Adhesion of car tires to the road surface during reconstruction of road accidents

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Abstract. Road and weather conditions have a significant impact on the occurrence of road accidents and their development as events. According to these circumstances, the system “Driver – Car – Road – Environment” identifies certain types of expertise that are engaged in determining the presence and magnitude of the parameters of the road environment that affect the development of the road transport situation. When conducting relevant investigations, the experts calculate the speed and length of the stopping distance of the vehicle, using coefficients that determine the impact of road conditions on the road traffic situation under study. One of these important indicators is the coefficient of adhesion of car tires to the road surface. Due to the lack of technical capability to experimentally determine the coefficient of adhesion at the place of an accident, many experts are forced to use values from the reference literature. This study is devoted to checking the agreement of reference values of this indicator with actual values that correspond to the conditions of driving on Russian roads. To solve this problem, full-scale measurements were made of the coefficient of adhesion of tires with a coating on more than 2000 km of roads in different regions of Russia (with different climatic and topographic conditions) and the results of field research were analyzed.

1 Introduction

Road accidents involving overturning vehicles have more serious consequences than other types of road accidents. Overturning the car can be caused by various reasons, in particular, related to road conditions, for example:

- driving a vehicle with skidding on a road surface with a high coefficient of adhesion or with a viscous loose soil into which the wheels crash when they move laterally;
- a sharp turn of the vehicle with a radius that does not correspond to the selected speed under the conditions of stability against overturning on roads with a high value of the coefficient of adhesion (or the coefficient of resistance to the movement of the wheels in the transverse direction on an uneven solid surface). In this case, overturning is possible without skidding.

As can be seen from these points, a large influence on the development of the road transport situation is influenced by the coefficient of (longitudinal) adhesion of tires to the

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road surface and its value. The coefficient of adhesion is the ratio of the maximum tangential force acting along the road on the contact area of the interlocked wheel with the road surface to the normal reaction in the contact area of the wheel with the surface [1,2,3].

In the “Driver-Car-Road-Environment” system, two lines of scientific research are allocated for this circumstance:

“Car-Road” – Wear and other destruction of the road surface, changes in the micro-profile, rolling coefficients and adhesion;

“Environment (external) – Road” - accounting for influence of the environment on the rolling resistance and adhesion coefficients; changes in the road’s micro-profile (the appearance of ice growths).

The coefficient of adhesion of tires to the road surface must be taken into account and determined for the following types of road accidents and road sections: a collision when overtaking on a convex (concave) curve, a collision in the plan (with an exit to the side of the oncoming traffic direction), a collision of oncoming vehicles on a horizontal road section, a vehicle skid caused by the destruction of suspension elements of one of the wheels and/or the destruction of the wheel tire, a collision of vehicles at an unregulated intersection [4,5].

Thus, the definition of the coefficient of friction is especially important during reconstruction of a traffic accident, it may significantly affect the results of calculations of stopping distances, vehicle speed, and to clarify the circumstances causing study emergency. As a result of calculations, the expert is obliged to determine whether the driver violated the requirements of traffic rules, technical means of traffic management (road signs, markings) and whether it was technically possible to prevent a traffic accident [6,7,8].

2 Materials and Methods

In the expert practice of investigating the circumstances of road accidents when determining the full stopping distance of the car the formula is used:

$$S = (t_1 + t_2 + 0.5t_3) \frac{V_c}{3.6} + \frac{kV_c}{254\varphi}, m \quad (1)$$

S – length of the full stopping distance of the car, m

t_1 – driver response time, s

t_2 – brake response time, s

t_3 – deceleration rise time to the maximum value, s

V_c – car speed, km / h

k – coefficient of braking efficiency

φ – coefficient of adhesion of tires to the road

The coefficient of adhesion of the coating must provide safe driving conditions with the speed permitted by the traffic Rules and be at least 0.3, and the coefficient of adhesion of the marking must be at least 0.75 of the values of the coefficient of adhesion of the coating.

