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Tyre-Road friction Coefficient: Estimation Adaptive System

This paper offers an upgraded method for estimating the magnitude of friction between tyres of a motor vehicle and a road surface while investigating road accidents. The above-mentioned method is based on the resultant data of tyre-and-road interworking field tests in case of emergency braking. Such estimation of the magnitude of friction is to be carried out with a focus on the factors affecting the friction processes in the tyre-and-road contact. The most important factors, which are included in the synthesized adaptive system used for friction coefficient estimation, have been defined based on the theoretical analysis of the data of deceleration and braking length of motor vehicles. The study of the existing expert methods used for estimating the level of tyre-and-road engagement and the effect of such level on the motional parameters of a motor vehicle has demonstrated the need for upgrading of the existing approaches. Unlike the existing practices, the friction coefficient estimation adaptive system offered by the authors hereof is a self-trainable system. Such system reduces any simulation uncertainty and the probability of occurrence of Type 1 and Type 2 errors. Such result is achieved owing to the fact that the system takes into account the upgraded design of the present-day brake systems and tyres, as well as the speed of motor vehicles and load of their wheels; the system is also efficient because it makes use of the up-to-date mathematical methods which are able to process raw (initial) data under conditions of stochastic and fuzzy uncertainty. The approach offered hereby has demonstrated its efficiency for motor vehicles belonging to categories M1 and N1 and has proven its potential applicability for other categories of motor vehicles.

Keywords: friction coefficient, tyre, road surface, deceleration process, estimation adaptive system, road accident investigation.

Introduction

Braking of motor vehicles (MVs), where the efficiency of braking depends on the tyre-to-surface frictional capacity, is the basic technique to prevent road accidents [1, 2]. The parameter used to assess the efficiency of tyre-and-road engagement is the value of the static friction coefficient (friction coefficient φ), while, when the wheels are being locked, such parameter is the value of the coefficient of sliding friction (frictional drag coefficient) which is usually lower than the friction coefficient. The non-dimensional value φ for ordinary tyres varies within the range of (0; 1] [3]. The near-zero values φ indicate a smooth slippery surface in the tyre-and-road contact, which is characterized by low values of frictional forces (longitudinal, latitudinal and sidewise friction). The higher the value φ, the higher frictional forces which are to be overpowered or transferred.

The tyre grip on the road is a result of complex processes running within the tyre-and-road contact area. It depends on a number of factors (Fig. 1), of which the most significant are the type and condition of the road surface; the tyre's design and condition, as well as the operating conditions [4, 5].

The resultant force applied by the tyre to the road is a vectorial sum of the latitudinal and longitudinal forces (Fig. 2). It increases in line with the increasing frictional capacity within the tyre-and-road contact area or in line with the increasing load on the wheel [3, 4].

The value of the coefficient of adhesion (the tyre-road friction coefficient) in the course of analyzing the road accident (RA) can be determined in one of the three ways [1, 2, 6]:

– basing on the data provided by the motor vehicle's steering, safety and comfort electronic systems;
– by the way of test and trial;
– using the experimentally determined reference data.

