ESTIMATION OF FREE-FLOW SPEEDS ON RUTTED ASPHALT TWO-WAY, TWO-LANE ROADS WITH THE SOFT SHOULDERS

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Abstract. Within the framework of research into the road condition assessment considering the utility values, the *West Pomeranian University of Technology in Szczecin Dept of Roads, Bridges and Building Materials* has made a number of spot-speed measurements in free traffic flow under adverse weather conditions and on variously rutted asphalt road surfaces. This paper presents the findings on the impact of the rut depths on the 85% speed quantile, v_{85}. Furthermore, the average speeds for passenger vehicles, v_{av}^{o}, and for goods vehicles, v_{av}^{c}, reached at various available stopping sight distances, l_z, are also presented herein.

Keywords: free-flow speeds, rutted asphalt road surfaces, available sight distance, bendiness.

1. Introduction

A significant increase in traffic volume becomes visible in Poland (Judycki 2006), due to which, unfortunately, most existing roads of a flexible pavement structure are not optimally-sized. In the summertime, this increased traffic flow adds to the adverse effect of high temperatures, resulting in permanent deformations of the pavement structure (in the form of ruts) as well as has an impact on road user safety, driving comfort and the overall technical condition of roads (Sokolovskij 2007; Sokolovskij *et al.* 2007; Vansauskas, Bogdevičius 2009; Viba *et al.* 2009). In Poland, as in other countries, the very road operation, the pavement degradation and the progress in structural damages stimulate the development trend in the evaluation methods of road conditions.

According to the *Catalogue of Reinforcements for Flexible and Semi-Rigid Pavements* (2001) Poland uses the *Road Surface Assessment System* (SOSN), which remains in effect since 1989, the rut depths are measured on the yearly basis and they are the essentials in the assessment of road maintenance class. Based on the SOSN specification limits for operational parameters the individual Road Departments are working out plans either for the road surface repairs or for rebuilding the rutted road sections.

After repairing or rebuilding road, unfortunately, nobody assesses how far the road conditions are really improved, or to what extent the road users took the advantage of such a repaired pavement. As a rule, the driving speeds on the dangerous road sections shall be measured or evaluated before the road rebuilding starts, but this is hardly ever the case (Sołowczuk 2009). Occasionally, the driving speed is measured after rebuilding, leaving no chance to compare the before and the after speeds.

In consideration of the above, in 1998–2004 the present author – within the framework of her research partially supported by KBN (*State Committee for Scientific Research) through the grant No. 1829/IA/108/96 and by RKH (Vice-Chancellor's Staff of Postdoctoral Candidates) and the grant No. 17-0123/17-99-2001*) – carried out a number of investigations into the spot speeds under adverse weather conditions and on variously rutted two-way, two-lane national roads with the soft shoulders. Those investigations were made in order to determine to what extent the variously rutted pavements have an impact on the individual measures of speed position in free traffic flow.

Estimation of the impact of a single operational feature, however, does not establish credibility for the evaluation of economical effects gained after the road repair, because the overall road operation is affected by an array of the other road features. In 1995, after many years of investigations, Prof. T. Szczuraszek, then at the University of Technology and Agriculture in Bydgoszcz, Poland, and his collaborators developed a free-traffic-flow math model for the roads of various cross-sections. The model consists of both a selective sampling approach to individual road features and a segmented developing of the basic mathema-

tical model. Following that five-stage free-flow model, one can evaluate the speed distribution parameters in free-flow conditions on the wet pavement as a function of variables of several chosen road features (Szczuraszek, Kempa 1995)

Even though the above free-traffic-flow model (Szczuraszek, Kempa 1995) enables one to evaluate the speed distribution parameters, yet its mathematical functions for evaluating the individual measures of speed position have not been fully developed for all the five stages of such evaluation. In comparison with other systems or models, however, that math model allows for most road features, mainly the geometrical parameters. Still, in the process of its development the authors of that model carefully endowed it with some priorities and capabilities enabling its later development. This manifests itself in readiness of that model for being extended by the newly developed segments or stages, which definitely proves both its merit and advantage over the other similar models.

Considering the easiness and usefulness of the estimation based on the free-traffic-flow model and the fact of making only theoretical assumptions about the dependence of the speed upon some road features (e.g. as a function of $v = f$ (SOSN averaging class for the geometrically uniform road fragment), the present author has proposed to enhance the free-flow model by several analytical relationships (Sołowczuk 2005; 2009). These include, among other things, the analytical correlations between the vehicle speed and the rut depths, anti-skid/anti-slip properties, the soft shoulder maintenance, the available sight distance and the road bendiness. With this end in view, the present author has conducted experimental research on two-way, two-lane roads with the carriageways of 6 and 7 m respectively in years 1998–2004. This paper presents the findings and analytic functions for the evaluation of the impact of the rut depths on free traffic flow on the wet pavement.

2. Methodology

Within the framework of research on the assessment of road conditions, the *West Pomeranian University of Technology in Szczecin Dept of Roads*, Bridges and Building Materials has conducted the longstanding experimental investigations into the spot speeds in free traffic flow under adverse weather conditions and on the variously rutted asphalt road surfaces. Based on the meteorological data, it has been assumed that research on the spot speeds shall be conducted during the rainfalls with parameters below the 85% quantile of the most frequent rains recorded heretofore (Sołowczuk 2005; 2009).