The coefficient of adhesion is one of the main values that characterize the performance of road surfaces, as well as the interaction of the wheel with the road. Its value is used to judge the safe speed of a car [9,10].

The analysis of numerous data shows that the magnitude of the coefficient of adhesion depends on many different factors, and primarily on the type of coating and its condition, design and material of the tires, the pressure of the air, loads on the wheel, speeds, temperature conditions, values of the sliding and slipping of wheels (table 3.68).

Often, experts do not have the ability (technically) to experimentally determine the coefficient of adhesion at the site of a road accident, and therefore have to use the reference data presented in table 1.

Table 1. Coefficient of adhesion for various road surfaces in summer and winter conditions.

No	Type of road surface	The condition of the coating	Coefficient of adhesion
1	Asphalt, concrete	Dry	0.7-0.8
		Wet	0.5-0.6
		Dirty	0.25-0.45
		Covered with a layer of snow, up to 5 cm thick	0.2-0.4
2	Cobblestone, paving stones	Dry	0.6-0.7
		Wet	0.4-0.5
3	Dirt road	Dry	0.5-0.6
		Wet	0.2-0.4
		Dirty	0.15-0.30
4	Sand	Wet	0.4-0.5
		Dry	0.2-0.3
5	Loam	Dry	0.4-0.5
		Moistened to a plastic state	0.2-0.4
		Moistened to a fluid state	0.15-0.25
6	Meadow, swampy meadow	Covered with turf	0.1-0.4
7	Snow	Loose	0.2-0.4
		Compacted (rolled road)	0.3-0.5
8	Ice	Smooth (air temperature below 0°C	0.05-0.1

The aim of the study was to establish experimentally the correspondence of the reference data of the coupling coefficients with the real ones determined using the PCRS2-RDT device (Evenness and adhesion control device). The process of measuring the coefficient of adhesion of tires to the road surface can be represented in the form of an algorithm presented in figure 1 [11, 12, 13].

Fig. 1. Algorithm for measuring the adhesion coefficient.

The obtained measurement results are subject to mathematical processing – the adhesion force on the measuring section is calculated as the arithmetic mean of the adhesion forces obtained from the measurement results, the adhesion coefficient is calculated using the formula:

$$\varphi = \frac{F}{N} + K \quad (2)$$

F – adhesion force on the measuring section, N.

N – normal reaction of the road surface in the area of contact with the measuring wheel, N.

K - temperature correction (accepted according to table 2).

Table 2. Value of temperature corrections to the value of the adhesion coefficient.

Air temperature at the time of measurement, °C	5	10	15	20	25	30	35	40
The correction value	-0.04	-0.03	-0.02	0.00	+0.01	+0.01	+0.02	+0.02

In measuring the coefficient of adhesion between tire and the road surface was carried out in 2 regions of Russian Federation: region of the middle Urals (the area, according to the map of road-climatic zoning refers to category II, which includes area of forests with abundant moisture and the soil is in a zone inland climate, characterized by hot summers and cold snowy winters, the average duration of snow cover is 160-175 days, the average annual temperature ranges from 1.0 °C to 2.5 °C) and the North-Western region of the European part of Russia (the climate of the Atlantic-continental is relatively mild winter with frequent thaws and moderately warm, sometimes cool summers, the average temperature in January is -8... -11 °C, July +16...+18 °C). For the study, a complex of measuring mobile airfield and road laboratory KP-514 RDT was used, with a system for measuring the coefficient of adhesion of coatings (a trailer device “PCRS2-RDT” the technical characteristics are presented in table 3, and the general view is shown in figure 2 according to Russian GOST 33078-2014 “Automobile roads of general use. Methods of measuring friction of vehicle wheel with the road surface”, as well as manufacturer’s instructions AO “SNPC” RDT” [14,15,16].

Table 3. Technical characteristics of the trailer device “PCRS2-RDT”.

No	Parameter	Value
1	The normal load of the wheel on the road. coating, kN	3.0±0.03
2	Range of adhesion coefficient measurements	from 0.1 up to 1.0
3	Margin of error,%, not more than	±4
4	Electro-pneumatic control system for locking (braking) the measuring wheel, the range of adjustment of the duration of the braking cycle	from 2 up to 5 seconds;
5	The transducer measuring the brake force	Laser

Fig. 2. General view of the trailer device “PCRS2-RDT”.