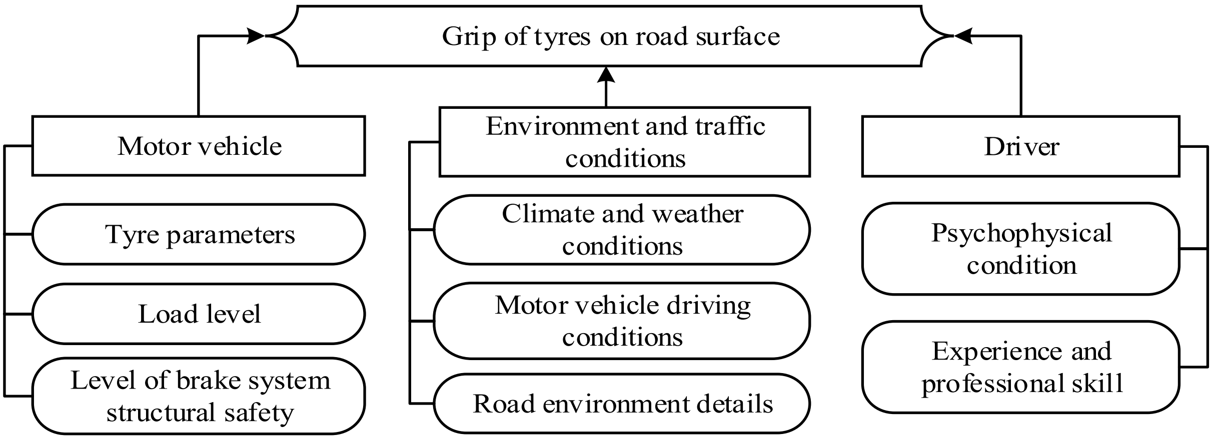

Figure 1. The factors affecting the potential tyre-to-surface grip capacity

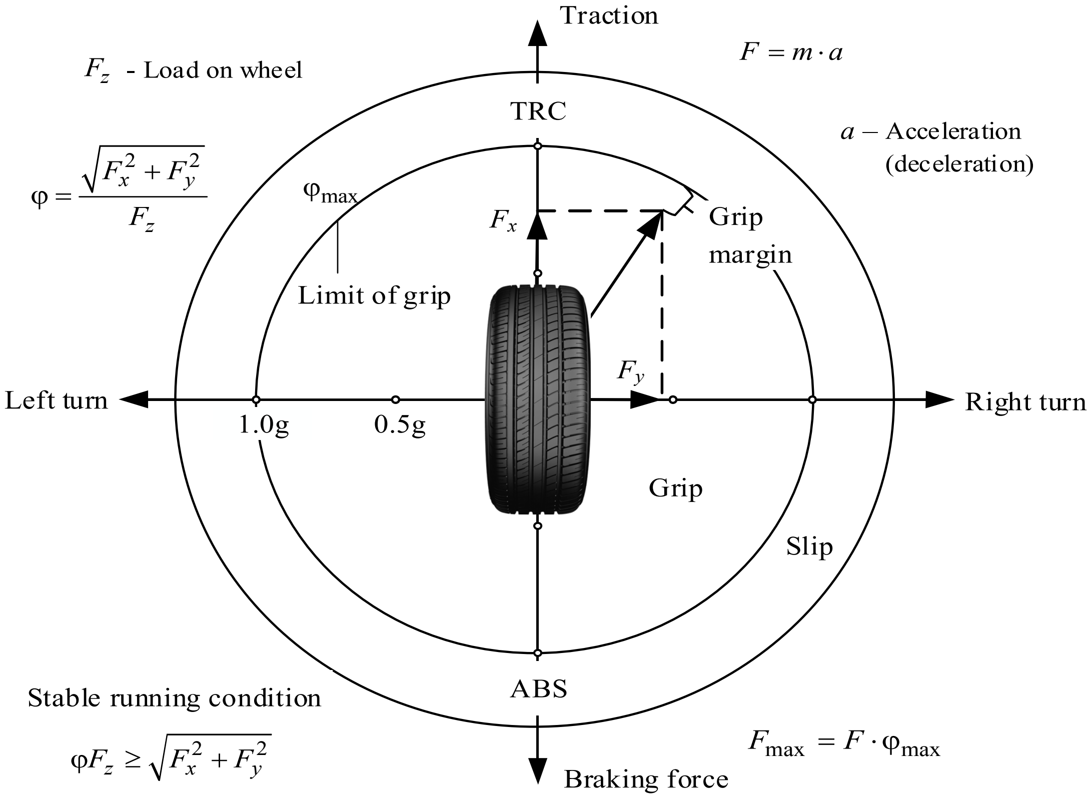

Figure 2. Forces applied on within tyre in Kamm Circle

The first method is rather new. Its wide application is, however, restricted because determining the traffic parameters on the basis of the data provided by the on-board electronic data recorders (EDR) is only possible where such systems are installed on board. The percentage of such motor vehicles in the global fleet of motor vehicles is rather low, yet tending to grow each year [7, 8].

The Best Practice Manual for Road Accident Reconstruction issued by the European Network of Forensic Science Institutes [2] recommends, while assessing the tyre-and-road engagement, to perform an investigative experiment under the on-scene or similar roads conditions. In doing so, experts experimentally determine the coefficient of adhesion (the tyre-road friction coefficient) or the braking length, or, else, the rate of deceleration, for such parameters identify the friction processes occurring in the tyre-and-road contact. However, application of such method is not always possible for a number of external reasons [1].