To evaluate the impact of the rut depth on the vehicle speed in free traffic flow, three parameters of speed distribution have been chosen, i.e. quantile v_{85} of passenger vehicles, and the average speeds for passenger and goods vehicles (v_{av}^o and v_{av}^c). According Lamm (1995), it has been assumed here that the free traffic flow is the one where the specific time slots occurred, i.e. a 7 s slot in front of and a 4 s slot behind a vehicle. In (Lamm 1995), it has also been

estimated that for the traffic volume up to 300 vehicles per hour on one lane (vph/lane) the motor-vehicle participation in free traffic flow ranges from 25% to 60%.

For their free-flow model, its authors formulated the necessary conditions to ensure the likelihood of the desired one-parameter relationship evaluating the impact of a single road feature on the speed form of a difference, i.e. $v = v_w - f(x)$ (Szczuraszek, Kempa 1995), on the assumption that all the other road features are of benchmark values. Here, the first element, v_w, defines the benchmark speed for a road section of which all the features have the benchmark values. The second element, $f(x)$, estimates the reduction in speed when the to-be-investigated feature, x, consecutively takes on other-than-benchmark values.

In consideration of the above, in her estimation of the dependence of the speed on the rut depth, the present author adopted the following criteria for selection the research sections: all the measuring sections should run along the level and straight-ahead road fragment, whereas the soft shoulders should drain all rainwater swiftly and effectively. Aside from the permanent deformations in the form of ruts, the pavement structure should be free of any damages and should have the anti-slip properties of SOSN class A. In order to avoid any disturbances in the road traffic, there should be no intersections, level crossings, bus stops, or local speed limits near such measuring sections. It was the foregoing assumptions that ensured the likelihood of one-parameter function in evaluation of the rut-depth impact on the speed.

Other assumptions were made for the measuring method, all investigations have been carried out by means of the electronic device dedicated for measuring both the vehicle speed and the traffic generic structure (Sołowczuk 2005; 2009).

To determine the min sample size at two confidence levels: $1 – \alpha = 0.9$ and $1 – \alpha = 0.95$, the field surveys started with pretesting of the spot speeds. The standard error of the spot-speed measurement was approx 3 km/h, whereas the max estimation error for the average speed was below 5%, i.e. in compliance with the recommendations given in Greń (1982). Basing on the analysis of preliminary measurements taken in free traffic flow, it was assumed that the min sample size for the passenger vehicles be that of 120, whereas for the goods vehicles be that of 60.

Next, the methodology for statistical inference and for the verification of deduced analytical functions were adopted. For the purpose of analytical relationships describing the dependence of the speed upon the chosen road features, and in relation to the measurement results for the spot speeds, the present author adopted the following methodology: a hypothesis that the population of data has a normal distribution is to be tested by goodness-of-fit tests, whereas the tests for homogeneity are to be performed to verify whether the boundary elements belong to the relevant population or not (Greń 1982).

Trueness of mathematical models, which describe the dependence of the speed on the road features, are estimated in two ways:
- by valuating the average estimation error of speed distribution parameters;
- by verifying the goodness of fit of theoretical and empirical speed distribution functions.

For the purpose of statistical analysis, the following parameters of speed distribution have been chosen: the 85% quantile of car speeds, the expected values and the standard deviations of passenger and goods vehicles. An estimation error of the chosen parameters has been calculated based on the deduced probability functions of residues, i.e. the differences between the empirical and theoretical values (Fig. 1). In compliance with the methodology for the statistical analysis of the measured spot-speed data adopted in Poland (Szczuraszek, Kempa 1995), it has been assumed that:
- the average error is the standard deviation of a difference between the empirical and theoretical values for the speed-distribution function, i.e. the quadratic error of approximation;
- the max error is the 97.5% quantile of a difference between the empirical and theoretical values, which approx equals twice the average error.

The above assumptions correspond with the significance level of $\alpha = 0.05$, i.e. the acceptance of 5% cases burden with an error greater than the max value (Greń 1982).

To test the hypothesis that the analyzed population of data has a normal distribution $H_0 : F(x) \in \Omega$, the *Pearson* χ^2 & *Kolmogorov* goodness-of-fit λ–tests were performed. At the significance level $\alpha = 0.05$, the spot speed measurements for all research sections passed both tests. For all the considered cases, the statistic values of χ^2 and l were lower than the relevant critical values of χ_α^2 and λ_α.

Classical methods for the regression and correlation analyses as well as for a design of the experiment were used in developing the mathematical models of the relationships under investigation. That classical methodology for developing mathematical models is explained in detail in such works as (Greń 1982), and is widely used in the experimental research. Both, classical and traditional methods in use to solve that problem consist in proving the specific hypothesis through the statistical inference and the consistent verification of empirical values against those estimated by means of the proposed model, and thanks to the relevant statistical tests (criteria).