3 Results

The adhesion coefficient was measured on more than 50 paved roads with a total length of more than 2000 km, in accordance with all the requirements for this type of measurement. According to the results of the survey of the coefficient of adhesion of each road, a protocol was drawn up, the basis of which was a table (its analogue is presented in table 4).

Table 4. An example of the main indicators reflected in the protocol for measuring the coefficient of adhesion of a car wheel with a road surface.

Measurement location, km+m	Value of the adhesion	The speed of the vehicle during measurement, km/h	Measurement location, km+m	Value of the adhesion	The speed of the vehicle during measurement, km/h
	Forward stroke (1 lane)			Forward stroke (2 lane)	
0+167	0.334	60	0+152	0.339	60
0+453	0.335	60	0+521	0.337	60
0+792	0.332	60	0+872	0.338	60
1+229	0.347	60	1+267	0.348	60
1+568	0.346	60	1+601	0.345	60
1+977	0.344	60	1+843	0.346	60
2+211	0.366	60	2+346	0.362	60
2+568	0.363	59	2+598	0.364	61
2+987	0.365	59	2+973	0.363	61
3+191	0.359	59	3+199	0.361	61

It should be noted that the measurements were made only under favorable weather conditions on a dry surface.

Thus, after analyzing all the measurements made and structuring them, we can present the data in the form of table 4, where the average values of the adhesion coefficients with a

division by kilometers are indicated (for reduction, table 4 shows the values of the first 10 km of long roads).

Table 4. Measured values of adhesion coefficients.