In case when such experiment cannot be conducted, the values of the coefficient of adhesion, the rate of deceleration or the braking length can be determined with the use of using the experimentally determined reference data [2] or assumed as standard values, as defined by the Traffic Rules and/or a regulatory document such as Council Directive 71/320/EEC. The braking efficiency parameters can also be determined by way of calculations using the formulas widely applicable in the expert practices [1, 9] and found out on the basis of the driver-vehicle-road-environment (DVRE) mathematical models.

In using the DVRE systemic mathematical models, the level of uncertainty of the rated parameters depends on the accuracy of the input parameters and on the assumed structure of the model which is just an approximation to the reality. While using the data provided by the EDRs, an uncertainty of the rated parameters can result from errors in the motor vehicle’s running measurements and from an inaccurate result of the recorded data processing. The accuracy of experimental methods depends both on the test procedure, on the test equipment and on the quality of the measured data processing [10, 11].

This study is intended to upgrade the existing approaches to estimating the coefficient of adhesion and the braking efficiency parameters in the course of a road accident investigation while performing a technical examination of a motor vehicle under the conditions of stochastic and fuzzy uncertainty.

Identification Methods and Structure of Adhesion Coefficient Estimation System

The adaptive system for estimating the coefficient of adhesion has been developed on the basis of the method for identification of nonlinear objects by fuzzy knowledge bases [**Ошибка! Источник ссылки не найден.**] in Anfis Neuro-Fuzzy Inference System [13] included in the Fuzzy Logic Toolbox for Matlab computing environment [14]. The system was built up in a two-phase process, where the first phase focuses on the structural identification and the second one on the parametric identification.

During the structural identification phase, the structure of dependence of the tyre-road friction coefficient (coefficient of adhesion) on the impact factors (Fig. 3) was built on the basis of the if-then rule. The parametric identification was performed via selecting such parameters in the knowledge base which would have provided the maximum approximation between the simulation results and the experimental data.