When developing the mathematical models with respect to the spot-speed measurement results and the estimated values of the road feature under investigation, the test statistics were performed and the relevant correlation coefficients were defined by the significance tests for correlation coefficients: *Student's and Pearson's Tests*. To test the linear dependence of the vehicle speed upon the investigated road feature, $v = f(x)$, each correlation was additionally investigated by the *Series Test*.
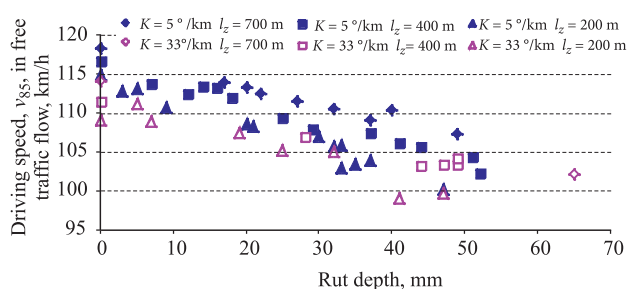

Fig. 1. Estimated speeds, v_{85}, for the research sections grouped in respect of the available sight distance, road bendiness and the rut depth (*k*)

During data analysis, it became visible that the available sight distance and the bendiness of practically level and straight-ahead sections with the shoulders in benchmark condition should also be taken into account. Thus, in the first place, the road sections were segregated into a group in respect of the available sight distance and, then, into a group in respect of the bendiness (Fig. 1).

The speed distribution analysis for the sections with the non-rutted pavement reveals that for those road fragments of benchmark bendiness and of various available sight distances, the cumulative distribution functions are differentiated insignificantly (Fig. 2). However, for the pavements with the ruts of about 35 mm in depth the differences in the speed distributions are noticeable and are significant for the rut depth of about 50 mm (Fig. 2).

Research was conducted on two road sections, one with the bendiness *K* of 5 °/km and another of 33 °/km. Bendiness is a sum of a turning degree measured in degrees, calculated over a distance of at least 40 km or between two cities, divided by the length of the calculated distance measured in km. Fig. 2 represents the results from the 5 °/km fragment and Fig. 3 represents the results from 33 °/km fragment.

The analogous analysis of the differences between the distribution functions were made with respect to the speed distributions on the road sections with the non-rutted pavement and running along the road fragments with a bendiness of 5 °/km and 33 °/km respectively, but with various available sight distances. For the available sight distance of $l_z = 700$ m, the differences between the distribution functions are insignificant, but become noticeable for the shorter available sight distances (Fig. 3).

3. Estimating the dependence of the speed upon the rut depth

3.1. An analysis of the speed variations on the research sections

As regards the investigation into the dependence of the speed distribution parameters upon the rut depth, it should be emphasized that for Poland low-country roads it was a depth of rainwater collected in a rut on the roads
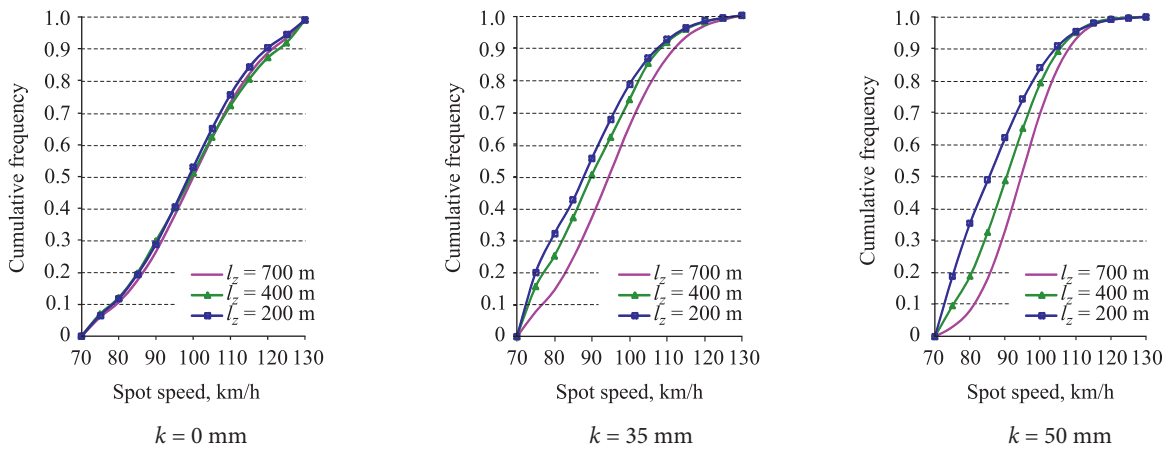
Fig. 2. Speed distribution functions for the road sections with various pavement conditions and the benchmark bendiness of 5 °/km
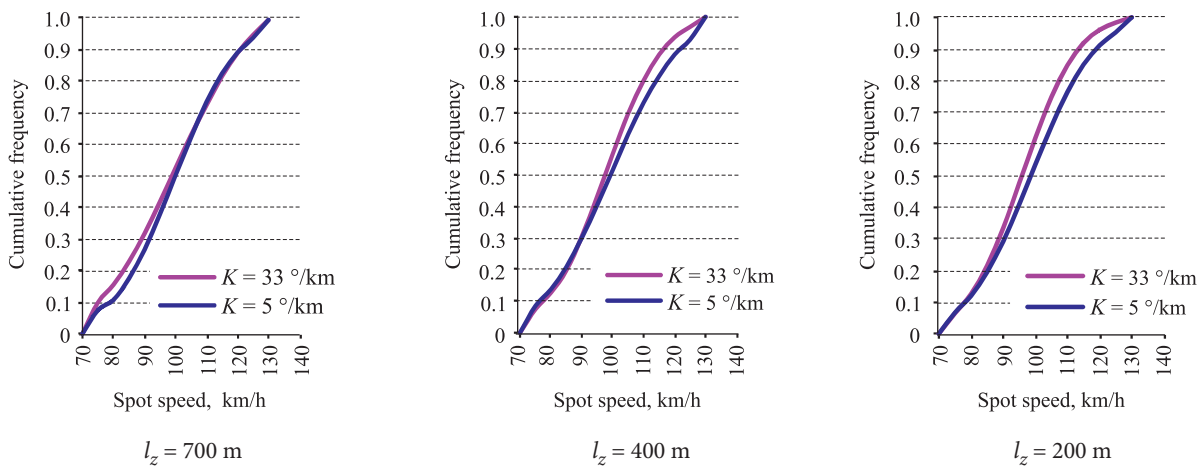

