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MODEL OF VEHICLE SPEED DETERMINATION BASED ON CAR BODY STRAIN

Abstract. The article presents the model of the motor car speed determination based on failures of the car body structure. Based on statistical analysis of studied road accidents the model of functional relation, taken from the ruched factographic database, was determined. The model allows for quick determination of speed based on the strain of the car body structure at the moment of a road accident.

Keywords: speed, road accident, car accidents causes, car body.

INTRODUCTION

Browsing through papers regarding problems of road traffic safety and, what is more, the reconstruction of car accidents where passenger cars were involved, advances in car construction and traffic congestion it can be noticed that reconstruction of a real car accident can be quite difficult. It is caused mostly by covering the tracks of the accident or by difficulties revealing them. Such situations indicate that reconstruction of the particular car accident requires extensive analysis which could exclude circumstances that do not fulfill conditions of the coherence of the physical process of events and other circumstances coming out from the file, which led to the collision and condition after the accident. In practice, a very common type of collision is the car impact where the evidence is related only to the position of the vehicle after the accident, approximate determination of the scope and the location of damages, as well as conflicting testimony of persons involved in the accident, especially about the causes of the crash. Evidence of the accident usually does not contain material data connected with the location of the accident and involved cars' tracks just before the collision. According to physical law, obtaining data about the particular location of the vehicles after the accident can be done at any place of the collision but the necessary requirement is to know the suitable parameters of the vehicle track before the accident and the strains regarding those parameters. That is why the analysis of the course of the accident must be conducted for the whole area of a possible place of the

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collision, including the conditions of the accident. A very important issue at a reconstruction of the course of the accident is to use as much information as it is possible after the accident. However, the problem is that the information must be processed onto the parameters which determine behavior of people involved in the accident both at a time preceding the threat of the accident and during the attempt to avoid the accident. Ability to process the information requires the knowledge of laws that combine these values. Basic knowledge of Physics or Mechanics is not enough here. Phenomena of an accident are quite complicated and they do not allow for a simple mathematical description. That is why in most cases relevant information about relations between the extent of effects after the accident and the causes of the accident can be obtained from experiments, laboratory tests or detailed analysis of previous accidents. They allow recording the motion parameters of the people involved in the accident.

The situation described above causes the necessity of solving the following research problems:

- Searching for a better way of using data about the extent and location of car damages that would allow determining the strain dimensions occurred during the collision.
- Verifying the traditional methodology of the road accident course reconstruction and determining the vehicle speed during the impact by means of it.
- Formulating a method of quick estimation of the vehicle speed based on damages of the vehicle during the accident.

That is why the aim of the article is to formulate the model that will allow estimating the vehicle speed on the basis of damages of car body structure at a time of the accident.

STUDY OF LITERATURE

Problem of road traffic safety contains different fields. So far the issue of safety on the roads has not been featured in a special way. However, a very high accident rate and threat to life in road traffic caused that this part of science is still being intensively developed, for example by different conferences and papers about that topic. But debates on most important definitions and measures of the road safety traffic are still open.

Among the works, wider in scope, devoted to the topic of road traffic safety, the paper by Witold Konczykowski „Zagadnienie pracy odkształcenia pojazdu podczas zderzenia" could be worth mentioning. The paper contains the issues of car strain at a time of car impact. The author mostly presents the character and size of car strain after the road accident. A problem of energy-consuming structure of the vehicle has been the topic of theoretical contemplation for a long time. Many physical models enabling the estimation of the amount of energy necessary to obtain given car deformation have been built. However, a ground-breaking development was the introduction of obligatory tests to improve the safety on the roads. The author emphasizes that one of essential car tests was an attempt to strike a rigid barrier. Such a test is usually performed under specific conditions with the registration of motion parameters of the car, from a moment immediately before hitting the obstacle until the time of ending the motion, after bouncing from the obstacle. The results of such tests allow for determination of much data required for reconstruction of the course of car accident, in which car strain appeared. Figure 1 presents the result of factory test collision for one of European cars. There are three lines in it: lines of delays run *b(t)*, lines of changes in traffic speed *v(t)* and lines of displacement (crease) of vehicle's front part *s(t)*.