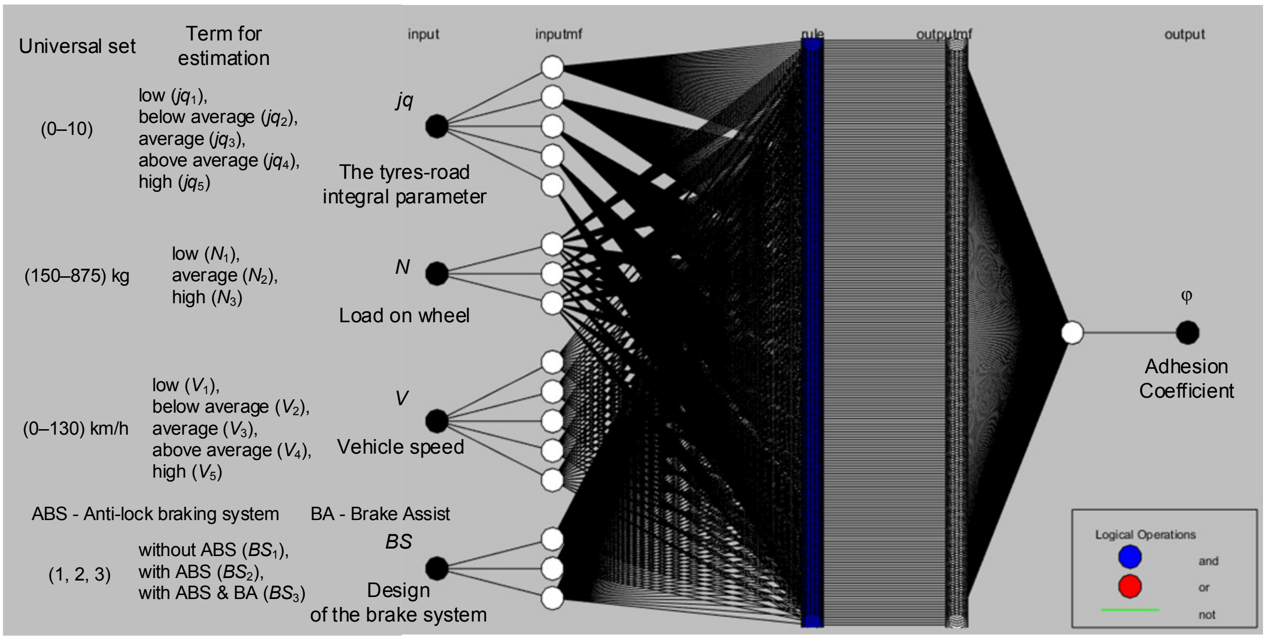

Figure 3. Structure of Tyre-Road Friction Coefficient Estimation System

As shown by Fig. 3, the neuro-fuzzy network of the system consists of five layers. Each node of the first layer is a term incorporating the Gaussian membership function [14]

$$\mu_j(x_i) = e^{-\frac{1}{2}\left(\frac{x_i - c_{ij}}{\sigma_{ij}}\right)^2}, \tag{1}$$

where $\mu_j(x_i)$ is a fuzzy set membership function a_{ij}; c_{ij} and σ_{ij} are a maximum coordinate and a concentration factor – the membership function parameters.

The quantity of the second-layer nodes is equal to the quantity of rules in Sugeno fuzzy knowledge base [13] (as is clear from Fig.3, for this case the number of the rules amounts to m = 5*3*5*3 = 225). Each second-layer node is associated with those first-layer nodes which make up antecedents of the respective rule. The node output is a degree of fulfillment of the rule τ_r, incorporated by the node which is equal to the product of the input signals.

All two hundred and twenty five nodes of the third layer determine the relative degree of fulfillment of the relevant fuzzy rule τ_r*

$$\tau_r{}^* = \tau_r \,/\, \sum_{j=\overline{1,m}} \tau_j. \tag{2}$$

The fourth-layer nodes specify the contribution of the fuzzy rules to the network output φ.

$$\varphi_r = \tau_r{}^* \cdot \left(b_{0,r} + b_{1,r} \cdot jq + b_{2,r} \cdot N + b_{3,r} \cdot V + b_{4,r} \cdot BS\right), \tag{3}$$

where $b_{q,r}$ – are the coefficients of the r-rule consequent function (r = 1, 2, …, 225; q = 0, 1, 2, 3, 4).

The single node of the fifth layer aggregates the contributions of all rules

$$\varphi = \varphi_1 + \ldots + \varphi_j + \ldots + \varphi_m. \tag{4}$$

All factors which affect the tyre-road friction coefficient (the coefficient of adhesion) (Fig. 3) are considered as linguistic variables which are assigned to the respective universal sets and are estimated via the fuzzy terms. The list of the most significant factors has been established by reviewing the data furnished by the Bosch experts [3, 15] and based on our own theoretical findings [10, 16, 17].

The recommendations for estimating the tyres-road integral parameter jq are given in Table 1 below.

The rules for the if-then logical statement have been automatically formulated in Anfis neuro-fuzzy editor in the Matlab computing environment.

Experimental Research into Tyre-Road Engagement in Case of Emergency Braking and System Parametric Identification

The potential engagement between the automobile's wheels and the road surface can be estimated based on the results of the experimental assessment of the rate of steady deceleration j in case of emergency braking. Basing on the given values j, a motor expert is able to estimate objectively the braking length of the motor vehicle and its speed at the start of braking. The acquired experimental data relating to the braking dynamics of Category M1 and N1 motor vehicles, which were published by the authors hereof in their paper [17], were used to ensure the process of parametric identification of the neuro-fuzzy system (Fig. 4).