Fig. 3. Speed distribution functions for the road sections with the non-rutted pavement, various available sight distances and the bendiness of 5 °/km and 33 °/km respectively

with a longitudinal grade of ±1% that was of great importance. In consideration of this, it was assumed that all speed measurements for the road sections with various rut depths would be taken only if the rainfall intensity is $q_{85} \leq 12$ l/ha s, i.e. in compliance with the assumptions made in item 2.

A selection of hectometer sections for the investigation into the impact of the rut depth on the speed distribution parameters was made on the premises stated earlier (item 2): all the research sections should be differentiated only by the rut depth, while the other road features should be of benchmark values. Such selected road sections were characterized by various available site distances, l_z, ranging from 100 m to 1000 m. Moreover, all those sections were run along practically level (< ±1%) and straight-ahead road fragments of 7 m (width of the road) carriageways with a bendiness of 5 °/km or 33 °/km.

Based on the assumptions made in item 2, the spot speed measurements taken for both groups of vehicles and for the singled-out three groups of the available sight distances: $l_z = 200$ m, $l_z = 400$ m and $l_z = 700$ m, were statis-

tically analyzed. Those statistical findings are presented in Table 1 and in Figs 4, 5.

The result linear regressions and the statistically significant correlation between variables have been verified with the relevant tests:

$$v^{(k)} = a_1 + a_2\, k, \tag{1}$$

where $v^{(k)}$ – three parameters of speed distribution for the level and straight-ahead road fragments of 7 m carriageways with a bendiness of 5 °/km and variously rutted sections, km/h; k – rut depth ($0 \leq k \leq 50$ mm), mm; a_1, a_2 – the relevant coefficients of linear regression, Table 1.

To verify the one-parameter dependence of the speed on the rut depth, ($v_{85} = f(k)$, $v_{av}^o = f(k)$, $v_{av}^c = f(k)$), the similar test statistics were used to evaluate – on the road sections under investigation – the dependence of the speed-distribution parameters on the other road features (Sołowczuk 2005, 2009). In all these instances, the low correlation coefficients showed the lack of evidence for the dependence of the speed on the other road features. To re-

Table 1. Correlation and model coefficients (1) (for various available sight distances) (Sołowczuk 2005)

Available sight distance, m	Speed distribution parameters for free traffic flow	Coefficients of correlation and determination and confidence interval			Correlation significance by test:		Model coefficients (1)	
					Student	Pearson		
		R	R^2	$R \pm u_a \dfrac{1-R^2}{\sqrt{n}}$	$\left\| t = R\sqrt{\dfrac{n-2}{1-R^2}} \right\| > t_\alpha$	$\|R\| > R_\alpha$	R	R^2
		$n = 13$ road sections			$t_{0.05} = 2.20$	$R_{0.05} = 0.55$	range $k = 0–47$ mm	
200	v_{85}	0.98	0.96	0.98 ± 0.02		v_{85}	0.98	0.96
	v_{av}^o	0.91	0.83	0.91 ± 0.09		v_{av}^o	0.91	0.83
	v_{av}^c	0.91	0.82	0.91 ±0.095		v_{av}^c	0.91	0.82
		$n = 13$ road sections			$t_{0.05} = 2.20$	$R_{0.05} = 0.55$	range $k = 0–52$ mm	
400	v_{85}	0.99	0.97	0.99 ± 0.01		v_{85}	0.99	0.97
	v_{av}^o	0.91	0.83	0.91 ± 0.09		v_{av}^o	0.91	0.83
	v_{av}^c	0.90	0.81	0.90 ±0.10		v_{av}^c	0.90	0.81
		$n = 9$ road sections			$t_{0.05} = 2.37$	$R_{0.05} = 0.67$	range $k = 0–49$ mm	
700	v_{85}	0.98	0.96	0.98 ± 0.03		v_{85}	0.98	0.96
	v_{av}^o	0.85	0.73	0.85 ± 0.18		v_{av}^o	0.85	0.73
	v_{av}^c	0.82	0.68	0.82 ± 0.21		v_{av}^c	0.82	0.68

cap, the statistical findings proved theoretical assumptions that for estimating the one-parameter dependence of the speed upon a given road feature, the only research sections which have to be chosen are those being uniform in respect of bendiness and the available sight distance.