No	Road	Kilometer										Average value
		0-1	1-2	2-3	3-4	4-5	5-6	6-7	7-8	8-9	9-10	
1	2	3	4	5	6	7	8	9	10	11	12	13
The Region of The Middle Urals												
1	A	0.472	0.503	0.531	0.478	0.603	0.598					0.531
2	B	0.336	0.346	0.364	0.360							0.352
3	C	0.312	0.292	0.374								0.326
4	D	0.335	0.440	0.453	0.438	0.139	0.417	0.522	0.408	0.456		0.401
5	E	0.451	0.450	0.489	0.457	0.508	0.340					0.449
6	F	0.516	0.501	0.479								0.499
7	G	0.500	0.473	0.481	0.490	0.502	0.431	0.509	0.525	0.509	0.531	0.495
8	H	0.496	0.432	0.382	0.520	0.372	0.512	0.346	0.241	0.460	0.421	0.418
9	I	0.422	0.366	0.444	0.472	0.499	0.472	0.479	0.411	0.450	0.431	0.445
10	J	0.495	0.43	0.425	0.435	0.45	0.545	0.515	0.485	0.515	0.525	0.482
11	K	0.360	0.320	0.410	0.325	0.310	0.310	0.325	0.380	0.340	0.505	0.359
12	L	0.480	0.485	0.480	0.465							0.478
13	M	0.425	0.415	0.490	0.510	0.520	0.475	0.475	0.495	0.490	0.530	0.483
14	N	0.300	0.345	0.370	0.355	0.330	0.325	0.380	0.355	0.365	0.450	0.358
15	O	0.410	0.330	0.425	0.460	0.530	0.555	0.495	0.500	0.450	0.360	0.452
16	P	0.490	0.505	0.485	0.445							0.481
17	Q	0.395	0.425	0.380								0.400
18	R	0.505	0.550	0.520	0.520	0.285	0.285	0.205	0.265	0.305	0.330	0.377
19	S	0.393	0.483	0.459	0.476	0.491	0.543	0.450	0.497	0.429	0.374	0.460
20	T	0.405	0.480	0.715	0.510	0.520	0.475	0.475	0.495	0.490	0.530	0.510
21	U	0.365	0.390	0.410	0.390	0.425	0.435	0.450	0.500	0.480	0.395	0.424
22	V	0.166	0.402	0.229	0.405	0.504	0.393	0.444	0.520	0.510	0.531	0.410
23	W	0.470	0.470	0.455								0.465
24	X	0.371	0.338	0.359								0.356
25	Y	0.238	0.261									0.250
26	Z	0.245	0.260	0.255	0.380	0.338	0.407	0.408	0.404			0.337
27	AA	0.408	0.418	0.194								0.340
28	AB	0.335	0.356	0.268	0.272	0.431	0.302	0.257	0.292	0.257		0.308
29	AC	0.480	0.390	0.310	0.190	0.310	0.365	0.295	0.300	0.480	0.245	0.337
30	AD	0.445	0.515	0.410	0.510	0.565	0.540	0.480	0.495	0.440	0.490	0.489
31	AE	0.245	0.195	0.275	0.415	0.465	0.430	0.410	0.455	0.440	0.470	0.38
32	AF	0.435	0.451	0.446	0.592	0.536	0.419	0.409	0.398	0.419	0.440	0.455
33	AG	0.245	0.242	0.184	0.215	0.259	0.482	0.217	0.316	0.400	0.304	0.286
34	AH	0.440	0.481	0.434	0.481	0.488	0.523	0.452	0.413	0.412	0.425	0.455
35	AI	0.375	0.155	0.225	0.446	0.489	0.485	0.347	0.201	0.159	0.459	0.334
North-Western region of the European part of Russia												
36	AJ	0.280	0.405	0.535								0.407
37	AK	0.485	0.486	0.491	0.486	0.489	0.480	0.461	0.451	0.480	0.508	0.482
38	AL	0.459	0.515									0.487
39	AM	0.522	0.447	0.488	0.484	0.509						0.49
40	AN	0.540	0.568	0.488	0.542							0.535
41	AO	0.507	0.458	0.523	0.521	0.504	0.540	0.527	0.510			0.511
42	AP	0.439	0.494	0.434	0.422	0.431	0.432	0.436	0.457			0.443
43	AQ	0.496	0.530	0.504	0.517	0.542						0.518
44	AR	0.48	0.557									0.519
45	AS	0.485	0.490	0.460	0.480	0.485	0.505	0.550	0.500	0.495	0.575	0.503
46	AT	0.595	0.575	0.555	0.570	0.50	0.575	0.630	0.610	0.460	0.540	0.561
47	AU	0.420	0.410	0.470	0.515	0.585	0.545	0.500	0.520	0.575	0.600	0.514
48	AW	0.403	0.417	0.441	0.455	0.423	0.375	0.345	0.377	0.439	0.506	0.418
49	AX	0.488	0.525	0.53	0.55	0.534	0.557	0.519	0.503			0.526
50	AY	0.460	0.500	0.490	0.455	0.350	0.340	0.400	0.300	0.335	0.335	0.397
51	AZ	0.490	0.570	0.490	0.460	0.490	0.460	0.490	0.510	0.500	0.560	0.502
52	BA	0.335	0.335	0.375	0.405	0.426	0.355	0.385	0.29	0.375	0.385	0.367
53	BB	0.451	0.472	0.486	0.484	0.490	0.437	0.463	0.425	0.452	0.432	0.459
54	BC	0.414	0.477	0.426	0.350	0.417	0.480	0.465				0.433
55	BD	0.415	0.447	0.439	0.430							0.433
56	BE	0.397	0.401	0.409	0.413	0.425	0.444					0.415
Average value												0.434

4 Discussion

As shown in table 4, most of the values are in the range 0.2-0.6, that is, the actual coefficient of adhesion is less than the reference value (from table 1), which for dry asphalt is $\varphi=0.7-0.8$. Also, 205 values of the adhesion coefficients (of 422 presented in table 4) are in the range of 0.4-0.5, which according to table 1 corresponds to a dirty, wet or snow-covered road, which is categorically incorrect – figure 3 shows a photo of weather and climate conditions and the condition of the road surface when measuring the adhesion coefficient.