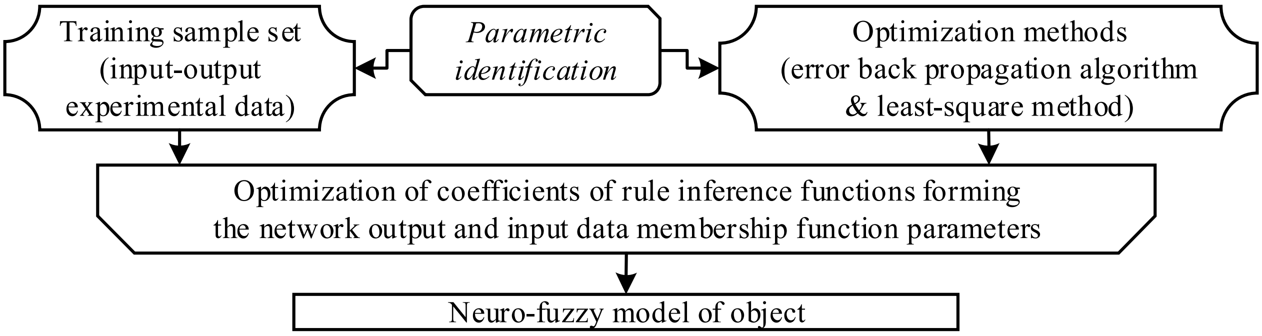

Figure 4. Schematic diagram of neuro-fuzzy system parametric identification

In order to create a training sample set and a test sample set for neuro-fuzzy system parametric identification, the authors hereof kept writing down the values of the factors influencing the tyre-road friction coefficient (the coefficient of adhesion) (see Fig. 3) and the tyre-road friction coefficient per se. As a result, the authors have acquired an experimental database (5670 input-output data pairs), a fragment of which is shown in Table 2, below. The said database was then used to create a training sample set (3400 input-output data pairs) and a test sample set (2270 input-output data pairs).

Table 1

Recommended Values for Tyre-Road Integral Parameter *jq*

Type of Road Surface	Tyre Condition	Road Surface Condition		
		Dry	Wet & Clean	Wet & Dirty
Cement-concrete pavement	New*	7,85-8,34	6,38-6,87	3,92-4,41
	Worn-out**	8,83-10,0	4,91-5,40	1,96-2,45
Asphalt-concrete pavement with roughening treatment	New	7,85-8,34	5,89-6,38	4,41-5,40
	Worn-out	8,83-10,0	4,41-4,91	2,45-3,43
Hot asphalt-concrete pavement w/o roughening treatment	New	7,85-8,34	4,91-5,89	3,43-3,92
	Worn-out	8,83-10,0	3,92-4,41	2,43-2,94
Cold asphalt-concrete pavement	New	5,89-6,87	3,92-4,91	2,94-3,43
	Worn-out	7,36-8,34	2,45-3,43	1,96-2,94
Bitumen-coated crushed-stone and gravel pavement with roughening treatment	New	5,89-6,87	4,91-5,89	2,94-3,43
	Worn-out	7,36-8,34	3,43-4,41	1,96-2,94
Bitumen-coated crushed-stone and gravel pavement w/o roughening treatment	New	5,4-5,89	4,41-4,91	2,43-2,94
	Worn-out	6,38-7,36	2,45-3,43	1,96-2,45
Crushed-stone and gravel surface	New	5,89-6,87	5,40-5,89	2,43-2,94
	Worn-out	7,36-8,34	3,92-4,41	1,96-2,45
Surfaced earth road	New	4,41-4,91	2,45-3,92	1,96
	Worn-out	5,4-5,89	1,96-2,94	1,96
Loose snow	New	1,47-3,43		
	Worn-out	1,18-2,45		
Grader-rolled snow	New	2,35-2,75		
	Worn-out	1,67-2,06		
Rolled smooth snow w/o ice crust	New	2,16-2,45		
	Worn-out	1,47-1,77		
Rolled smooth snow with ice crust	New	1,18-1,47		
	Worn-out	1,18-1,47		
Rolled smooth snow with ice crust after sanding at the rate of 0.1 m^3 per 1000 m^2 of road	New	1,67-1,86		
	Worn-out	1,47-1,67		
Rolled smooth snow with ice crust after sanding at the rate of 0.4 m^3 per 1000 m^2 of road	New	2,45-3,73		
	Worn-out	1,96-2,94		
Icy road	New	0,88-1,47	0-0,78	
	Worn-out			