3.2. Estimating the speed variations induced by various rut depths at the benchmark available sight distance and bendiness

According to the mathematical modelling proposed herein, it has been assumed that road assessment will be based upon the differences in speed, which will be evaluated relative to the speed distribution parameters for the sections of which the other road features have benchmark values, and at the available sight distances as follows v_w:

The above measures of speed position shall be recorded on the road sections with the pavement of which the other operating features are benchmarks, and with the soft shoulders in benchmark condition. It turned out, however, that the pavement of road fragments just upstream of hectometer research sections, and that of rutted research sections, were in various condition, so the estimation by (model 1) for the rut depth of $k = 0$ mm yielded a slightly lower coefficient values, a_1, then the speed values, v_p, estimated for the road sections with all benchmark features (Table 2), and for the relevant groups of the available sight distances (Sołowczuk 2005, 2009).

The resultant slight differences in speed were possibly related to the pavement condition (mostly to the rut depth) of the road fragments just upstream of research sections. Values for the coefficient a_1 (model 1) only slightly differ from those for the speed $v_{p\,85}$ (Table 3) and running from 0.6 km/h to 0.9 km/h.
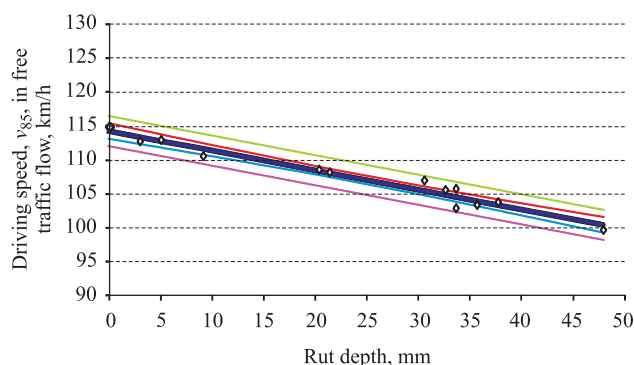
Fig. 4. Vehicle speed v_{85} the rut depth (at the available sight distance of $l_z = 200$ m): ◇ v_{85}, — Regression function, — Upper limit of confidence interval for a single observation, — Upper limit of confidence interval for a linear regression, — Lower limit of confidence interval for a linear regression, — Lower limit of confidence interval for a single observation.
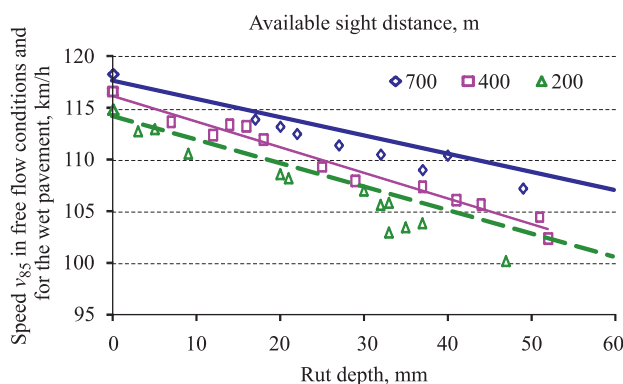
Fig. 5. Dependence of the speed v_{85} on the rut depth for the level and straight-ahead road fragments with benchmark bendiness 5 °/km and at various available sight distances

Table 2. Road features benchmark values summary (Sołowczuk 2005)

Available sight distances at l_z, m	v_{85}, km/h	v_{av}^o, km/h	v_{av}^c, km/h
200	115.0	98.4	79.8
400	116.8	99.1	80.9
700	118.3	99.8	81.7

3.3. Estimating the speed variations induced by various rut depths on the road fragments with various available sight distances and bendiness

Considering the basic principles of mathematical modelling applied to the proposed assessment method of road utility values, the model $v^{(k)} = a_1 + a_2 \, k$ had to be transformed into a suitable form, as per $v_{(k)} = a_3 v_p + a_2 k$, according to modelling presented in (Sołowczuk 2005, 2009). On the assumptions made in items 2 and 3, for the ultimate estimation of the dependence of the speed on the rut depth, only the sections run along the road fragments with benchmark bendiness were selected.

Comparative analysis of the findings for the 7 m carriageway road fragments having a bendiness of 5 °/km and 33 °/km respectively conclusively revealed that the speed is not only depended upon the rut depth, but also upon the bendiness at the available sight distance on a given hectometer section (Fig. 5).