During such a test, the delays run of car movement is registered immediately. Figutre 2 presents that kind of run.

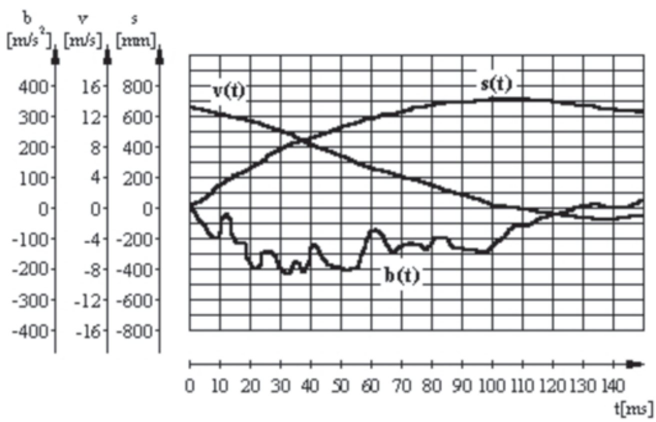

Fig. 1. Result diagram of a factory test collision for one of European cars [7]

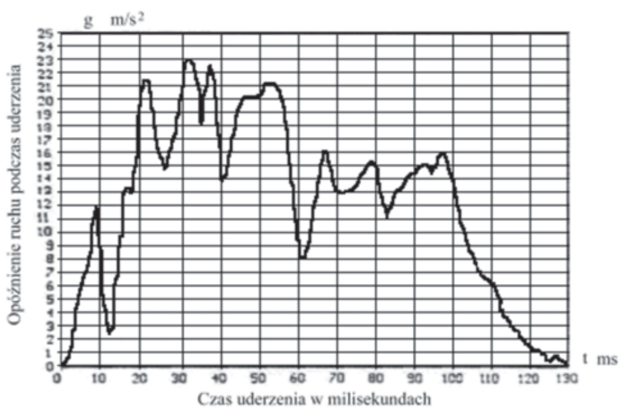

Fig. 2. Example of delays run of car movement [7]

As the delay (retardation) is a derivative of speed in time, the changes of speed at a time of bounce run can be determined by integration of delays run and by separate measure of initial velocity determined in a standard way in conditions of carrying through the test.

An interesting way of determining the bounce speed on the basis of the extent of car damages was presented in a paper ”Determining of bounce speed based on car damages extent”.

The authors emphasize that during the car accidents and collisions evaluations a necessary thing is to determine the speed of the vehicle based on its structure strain. The decrease is a measure of the part of lost kinetic energy of the vehicle that was dissipated during its movement at a time of the car accident. On the basis of the tests of strain it is possible to define the range and the character of the strain and, especially, to determine the main dimensions of the deformed part: depth, width and height. The data allows determining so called Energy Equivalent Speed (EES). Earlier that kind of speed was named Equivalent Barrier Speed or Equivalent Test Speed.

Energy Equivalent Speed is determined by the relationship:

$$\mathrm{EES}_{\text{of the vehicle}} = (2 \cdot \mathrm{E}_{\text{absorbed by a car}}/\mathrm{m})^{0,5} \tag{2.1}$$

where:

$$\mathrm{E}_{\text{absorbed by a car}} = \mathrm{E}_{\text{kinetic before collission}} - \mathrm{E}_{\text{absorbed by obstacle}} - \\ - \mathrm{E}_{\text{transverse displacement}} - \mathrm{E}_{\text{longitudinal displacement}}$$

Results of impact tests helped to work out simplified method of determining amount of work required to obtain the particular car strain and then to determine the speed lost during the impact. Strain work E_0 can be determined by the following relation:

$$E_0 = \frac{b \cdot h \cdot f^2}{2} \cdot k \ \mathrm{J} \tag{2.2}$$

where:

f – is an average depth of strains measured in the direction of force impulse vector,

b –is an average width of strains measured perpendicularly to the direction of force impulse vector,

h –is an average height of deformed part of the vehicle.