Fig. 4. Weather and climate conditions and the condition of the road surface when measuring the coefficient of adhesion of tires to the road.

The average value of the coefficient of adhesion of tires with a coating for each road surveyed is shown in column 1, the average value of the presented measurements is 0.434, and the percentage distribution of the coefficients of adhesion with a step of 0.1 is shown in figure 5.

Fig. 5. Percentage ratio of the obtained adhesion coefficients in 0.1 increments.

5 Conclusions

Thus, on the example of the surveyed roads, it can be concluded that the reference values of the coefficient of adhesion of tires with a surface (dry) are overstated in comparison with the actual ones. Therefore, when calculating the stopping distance and vehicle speed using reference information, the result may be an error, which categorically affects the expert's conclusion on the case on the road accident. The influence of fluctuations in temperature, humidity and road surface conditions on the coefficient of adhesion of tires to the road is an urgent scientific task and is planned by the authors as further research.

References

1. X. Li, J. Shao, G. Wei, R. Hou, *International Symposium on Pervasive Systems, Algorithms and Networks I-SPAN 2019: Pervasive Systems, Algorithms and Networks*, 335-34 (2019) doi:10.1007/978-3-030-30143-9_28
2. K. Doi, T. Sunagawa, H. Inoi, K. Yoh, *IATSS Research*, Elsevier **39(2)**, 87-94 (2016) doi: 10.1016/j.iatssr.2016.03.001
3. M.M. Minderhoud, P.H.L. Bovy, *Accident Analysis & Prevention* **33(1)**, 89-97 (2001) doi: 10.1016/S0001-4575(00)00019-1
4. Á. Török, G. Pauer, T. Berta, *Procedia Engineering* **187**, 712-721 (2017) doi: 10.1016/j.proeng.2017.04.445
5. Li-Lu Sun, Dan Liu, Tian Chen, Meng-Ting He, *Chinese Journal of Traumatology* **22(5)**, 290-295 (2019) doi: 10.1109/ICTIS.2015.7232140
6. E. Kurakina, S. Evtiukov, J. Rajczyk, *Transportation Research Procedia* **36**, 380-385 (2018) doi: 10.1016/j.trpro.2018.12.111
7. E.V. Kurakina, *Bulletin Of Civil Engineers* **2(67)**, 231-237 (2018) doi: 10.23968/1999-5571-2018-15-2-231-237

8. S. Evtukov, E. Golov, Transport of the Urals **2(53)**, 85-89 (2017) doi: 10.20291 / 1815-9400-2017-2-85-89
9. S. Evtiukov, E. Golov, G. Ginzburg, Transportation Research Procedia **36**, 157-165 (2018) doi: 10.1016 / j. trpro.2018.12.058
10. S. Evtukov, E. Golov, T. Sazonova, *Siberian Transport Forum - Transsiberia* (Novosibirsk, 2018)
11. I.S. Gladushevskiy, S.S. Evtukov, Bulletin Of Civil Engineers **6(71)**, 175-179 (2018) doi: 10.1051 / matecconf / 201823904018
12. I. Novikov, D. Lazarev, Transportation Research Procedia **20**, 463 – 467 (2017) doi: 10.1016 / j. trpro.2017.01.075
13. H. Chena, M. Ishida, A. Namura, K.-S. Baek, T. Nakahara, B. Leban, M. Pau, *Proceedings of the 8th International Conference on Contact Mechanics and Wear of Rail, Wheel Systems* **271(1–2)**, 32-3918 (2011) doi: 10.1016/j.wear.2010.10.022
14. F.M. Fernandes, J.C. Pais, Construction and Building Materials **154**, 1130-1138 (2017) doi: 10.1016/j.conbuildmat.2017.08.022
15. M.-T. Do, Z. Tang, M. Kane, F. Larrard, Wear **263(1–6)**, 36-42 (2007) doi: 0.1016 / j.износ.2006.12.086
16. F. Kilic, J. Hilsmann, IFAC-Papers On Line **49(15)**, 260-265 (2016) doi: 10.17531 / ein.2017.3.7