Analysing the results of the significance test of linear regression coefficient (Table 2, Column 5), and comparing results by estimating values of v_p and calculated according to model (1) (Table 2, Columns 8 and 9), one can arrive at the conclusion that the main factor influencing the parameters of speed distribution is the rut depth. However, in the case of other-than-benchmark bendiness, and following the model (2), one shall make the necessary corrections. In consideration of the above, it is conclusively proposed that for the estimation of the impact of the rut depth on the parameters of speed distribution for the 6 m and 7 m carriageway road fragments with a bendiness of $5\,°/\text{km} \le K \le 66\,°/\text{km}$, and at the available sight distance of $200\,\text{m} \le l_z \le 700\,\text{m}$, the following equation is to be used:

$$v_{(k)} = a_3 v_p + a_2 k - (v_p - v_o), \qquad (2)$$

where $v_{(k)}$ – three parameters of speed distribution for the level and straight-ahead 6 m or 7 m carriageway road fragments with a bendiness of $5\,°/\text{km} < K \le 66\,°/\text{km}$, at the available sight distance of $200\,\text{m} \le l_z \le 700\,\text{m}$, and for the road sections of various rut depths, km/h; a_3 – the relevant coefficient of linear correlation, (Table 3); v_p – three parameters of speed distribution for the 7 m carriageway road section having a bendiness of $K = 5\,°/\text{km}$ (Sołowczuk 2005, 2009) and at the available sight distance on the ith section, km/h; a_2 – the relevant coefficient of linear correlation, (Table 3); k – rut depth, mm; v_0 – three parameters of speed distribution for the 6 m or 7 m carriageway road

Table 3. Speed values v_p and coefficient values a_1, by model (1), at the available sight distances and for $k = 0$ mm (Sołowczuk 2005)

Available sight distance, m	Speed distribution parameters	SKB[1]	t_α[2]	t[3]	Speed values v_p, equal to the relevant parameter of speed distribution, km/h	Coefficient values a_1, model (1), [numerically] equal to the relevant parameter of speed distribution, km/h	The difference of $(v_p - a_1)$ and the ratio of $a_3 = \dfrac{a_1}{v_p}$	
					for $K = 5$ °/km	$k = 0$ mm	km/h	$a3$
200	v_{85}	0.5	1.90	12.65	$v_{85} = 115.2$	$v_{85}^{(k)} = a_1 = 114.3$	0.9	0.992
	v_{av}^o	0.8	1.90	4.06	$v_{av}^o = 98.6$	$v_{av}^{o\,(k)} = a_1 = 98.4$	0.2	1.000
	v_{av}^c	0.8	1.90	3.78	$v_{av}^c = 79.9$	$v_{av}^{c\,(k)} = a_1 = 79.9$	0.0	1.000
400	v_{85}	0.3	1.80	18.38	$v_{85} = 116.9$	$v_{85}^{(k)} = a_1 = 116.2$	0.7	0.994
	v_{av}^o	0.7	1.80	7.23	$v_{av}^o = 99.2$	$v_{av}^{o\,(k)} = a_1 = 99.2$	0.0	1.000
	v_{av}^c	0.9	1.80	7.01	$v_{av}^c = 80.9$	$v_{av}^{c\,(k)} = a_1 = 80.8$	0.1	1.000
700	v_{85}	0.4	1.80	15.29	$v_{85} = 118.3$	$v_{85}^{(k)} = a_1 = 117.7$	0.6	0.995
	v_{av}^o	0.5	1.80	6.82	$v_{av}^o = 99.8$	$v_{av}^{o\,(k)} = a_1 = 98.9$	0.9	0.995
	v_{av}^c	0.5	1.80	7.04	$v_{av}^c = 81.7$	$v_{av}^{c\,(k)} = a_1 = 80.9$	0.8	0.990

[1] SKB – least-squares approximation error, as the standard deviation of the speed difference $(v - \hat{v})$, where: v – measured speed; $\hat{v}$ – estimated speed, by model 1.

[2] t_a – critical value of the right-sided rejection region, as per Student's table, for the degrees of freedom $\gamma = n - 2$ and at the significance level $\alpha = 0.05$ – according to Greń (1982).

[3] t – value of the significance test of linear regression coefficient.

section (Sołowczuk 2005, 2009) and at the available sight distance on the ith section with a bendiness of 5 °/km and 66 °/km.

4. Evaluating the economic effectiveness of rutting removal

Considering the fact that the road condition assessment in respect of road utility values is strictly related with evaluating the economic effectiveness of roadworks (maintenance, repairs or rebuilding), it was vital to show a statistically significant difference between the average speeds before and after the roadworks related to the betterment of a given road feature. In our case, all the economic effectiveness analyses were concerned with rutting removal. To this end, the spot speeds were re-measured after rutting removal. Practically, in all considered cases the re-measurement results revealed the increase in the parameters of speed distribution.

To evaluate the economic effectiveness of rutting removal, standard test statistics, i.e. the significance test for the two means and the *Kolmogorov-Smirnov* goodness-of-fit λ-test (Greń 1982), were used.

In the significance test for the two means, the values for two speed populations of normal distribution, $N(\overline{v^{"before"}}, \sigma_{"before"})$ and $N(\overline{v^{"after"}}, \sigma_{"after"})$, are compared. In our case, the average speeds reached by the passenger and goods vehicles respectively on the research sections before and after rutting removal were compared. Following the usual test procedure, two hypotheses were formulated: a null hypothesis, H_0, and an alternative hypothesis, H_1, for each group of vehicles respectively, that is:

$$H_0: \quad v_{av}^{o\ (before)} = v_{av}^{o\ (after)},$$
$$v_{av}^{c\ (before)} = v_{av}^{c\ (after)},$$

$$H_1 \quad v_{av}^{o\ (before)} < v_{av}^{o\ (after)},$$
$$v_{av}^{c\ (before)} < v_{av}^{c\ (after)}. \quad (3)$$