In the relation k [N/m·m^2] is a coefficient dependent on strength properties of the car structure. In case when the strength structure of the car was broken, coefficient k equals: $k = (9.0 \div 11.0) \cdot 10^5$ N/m·m^2 and when tin or skin elements were damaged $k = (2.0 \div 4.0) \cdot 10^5$ N/m·m^2.

After suitable transformations the relation for speed v (m/s) lost by the car during the impact can be obtained:

$$v = f \cdot \sqrt{\frac{b \cdot h}{m}} \cdot k \tag{2.3}$$

where *m* means the vehicle weight [6].

Besides, the value of coefficient k depends on the size of a car. That is why the author of the paper included real values of coefficient *k* for nowadays cars also. For small cars $k = (13.5 \div 22.6) \cdot 10^5$ N/m·m^2, for middle-sized cars $k = (9.1 \div 13.5) \cdot 10^5$ N/m·m^2 and for big cars $k = (5.2 \div 7.2) \cdot 10^5$ N/m·m^2.

Derivative of impact tests is a method of determining the impact speed based on the extent of car damages in a distribution raster of work of the car structure strain [8]. They allow estimating the amount of work required to cause the strain of a particular extent. A step ahead at forming such diagrams was a thesis made by Walter Röhrich in 1976 at Berlin University of Technology. A medium class car of weight *m* = 950 kg and standard power transmission system was tested, that is with engine placed in the front part of a car and with rear-wheel drive. For each direction of a bounce the car was divided into segments, taking into account details of strength structure. Particular amount of work required to obtain the strain of the segment was assigned to each segment. Diagram model of distribution of strain work presents figure 3.

Similar results of the research on the car deformation at a bounce in a rigid fixed wall were published by Keneth L. Campbella on III International Conference on Road Safety in Michigan. They were presented in forms of nomograms. They let to determine the speed of the car bounce in a function of deformation size at a time of impact (frontal or oblique) in a rigid fixed obstacle, with a total loss of kinetic energy.

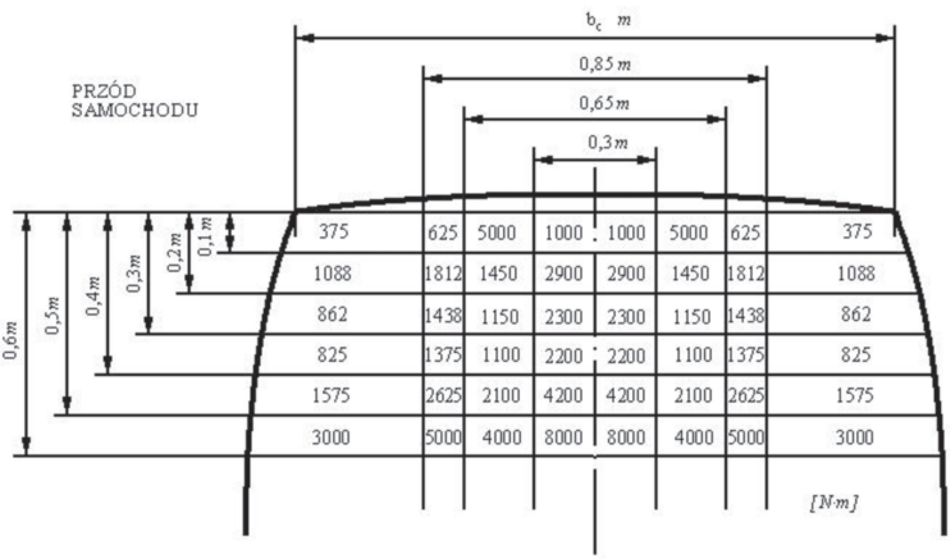

Fig. 3. Results of Walter Röhrich's tests regarding the front part of the car [10]

Those diagrams are related to GMC cars weighing 1100–1500 kg and 1800–2000 kg. Then the approximate speed of the impact can be calculated from the simplified dependences:

- for cars weighing 1100–1500 kg:

$$v = 1.34 + 23.76 \cdot f \ \text{m/s} \tag{2.4}$$

- for cars weighing 1800–2000 kg:

$$v = 3.06 + 15.49 \cdot f \ \text{m/s} \tag{2.5}$$

As it can be seen, the problem of the road safety traffic, and closer, the reconstruction of the car accidents, has not been specially exposed in theses results because the process of recreating the particular car crash was time-consuming and labor-intensive. Very useful could be the possibility of determining the speed of the vehicle just after the accident. That fact persuaded the author to try to determine the relation between the vehicle speed and the strain of the car body structure, as a model that would help to define the speed of the vehicle before the accident in a reliable and fast way.

MOTOR-CAR BODY DEFORMATIONS AT A FRONTAL IMPACT

Each motor car as a material body with particular mechanical and physical properties is subjected to all laws and rules existing in statistics and dynamics of the material body. Its motion lasts because of energy exchange, coming from the chemical process of fuel combustion, for mechanical energy or because of potential energy exchange for kinetic energy or inversely. Those vehicle properties play a really essential role during evaluation of car accidents. One of the most important results of the motor car impact is its strain. It results from the very basic physical law that if the body of the finite inflexibility is influenced by force, that body undergoes a finite strain. So if there is a relation between the force and strain, there is a relation between work used for this strain and force that induces that strain, too. To evaluate that work it is necessary to know both changes of the shape, which means the strain, and strength properties of the vehicle structure. It is also relevant that the work can be done only when equivalent energy is provided from the outside. In case of any impact, at least one of the colliding bodies must have been in motion before the collision. The impact causes a change of the motion so the speed change of that body occurs, which at the assumption of the constant body mass turns to the kinetic energy change. So in a general way, during the impact the strain work is the result of kinetic energy loss. Carnot Law describes that process in a more precise way: during an impact a reduction of energy corresponding to kinetic energy for “lost speed” is visible. So if the range of car strain is given, “lost energy” can be determined.

In motor cars three sections can be distinguished: the engine compartment, personal (passenger) compartment and the trunk compartment. In most cases, the engine compartment (engine section) is in the front part of the vehicle and the trunk compartment (trunk section) in its rear part. Description of damaged car elements that are the result of strain at a frontal impact, side impact and oblique impact concerns cars with engine compartment in the front and the trunk compartment it the rear part of the car.

The article shows the most general types of impacts: frontal impacts. Taking into consideration types of damage, car body structure strain was grouped in a following way:

Table 1. Size of car body structure strain versus type of damage

Size of car body structure strain	Type of damage
<10.00%	Front bumper, front reflectors (left and right), turn signals (left and right), front side of the engine part.
<20.00%	Front bumper, front reflectors (left and right), turn signals (left and right), front side of the engine part, engine compartment cover, front fenders (left and right), front suspension and the wheels, engine part damaged in 80%.
<30.00%	Front bumper, front reflectors (left and right), turn signals (left and right), front side of the engine part, engine compartment cover, front fenders (left and right), front suspension and the wheels, engine part damaged totally, windscreen, front pillars.
<40.00%	Front bumper, front reflectors (left and right), turn signals (left and right), front side of the engine part, engine compartment cover, front fenders (left and right), front suspension and the wheels, engine part damaged totally, windscreen, front pillars, driver's and passenger's front doors, dashboard and the steering column, car roof, partly damaged front driver's and passenger's car seats.
<50.00%	Front bumper, front reflectors (left and right), turn signals (left and right), front side of the engine part, engine compartment cover, front fenders (left and right), front suspension and the wheels, engine part damaged totally, windscreen, front pillars, driver's and passenger's front door, dashboard and the steering column, car roof, totally damaged front driver's and passenger's car seats, latch pillar, damages reach the passenger compartment.