*New – up to 50% tyre tread wear,

**Worn-out – 50 to 100% tyre tread wear, yet not less than 1.6-mm tyre tread height

Table 2

Experimental Database (fragment)

jq	9,7	0,78	3,92	6,87	5,89	5,4	8,34	7,85	4,91	9	2,45	1,96
N	150	250	325	325	725	200	650	275	475	375	300	500
V	20	60	80	80	80	20	100	40	80	130	60	100
BS	1	3	2	2	1	1	3	1	3	3	3	2
φ	0,825	0,075	0,333	0,584	0,384	0,453	0,665	0,627	0,427	0,754	0,232	0,157

Fig. 5, below, demonstrates the training process of the adaptive neuro-fuzzy system used to identify the tyre-road friction coefficient (the coefficient of adhesion) on the basis of the input-output data in Matlab Anfis Editor with the use of the error back propagation algorithm combined with the least-square method.

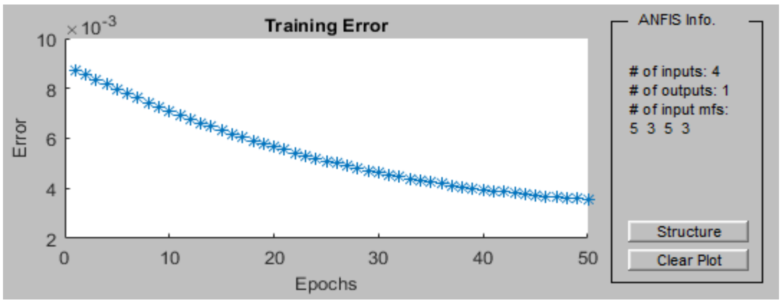

Figure 5. Adaptive neuro-fuzzy system training process

As is clear from Fig. 5, the training process was completed at Epoch 46, and since then the prediction error did not virtually change. The parameters of the membership functions for the input variables, upon completion of the training process, are given in Table 3, below.

Table 3

Parameters of Membership Functions for Factors Affecting the Coefficient of Adhesion

Factor	Universal set	Estimating terms	Post-training membership function parameters	
			Maximum coordinate c_{ij}	Concentration factor σ_{ij}
jq	(0–10)	*jq*1, *jq*2, *jq*3, *jq*4, *jq*5	0.0590850487694922 2.50888607968828 4.9965620984888 7.49073784735645 9.90873828689305	1.21303528289064 1.29362727632086 1.32563448443905 1.29871407906703 1.21900000000000
N	(150–875) kg	*N*1, *N*2, *N*3	150.000359668698 512.500041047082 874.999647086585	153.94025595164 153.940298272589 153.940274751047
V	(0–130) km/h	*V*1, *V*2, *V*3, *V*4, *V*5	0.0000334931228812 32.5000120855364 64.999862248206 97.4998567966736 130.000045723149	13.8014376704274 13.8015719754217 13.8014329230444 13.8016196963052 13.8013863343706
BS	(1,2,3)	*BS*1, *BS*2, *BS*3	0.999998025382338 1.99999606577894 2.99999810282448	0.424656245081971 0.424659477853096 0.424665371752738

The parameters of the membership functions (MF) for the output variable are given in Table 4, below.

Table 4

Specifications of Membership Functions for Coefficient of Adhesion (fragment)

MF Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
MF Parameter	-0.0255	-0.0218	-0.0496	-0.0092	-0.0276	0.0014	-0.0102	-0.0087	-0.0145	-0.0094	-0.0114	-0.0113	-0.0091	-0.0108
MF Number	15	16	17	18	19	20	21	22	23	24	25	26	27	28
MF Parameter	-0.0115	-0.0068	-0.0154	-0.0062	-0.0094	-0.0068	-0.0139	-0.0087	-0.0103	-0.0102	-0.0081	-0.0098	-0.0107	-0.0077
MF Number	29	30	31	32	33	34	35	36	37	38	39	40	41	…
MF Parameter	-0.0101	-0.0100	-0.0113	-0.0063	-0.0123	-0.0073	-0.0093	-0.0095	-0.0078	-0.0084	-0.0102	-0.0074	-0.0087	…
MF Number	46	47	48	49	50	51	52	53	54	55	56	57	58	59
MF Parameter	0.2205	0.2031	0.2812	0.2022	0.2251	0.2453	0.1950	0.2182	0.2424	0.1855	0.2194	0.2299	0.1755	0.2179
MF Number	60	61	62	63	64	65	66	67	68	69	70	71	72	…
MF Parameter	0.2183	0.1879	0.1931	0.2320	0.1808	0.1936	0.2253	0.1732	0.1953	0.2149	0.1643	0.1951	0.2043	…

