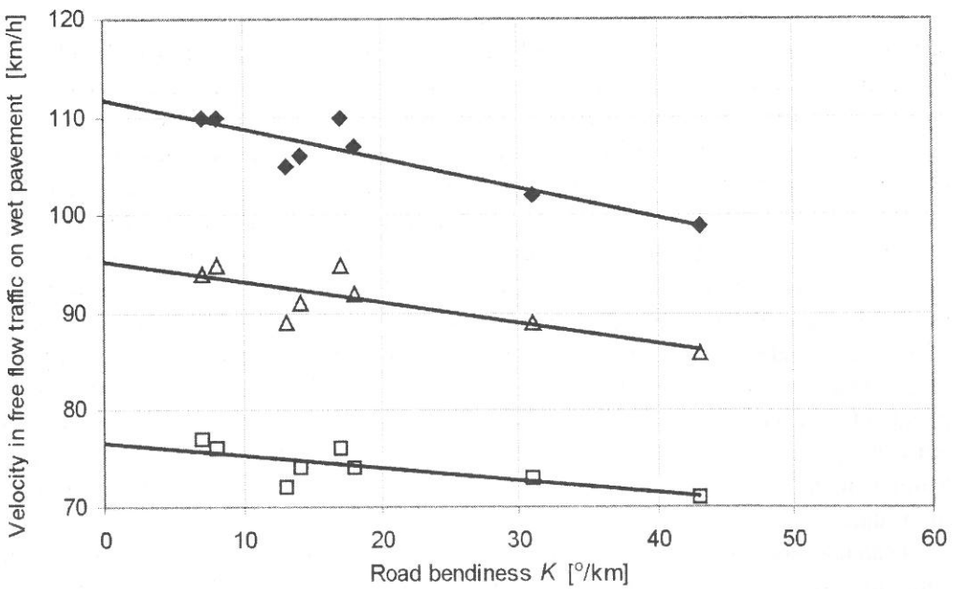


Fig. 7. Dependence of velocity in free flow traffic on road bendiness K; ♦ $\overline{v_{85}}$; Δ $\overline{v^{o}_{sr}}$; □ $\overline{v^{c}_{sr}}$
Rys. 7. Zależność prędkości w ruchu swobodnym od krętości drogi K

Table 4

Setting-up of coefficient values of linear equation (4.3)
(for highway bendiness in the range of 0°/km < K ≤ 40°/km).
Zestawienie wartości współczynników równania liniowego (4.3)
(dla krętości drogi w zakresie 0°/km < K ≤ 40°/km)

Parameters of velocity distribution in free flow traffic	coefficients		**correlation coefficient**
	a	b	
v_{85}	−0.296	112	**0.89**
v^{o}_{sr}	−0.210	95	**0.79**
v^{c}_{sr}	−0.127	77	**0.74**

As in the preceding cases, investigation results were subjected to statistical analysis applied to every analysed relation ($v_{85} = f(K)$, $v^{o}_{sr} = f(K)$, $v^{c}_{sr} = f(K)$). Apart from the calculation of correlation coefficient, three correlation significance tests (Student, Guilford and Pearson) [33] were carried out. All tests confirmed the significance of correlation of the

analysed data. In all analysed data linear regression methods were used (4.3). Dependent equation coefficients and correlation coefficients calculated using the classical formula are presented in tabular form (Table 4).

$$v = a \cdot K + b \qquad [\text{km/h}], \tag{4.3}$$

where v — three parameters of velocity distribution in free flow traffic and in wet state of pavement i.e.: vv_{85} — passenger cars velocity quantile, [km/h], v^{o}_{sr} — mean velocity of passenger cars, [km/h], v^{c}_{sr} — mean velocity of motor trucks, [km/h], K — highway bendiness, [°/km], a, b — corresponding coefficients of linear function given in Table 4.

5. CONCLUSIONS

Significant factors influencing traffic conditions on highways are constant and variable road parameters and external conditions altering in considerable way the real instantaneous velocities in free flow traffic present on the road and in consequence the real v_{85} velocity quantile. Share of the vehicles in free flow traffic is the function of traffic intensity occurring on the given traffic lane during one hour. The value of this intensity is varying in time and depends on hour of the day, day of the week and the month. From the free flow traffic analysis carried out during the hours with intensity $Q \leq 300$ P/h/lane on national highways, follows that about 20–60% of vehicles take part in free flow traffic (Fig. 2). These hours constitute about 80% of hours per day during the entire year, which proves that the change of v_{85} on the roads can be perceptible to the wide part of direct road users i.e. the drivers [28].

The analysis of the existing technical state evaluation methods carried out on the basis of available literature of the subject, proved that methods of calculating v_{85} velocity quantile from analytic expressions — used till now — do not consider all important necessary aspects when determining the changes of this velocity. State of the pavement (dry or wet) is not analysed and determined in every case. In addition, in formulae and analyses used now, the state of rutting commonly present in Poland and diverse states of ground shoulder maintenance are not taken into account.

On the ground of own research results the influence of several selected highway parameters on v_{85} velocity and mean velocities of passenger cars v^{o}_{sr} and motor trucks v^{c}_{sr} for two-lane, two-way highways with ground shoulders and bendiness lesser than 80°/km have been determined.

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WPŁYW WYBRANYCH PARAMETRÓW DROGI NA PRĘDKOŚĆ NA DWUPASOWEJ DRODZE DWUKIERUNKOWEJ

Streszczenie

W artykule przedstawiono problem zależności prędkości na dwupasowej drodze dwukierunkowej od wybranych parametrów drogi. Wykorzystując szereg zależności analitycznych lub wyznaczonych w sposób empiryczny można ocenić, jaką prędkość v_{85} będzie gwarantował swym stanem technicznym dany odcinek drogi. Wykreślony wzdłuż drogi profil prędkości v_{85} (gwarantowanej stanem technicznym drogi) umożliwia znalezienie miejsca, gdzie występują obniżone wartości prędkości v_{85} lub gdzie następują gwałtowne zmiany tej prędkości na następujących po sobie odcinkach.

Powyższą analizę wpływu poszczególnych parametrów drogi na prędkość autorka proponuje wykorzystywać do oceny stanu technicznego dróg ze względu na gwarantowaną wartość użytkową drogi, czyli prędkość v_{85} [30, 31]. Analiza oceny stanu technicznego dróg ze względu na prędkość jest potrzebna i konieczna, gdyż — jak pisze St. Lenczewski w przedmowie do [18] — „...statystyki wypadków drogowych wysuwają jako jedną z głównych przyczyn ich powstawania błędne działanie kierowcy. Analiza lokalizacji miejsc wypadków świadczy o grupowym sposobie ich występowania na określonych krótkich odcinkach drogi. Zjawisko to może oznaczać, że w pewnych określonych miejscach na drodze powstają nagle, nieoczekiwane przez kierowców zmiany i utrudnienia w warunkach ruchu, a wytworzone przy tym sytuacje doprowadzają do wypadków, w których droga odgrywa istotną rolę. ...".

Remarks on the paper should be sent to the Editorial Board not later than October 30, 2004

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