RESEARCH SCOPE

The following assumptions were taken into consideration in the research:

- the database involved car accidents in Szczecin area, the north-west of Poland, and its region (up to 10 km),
- only road accidents caused by motor cars with weight up to 3.5 tons were taken into consideration during data gathering,
- road accidents with frontal impacts were considered,
- vehicles taking part in road accidents were classified according to commercial sections. Particular sections were named by the following alphabet letters: A, B, C, D and E. The main criterion of such a vehicle arrangement is the total length of

Table 2. Number of cars taking part in car accidents depending on the car length

Car class	Frontal impacts
A	52
B	59
C	47
D	15
E	8

the vehicle which is the variable connected with the car body. Motor cars in forms of one-box body, two-box body and three-box body belong to those sections. Apart from those sections there are also F, G, H, I and L sections with luxury, general-purpose, sport, off-road and multifunctional cars. In this study only the first five vehicle groups were considered because of very large number of vehicles belonging to all those sections.

- next, the cars were grouped according to the size of a failure of the car body structure. The vehicles were divided into groups of proportional strain of 0% to 50% every 5 percentage points and for each road accident vehicle speed at a moment of the car accident was determined.
- for each accident vehicle speed at a moment of car accident was determined. That was a basis to conduct the dependence diagram of vehicle speed on the size of strain of its car body structure. It was done with statistic methods by linear regression. Linear and exponential functions were matched.

In total, 181 vehicles were used to carry out the frontal impacts tests.

RESULTS AND ANALYSIS OF THE TESTS

On the basis of database concerning the vehicle speed at a moment of impact and the size of car body strain, regression equation of this dependence was built. In the study two forms of regression were used:

1. linear regression $Y = a \cdot x + b$ (5.1)
2. exponential regression $Y = \exp(a \cdot x + b)$ (5.2)

where:
Y – vehicle speed in m/s,
x – size of car body strain in %.

The parameter a in a linear regression shows how much the vehicle speed changes in m/s at a change of strain by 1 percentage point. The parameter a in an exponential regression describes the percentage change of vehicle speed at a change of strain by 1 percentage point. The function was assessed in Statistica version 5.5. For each commercial section of car classes A, B, C, D and E both forms of regression were used [5].

Tables 3 and 4 present the results of calculations at a frontal impact for A class vehicles.

Table 3. Regression results for model $y = a \cdot x + b$

	R = 0.97874195; R^2 = 0.95793581; Correct. R^2 = 0.95709452; p<0.0000					
N = 52	BETA	Statistical error BETA	B	Statistical error B	t(50)	p level
b	–	–	2.628747	0.392252	6.70168	0.000000
a	0.988677	0.021222	0.579409	0.012437	33.74403	0.000000

In table 3, column B two coefficients can be visible: absolute term $b = 2.63$ and gradient $a = 0.579$. Directivity factor allows to determine the relative influence of independent variable on dependent variable. The value of gradient a shows that the increase of strain of car body structure by 1 percentage point causes the increase of vehicle speed by (0.58±0.01) m/s. So the form of the assessed regression equation is:

$$Y = 0{,}579 \cdot x + 2{,}629 \tag{5.3}$$

Correlation coefficient square $R^2 = 0.957$ is high which means that regression line matches the experimental data well. The speed values are determined by that function in 95.7%.

A very important value is the value of statistics t which for coefficient a $t(50)=33.7$ passes the critical value $t_{0,05/50} = 2.009$ for 50% latitude and at the level of significance of a = 0.05. Thus the hypothesis about the irrelevance of a gradient must be rejected and this way the hypothesis about the irrelevance of dependence between speed and car body strain must be rejected too. The proof for that is also the value p=0.0000 that is less than the assumed value level of significance a = 0.05. The value of statistics t for absolute term equals $t = 6.70$ and passes the critical value. That means the absolute term is significantly different from zero.

Obtained linear dependence describes the relationship between the vehicle speed and strain of its car body structure adequately.