To test the hypothesis (3), the standard statistical model (4) of the following notation was proposed:

$$u = \frac{\overline{v^{"after"}} - \overline{v^{"before"}}}{\sqrt{\dfrac{s_{"after"}^{2}}{n_{"after"}} + \dfrac{s_{"before"}^{2}}{n_{"before"}}}}, \quad (4)$$

where u – statistic values of the significance test for the two means; $\overline{v^{"after"}}$ and $\overline{v^{"before"}}$ – average speeds of the relevant group of vehicles; $s_{"after"}$ and $s_{"before"}$ – standard deviation for the relevant group of vehicles; $n_{"after"}$ and $n_{"before"}$ – sample size for the group of vehicles to be compared; subscript/superscript "*after*" is relating to the

speeds, standard deviation and sample size with reference to measurements taken on the research sections *after* rutting removal; subscript/superscript "*before*" is relating to the speeds, standard deviation and sample size with reference to measurements taken on the research sections in existing condition, i.e. *before* rutting removal.

Results of statistical analyses by Eq (4) are given in Table 4. The alternative hypothesis takes a form of inequality $H_1: v^{"after"} > v^{"before"}$, hence the right-sided critical interval $[u_\alpha, \infty)$ described by inequality $u \geq u_\alpha$. A critical statistic value, u_α, was estimated by the condition $P\{u \geq u_\alpha\} = \alpha$. Considering the above, for all analysed instances at the significance level $\alpha = 0.05$, the critical statistic value was $u_\alpha = 1.64$ (Greń 1982).

Analysis of the significance test results revealed that for all investigated groups of the available sight distance and for the rut depths greater than $k = 20$ mm, the hypothesis H_0 must be rejected and the hypothesis H_1 is to be adopted. It means that rutting removal significantly affects the increase in average speeds of passenger and goods vehicles alike. For the group of the road sections with the available sight distance $l_z = 400$ m, test results shown only a slight diversity. However, for the sections of which the friction factor m was evaluated between 0.51 and 0.57, or which run along the road grade of ~1%, the hypothesis H_0 was confirmed by isolated cases, i.e. statistically insignificant differences in speed after rutting removal.

Having defined – based on the significance tests for the two means – the range of rut depths, removal of which induced the increase in speed of passenger and goods vehicles alike, the Kolmogorov-Smirnov goodness-of-fit λ-tests were used to verify the null hypothesis assuming that the speeds on the research sections *before* and *after* rutting removal belong to the same population. In our case, and in compliance with recommendations presented in Greń (1982), the null hypotheses H_0 were tested on the assumption that the empirical distribution function of speed for the relevant group of vehicles on the road section *after* rutting removal is statistically insignificant when compared to the empirical distribution function of speed for the relevant group of vehicles on that road section *before* rutting removal.

Following the procedure for a goodness-of-fit test, the max difference between the empirical distribution functions of speed on the research sections *before* and *after* rutting removal were further searched for in the individual speed class-intervals of the relevant group of vehicles and finally calculating the statistic values of *Kolmogorov-Smirnov* λ.

Next, at the significance level $\alpha = 0.05$ and for $P\{\lambda \geq \lambda_\alpha\} = \alpha$, the critical value ($\lambda_\alpha$) was estimated. The (λ) statistic value calculated by equation *Kolmogorov-Smirnov Tests* was then compared with the estimated critical value (λ_α). In all considered instances and at the significance level $\alpha = 0.05$, the critical statistic value was $\lambda_\alpha = 1.36$ (Greń 1982). If the statistic value satisfied the inequality $\lambda > \lambda_\alpha$,

then the null hypothesis H_0: $F_e(v^{"after"}) = F_e(v^{"before"})$ rejected because the speeds on the road sections *before* and *after* rutting removal belonged to the different populations. It meant here that roadworks caused statistically significant increase in speed, so the hypothesis H_1 was adopted. Otherwise, if the statistic value satisfied the inequality $\lambda < \lambda_\alpha$, then the null hypothesis was confirmed because the speeds on the sections *before* and *after* rutting removal belonged to the same population, thus roadworks induced statistically insignificant increase in speed.

By the results of *Kolmogorov-Smirnov* goodness-of-fit λ –tests, we got $\lambda > \lambda_\alpha$ for the sections with the following available sight distances:

– $l_z = 200$ m; for both groups of vehicles under consideration, since for the rut depth $k > 20$ mm: in the group of passenger vehicles $\lambda = 2.42$–4.49, whereas in the group of goods vehicles $\lambda = 1.89$–2.39;

– $l_z = 400$ m; since for the rut depth $k > 20$ mm in the group of passenger vehicles $\lambda = 1.94$–2.39, whereas for the rut depth $k > 16$ mm in the group of goods vehicles $\lambda = 1.60$–3.62;

– $l_z = 700$ m; for both groups of vehicles under consideration, since for the rut depth $k > 20$ mm: in the group of passenger vehicles $\lambda = 1.38$–1.85, whereas in the group of goods vehicles $\lambda = 2.21$–2.45.

The statistical test results proved that within the above rut-depth ranges, the empirical cumulative distribution functions of speed on the sections *before* and *after* rutting removal differed significantly for both the passenger and goods vehicles alike, and that a considerable increase in average speeds is observed after repairing the road surface.