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
MF Number	101	102	103	104	105	106	107	108	109	110	111	112	113	114
MF Parameter	0.4498	0.4709	0.3596	0.4469	0.4470	0.3880	0.3889	0.4816	0.3708	0.4004	0.4592	0.3551	0.3999	0.4406
MF Number	115	116	117	118	119	120	121	122	123	124	125	126	127	…
MF Parameter	0.3371	0.3997	0.4184	0.3220	0.3994	0.4000	0.3507	0.3535	0.4342	0.3247	0.3500	0.4026	0.3138	…
MF Number	217	218	219	220	221	222	223	224	225	Universal set (0 1]				
MF Parameter	0.6367	0.7167	0.7898	0.6047	0.7173	0.7512	0.5728	0.7114	0.7115	Type: constant				

A comparison of the prediction error in estimating the value of the tyre-road friction coefficient (the coefficient of adhesion) using various methods is given in Table 5, below.

Table 5

Prediction Error in Estimating the Value of Tyre-Road Friction Coefficient Using Various Methods

Parameter	Hybrid neuro-fuzzy model	Existing fuzzy model [16]	Linear model	Nonlinear model
RMSE	0.0035	0.0089	0.0291	0.0101
Mean relative error	1.79%	3.97%	15.35%	14.76%
Maximum relative error	3.09%	8.12%	62.03%	40.22%
Number of data pairs in training sample and test sample sets	5670	64	5670	5670

The nonlinear model for predicting the value of the tyre-road friction coefficient (see Table 5 above) reads as

$$\begin{aligned}\varphi = -0.0316 + 0.0823\cdot jq + 0.00001\cdot N + 0.0001\cdot V + 0.0272\cdot BS + 0.00001\cdot jq^2 + \\ + 0.00001\cdot N^2 - 0.00001\cdot V^2 - 0.0041\cdot BS^2 - 0.00001\cdot jq\cdot N - 0.0001\cdot jq\cdot V + \\ + 0.008\cdot jq\cdot BS + 0.00001\cdot N\cdot V - -0.00001\cdot N\cdot BS - 0.0001\cdot V\cdot BS.\end{aligned} \tag{5}$$

The linear model for predicting the value of the tyre-road friction coefficient (see Table 5 above) reads as

$$\varphi = 0.0164 + 0.0789\cdot jq - 0.0001\cdot N - 0.0004\cdot V + 0.0392\cdot BS. \tag{6}$$

As is clear from Table 5, the offered adaptive neuro-fuzzy system for identification of the value of the tyre-road friction coefficient is the most accurate one (the mean prediction error being 1.79%, and the maximum error 3.09%), so it can be recommended for application in performing technical examination of amotor vehicle in the course of a road accident investigation.

The adaptive neuro-fuzzy system for identification of the value of the tyre-road friction coefficient, developed by the authors hereof, is a self-trainable system, provided the experimental database (see table 2 above) is being updated and replenished; it can demonstrate, as reference data, the unifactor and multifactor interrelations of the parameters under study. The quality of the interrelations of the parameters in question depends on the contents and scope of the experimental base.

Conclusions

1. The development of the on-board electronic steering, safety and comfort systems in motor vehicles, as well as innovations in the tyre production processes increase the tyre-and-road engagement capacity, thus entailing the need to upgrade the existing regulations and methods used for estimating the braking properties of motor vehicles.

2. Any expert findings, when used as evidence, are to be substantiated with true and veracious output data, as well as by the fitness and adequacy of the methods used to investigate the road accident in question. The widely-used methods which use the reference data to determine the rated parameters, can often only roughly estimate the range of probable values for the output variables, basing on the grounds of stochastic uncertainty, thus impairing the objectivity of the decision to be made in the course of investigation into the cause of a road accident.

3. The above-said approach allows dealing with the output data which can bear stochastic and/or fuzzy uncertainty. This decreases the range of probable estimates in the course of simulation and enhances the objectiveness of the decisions being made. Therefore, the offered adaptive neuro-fuzzy system for estimating the value of the tyre-road friction coefficient can be recommended as an alternative solution to the existing road accident investigation practices.