The second type of dependence in a form of linear regression (exponential function) was also tested:

In table 4 absolute term $b = 2.63$ and gradient $a = 0.579$ can be seen. And the following dependence was obtained:

$$\ln y = 0{,}0346 \cdot x + 1{,}882 \tag{5.4}$$

Table 4. Regression results for model $y = \exp(a \cdot x + b)$

	R = 0.98867661; R^2 = 0.97748144; Correct. R^2 = 0.97703107; p < 0.0000					
N = 52	BETA	Statistical error BETA	B	Statistical error B	t(50)	p level
b	–	–	1.882148	0.032338	58.20229	0.000000
a	0.978742	0.029005	0.034599	0.001025	46.58745	0.000000

In both cases *p* levels are much less than the accepted level of significance a = 0.05. That proves the relevance of directivity coefficient *a* and that absolute term is significantly different from zero. Correlation coefficient square $R^2 = 0.977$ is high, that means the regression and the experimental data were matched properly. Gradient $a = 0.0346$ indicates that the increase of strain of car body structure by 1 percentage point causes speed increase by (3.46 ± 0.10)%. For example, at 10% strain of car body structure, increase of strain by 1 percentage point (that is from 10% to 11%) causes the speed increase by 3.46% average. Comparison of correlation coefficients square R^2 in two models of function: linear and exponential, shows that the exponential function has a higher coefficient value R^2 ($R^2 = 0.977$) than the linear function ($R^2 = 0.957$). That means the exponential function matches the data in a better way. Similar analysis was conducted for remaining classes of cars: B, C, D and E. It was seen that in the other cases exponential function is better to describe the dependence of the vehicle speed on strain of car body structure at a frontal impact.

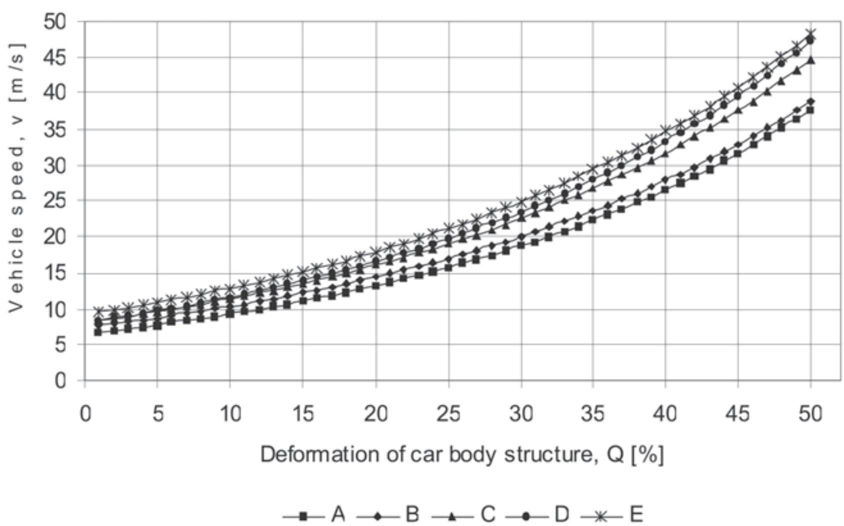

Fig. 4. Theoretical models of dependence of vehicle speed on strain at a frontal impact for A, B, C, D and E classes of vehicles

On the basis of the total theoretical characteristics of dependence of speed on car body structure strain (fig. 4) it was shown that the arrangement of theoretical models depends on a vehicle class.

The undermost exponential function is the theoretical model obtained for vehicles of A class. The noticeable fact is that the locations of models for A and B classes are almost on the same level. Similar dependence can be seen for D and E classes. C class is centered. It is visible on the graph that for particular size of percentage strain the different vehicle speed occurs at a moment of a road accident, depending on its length. For the same vehicle speed at a time of the accident, the lower class of the vehicle the bigger strain size. Gradients *a* of theoretical exponential functions for each vehicle class have the same value. 50% strain of car body structure for a frontal impact is found from 37.79 m/s for the A class vehicles. For the E class vehicles such 50% strain appears only at the speed of 48.23 m/s. For the other classes those speeds are respectively: B – 38.82; C – 44.61; D – 47.32.