5. Conclusions

By using a mathematical modelling, which considers various bendiness and the available sight distances on the road

Table 4. Results of the significance test and speed measurements for research sections before rutting removal (Sołowczuk 2005)

Item	Rut depth k, mm	Average speeds and a percent increase in speed after rutting removal, km/h				Statistic value u	
		v_{av}^o	%	v_{av}^c	%	Passenger vehicles	Goods vehicles
sections with the available $l_z = 700$ m							
1	0	99.8	–	81.7	–	–	–
2	17	97.1	2.8	75.9	7.6	1.54	**2.95**
3	20	97.9	1.9	77.8	5.0	0.99	**2.31**
4	22	95.3	4.7	75.8	7.8	**2.75**	**4.80**
5	27	95.4	4.6	75.4	8.4	**2.66**	**5.12**
6	32	96.5	3.4	77.4	5.6	**1.81**	**2.88**
7	37	94.3	5.8	76.6	6.7	**3.37**	**2.81**
8	40	96.0	4.0	75.5	8.2	**2.25**	**4.20**
9	49	94.4	5.7	70.8	15.4	**3.61**	**6.97**
sections with the available $l_z = 400$ m							
1	0	99.1	–	80.9	–	–	–
2	7	96.5	2.7	78.7	2.8	1.24	**1.67**
3	12	96.5	2.7	77.4	4.5	1.45	**2.64**
4	14	98.2	0.9	79.9	1.3	0.48	0.83
5	16	95.2	4.1	78.8	2.7	**1.85**	1.60
6	18	97.5	1.6	76.5	5.8	0.88	**3.72**
7	25	95.8	3.4	76.2	6.2	**1.80**	**3.34**
8	29	94.5	4.9	76.5	5.8	**2.54**	**3.10**
9	37	89.7	10.5	74.5	8.6	**5.38**	**5.28**
10	41	89.7	10.5	73.2	10.5	**4.86**	**5.60**
11	44	88.2	12.4	73.2	10.5	**5.59**	**6.09**
12	51	90.3	9.7	68.2	18.6	**4.95**	**8.19**
13	52	90.9	9.0	74.0	9.3	**4.64**	**4.40**
sections with the available $l_z = 200$ m							
1	0	98.4	–	79.8	–	–	–
2	3	96.5	2.0	78.6	1.5	1.22	0.86
3	5	96.6	1.9	78.6	1.5	1.11	0.90
4	9	95.6	2.9	78.7	1.4	**1.65**	0.80
5	20	94.7	3.9	75.9	5.1	**2.28**	**2.71**
6	21	94.9	3.7	76.8	3.9	**2.29**	**1.92**
7	30	92.8	6.0	76.8	3.9	**3.06**	**2.06**
8	32	93.0	5.8	74.9	6.5	**3.51**	**3.31**
9	33	90.6	8.6	72.0	10.8	**4.94**	**5.61**
10	33	88.4	11.3	71.4	11.8	**6.02**	**6.08**
11	35	92.6	6.3	71.3	11.9	**3.38**	**4.95**
12	37	87.8	12.1	70.8	12.7	**6.43**	**6.47**
13	47	85.2	15.5	71.4	11.8	**7.72**	**5.98**

* Boldfaced in the endmost columns are instances which confirm the hypothesis H_1.

section under investigation, and based on the statistical analysis of the field data collected at nearly a hundred sites (research sections), a set of nine mathematical models of speed distribution parameters upon the rut depth has been described.

Economic effectiveness of roadworks carried out on the sections with various rut depths has been tested based on the test results by test statistics, i.e. the significance test for the two means and the *Kolmogorov-Smirnov* goodness-of-fit λ–test. For the rut depth greater than $k = 20$ mm, test results by the significance test for the two means tested that rutting removal and pavement levelling significantly affect the increase in average speeds of motor vehicles (by 2%–16% for the passenger vehicles and by 5–15% for the goods vehicles respectively). *Kolmogorov-Smirnov* goodness-of-fit λ–test results showed that for the sections having the rut depths greater than 20 mm, the empirical distribution function of speed *before* rutting removal does considerably differ from that *after* rutting removal.

Likelihood of the described math models for estimating the dependence of speed-distribution parameters upon the road operating features has been tested by high values for the coefficients of correlation and determination, and by the Student's and Pearson's test results.

The mentioned relations of distribution parameter between speed and depth of rutting have a wider meaning. They can be used in various countries and they can be adjusted to traffic conditions that are present in those countries, for example: in Russia and some countries of former Soviet Union, which currently use or used complex method of road condition assessment, established values of speed were adjusted at the beginning of 21st century according to proposed in this article models to principles used in old method, which did not include the influence of rutting depth on traffic conditions. New rules of road condition maintenance and their technical assessment are in use in Russia and some countries of former Soviet Union since the year 2002.

Such modification can be used in other countries as well. If the problem lies in assessing influence of rutting depth on speed, then speed assessment or verification should be made on a benchmark section. In case when we need to assess the influence of other road characteristics on velocity, then at first fix the velocity at the benchmark section and apply also other models, which describe influence of other road characteristics on velocity accordingly with formulas set in the method developed by the author.

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