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Автомобиль шиналарының жолға ілінісу коэффициенті: бағалаудың бейімделген жүйесі

Жол-көлік оқиғаларын тергеу кезінде көлік құралдары шиналарының жолға ілінісу коэффициентін бағалаудың жетілдірілген әдістемесі ұсынылған. Базалық негізгі әдіс шұғыл тежеу кезінде автомобиль шиналарының жолмен өзара әрекеттесуін эксперименттік зерттеу нәтижелері болып табылады. Ілінісу коэффициентін бағалау шинаның жолмен байланысындағы үйкеліс процестеріне елеулі әсер ететін параметрлер бойынша жүргізілген. Ілінісу коэффициентін бағалаудың синтезделген бейімделу жүйесіне енгізілген ең салмақты параметрлер көлік құралдарының баяулауы мен тежегіш жолының көрсеткіштерін теориялық талдау негізінде анықталды. Автомобиль шиналарының жолмен өзара іс-қимыл сапасын және оның көлік құралдарының қозғалыс параметрлеріне әсерін бағалаудың қолда бар сараптамалық әдістерін зерттеу қолданыстағы тәсілдерді жетілдіру қажеттігін көрсеткен. Ілінісу коэффициентін бағалаудың әзірленген адаптивті жүйесі, қолданыстағылардан айырмашылығы, өзін-өзі оқытуға қабілетті. Ол модельдеудің белгісіздігін азайтуға және бірінші және екінші түрдегі қателердің пайда болу ықтималдығын қысқартуға мүмкіндік береді. Мұндай нәтижеге тежегіш жүйелері мен автомобиль шиналары конструкциясының дамуын, көлік құралдарының қозғалыс жылдамдығын және олардың дөңгелектерінің жүктелуін, стохастикалық және анық белгісіздік жағдайында бастапқы деректерді өңдеуге қабілетті қазіргі заманғы математикалық әдістерді қолдану есебінен қол жеткізілген. Ұсынылған тәсіл M1, N1 санаттағы автомобильдер үшін өзінің тиімділігін көрсеткен және көлік құралдарының басқа санаттары үшін одан әрі зерттеулер жүргізу келешегін растаған.

Кілт сөздер: ілінісу коэффициенті, автомобиль шинасы, жол жабыны, тежеу процесі, бағалаудың бейімделген жүйесі, жол-көлік оқиғаларының сараптамасы.

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Коэффициент сцепления автомобильных шин с дорогой: адаптивная система оценки

Предложена усовершенствованная методика оценки коэффициента сцепления шин транспортных средств с дорогой при расследовании дорожно-транспортных происшествий. Базовой основой методики являются результаты обработки экспериментальных исследований взаимодействия автомобильных шин с дорогой при экстренном торможении. Оценка коэффициента сцепления производится по параметрам, которые существенно влияют на процессы трения в контакте шины с дорогой. Наиболее весомые параметры, включенные в синтезированную адаптивную систему оценки коэффициента сцепления, были выявлены на основе теоретического анализа показателей замедления и тормозного пути транспортных средств. Исследование существующих экспертных методов оценки качества взаимодействия автомобильных шин с дорогой и его влияние на параметры движения транспортных средств показали необходимость усовершенствования существующих подходов. Разработанная адаптивная система оценки коэффициента сцепления, в отличие от существующих, способна к самообучению. Она позволяет уменьшить неопределенность моделирования и сократить вероятность появления ошибок первого и второго рода. Такой результат достигается благодаря учету развития конструкции тормозных систем и автомобильных шин, скорости движения транспортных средств и загруженности их колес, применения современных математических методов, способных обрабатывать исходные данные в условиях наличия стохастической и нечеткой неопределенности. Предложенный подход показал свою эффективность для автомобилей категорий M1, N1 и подтвердил перспективу проведения дальнейших исследований для других категорий транспортных средств.

Ключевые слова: коэффициент сцепления, автомобильная шина, дорожное покрытие, процесс торможения, адаптивная система оценки, экспертиза дорожно-транспортных происшествий.

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