CONCLUSIONS AND DISCUSSION

Based on performed analysis of literature regarding the topic of the road accident and the results of the study and the analysis of the measures results additional conclusions can be drawn:

- to describe dependence of the speed vehicle on the strain of the car body structure at a time of the road accident the models of regression can be used.
- that dependency can be described by the linear and exponential functions. Comparison of those two models presents that the exponential function matches the regression line to the study results in a better way. It is indicated by the correlation coefficient obtained during the statistical analysis.
- the location of the models, describing the dependency of the speed vehicle on its car body structure for the particular type of impact, is depended on the class of the vehicle. For the particular percentage strain of the car body structure, the higher class of the vehicle (longer vehicle), the higher speeds at the impact.
- 50% strain of the car body structure, regardless the type of impact, is found at the speed of approximately 30 m/s. Frontal impacts give 50% strain at higher speeds – over 35 m/s.
- it would be beneficial to create a system database containing the basic information for further model cross-check.

Studies conducted so far have shown that the formulated method can be efficient to evaluate the speed of the vehicle at a moment of collision with other vehicle or a static obstacle. Those studies are continued because, like every statistical research based method, it is more reliable the more observations can be described. Confirmation of the universal truth that the basic cause of road accidents is speeding, inadequate to prevailing road conditions, was obtained here.

LITERATURE CITED

1. Buzeman D.: Car-to-car and single car crash compatibility: Individual effects of mass, structure, stiffness and geometry. Thesis for the degree of licentiate in engineering. Chalmers University of Technology 1997.
2. Burckhardt M.: Zur Analyse und Synthese von Reaktionszeiten. Der Verkehrsunfall, 7–8, 1980.
3. Burg H.: Rekonstruktionsunterlagen aus einer Auswertung realer Unfall zwischen Zweirad und Vierradfahrzeugen.Der Verkehrsunfall, 9, 1979.
4. Burhardt E.: Aspekte zur Verkehrssicherheit auf Ausserortsstrassen. Asperg 1988.
5. Chmielewski K., Berczyński S.: Statystyka matematyczna – ćwiczenia laboratoryjne z wykorzystaniem pakietu STATISTICA PL. Wydawnictwo Uczelniane Politechniki Szczecińskiej, Szczecin 2002.
6. DiuperoT., Górny A., Wolski E.: Ustalenie prędkości zderzenia w oparciu o zakres uszkodzeń samochodu. Rzeczoznawca samochodowy, 8, 2000.
7. Kończykowski W.: Zagadnienie pracy odkształcenia pojazdu podczas zderzenia. Rzeczoznawca samochodowy, 1, 1997.
8. Kończykowski W.: Odtwarzanie i analiza przebiegu wypadku drogowego. Info – Ekspert, Warszawa 1993.
9. Mrozik M.: Oszacowanie prędkości jazdy samochodu osobowego na podstawie analizy wypadków drogowych. Praca doktorska niepublikowana. Politechnika Szczecińska. Szczecin 2006.
10. Praca zbiorowa pod redakcją Wiercińskiego J.: Wypadki drogowe – elementy analizy technicznej. WKiŁ, Warszawa 1895.
11. Siłka W.: Energochłonność ruchu samochodu. WNT, Warszawa 1997.
12. Wicher J.: Bezpieczeństwo samochodów i ruchu drogowego. WKiŁ, Warszawa 2002.
13. Zieliński A.: Konstrukcja nadwozi samochodów osobowych i pochodnych. WKiŁ, Warszawa 2003.

MODEL OKREŚLANIA PRĘDKOŚCI POJAZDU NA PODSTAWIE ODKSZTAŁCEŃ NADWOZIA

Streszczenie

W artykule przedstawiono sposób określania prędkości pojazdu na podstawie odkształceń jego struktury nadwozia. Na podstawie analizy statystycznej zaistniałych wypadków drogowych określono zależności funkcjonalne w postaci modelu wynikające z zebranego materiału faktograficznego. Zastosowanie modelu pozwala na szybkie określenie prędkości pojazdu osobowego na podstawie odkształceń struktury nadwozia pojazdu w chwili zaistnienia wypadku drogowego.

Słowa kluczowe: prędkość, wypadek drogowy, przyczyny wypadków drogowych, nadwozie pojazdu.