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RESEARCH OF CAR BRAKING IN WINTER CONDITIONS

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Abstract. This paper presents research of some car braking characteristics in winter conditions, such as dependence of car deceleration on the road surface state, type of tires (studded or not), peculiarities of the car braking system (with anti-lock brake system (ABS) or without it).

There were carried out braking experiments with cars at the mentioned road conditions – wet asphalt-concrete road surface and wet snow on it (initial speed, deceleration of cars were measured by the XL METER Pro Beta decelerometer). The experimentally obtained characteristics were analyzed by use of the SPSS software pack of mathematical statistics (the created statistical models were based on linear regression).

The results of the carried out research processed by help of the software pack of mathematical statistics first of all are recommended to be applied to examinations of road accidents.

Keywords: analysis of road accidents, braking characteristics, initial speed, braking system, type of tires, winter road conditions.

1. Introduction

In many reference sources, which are used in the praxis of road accident examination, limits of the adhesion coefficient μ_x in longitudinal direction for winter conditions are given usually for two cases, e.g., [1, 3, 5, 8, 9]:

– when the road surface is covered with snow – $\mu_x = 0.1 \div 0.4$;

– when the road surface is covered with ice – $\mu_x = 0.05 \div 0.2$.

Evaluating rather wide specified limits of the adhesion coefficient it can be said that the given values can be used for winter and also for summer tires. These values are not valid for studded tires use of which was banned recently in the most of European countries.

In Lithuania there are sufficiently large number of vehicles (cars, minivans, minibuses and their trailers), which are driving in winter with studded tires. But beginning with the year 2011 studded tires will be banned as well in Lithuania, therefore their sale recently decreased considerably. Now statistically at least 20 % cars are driving with studded tires in winter in Lithuania. There are too little information in reference sources about braking characteristics of cars with studded tires in different winter conditions. In reference [2, 6, 7] some comparable data about adhesion of studded and not studded tires in winter conditions can be found, as presented in Table 1.

Table 1. The comparative data about adhesion characteristics of studded and not studded tires

Road surface	Adhesion coefficient μ_x	
	Not studded	Studded
1. Dry concrete	$0.88 \div 1.00$	$0.86 \div 1.02$
2. Wet concrete	$0.50 \div 0.61$	$0.59 \div 0.70$
3. Dry asphalt-concrete	$0.87 \div 0.99$	$0.81 \div 0.89$
4. Wet asphalt-concrete	$0.77 \div 0.93$	$0.78 \div 1.02$
5. Pressed snow	$0.35 \div 0.45$	$0.41 \div 0.48$
6. Ice	$0.22 \div 0.41$	$0.29 \div 0.37$

It is seen from the Table 1, that in essence the adhesion characteristics of not studded and studded tires do not differ at different conditions: adhesion of studded tires is slightly higher when braking on the wet concrete or asphalt-concrete (further-asphalt) road surface, also on pressed snow. As also follows from the table, studded tires have no advantage also when braking happens on ice, even if a contrary opinion often is being heard from driver's side.

Statistically the most of road accidents (about 60 %) happens in settlements, where roads usually are cleaned off even in winter. In addition, in heavy traffic conditions speed of traffic flow decreases significantly, as well as the number of heavy road accidents, therefore road accidents in such critical conditions are not the object of research.

Therefore, during experimental research with the aim of evaluation of deceleration limits in winter conditions for driving in urban areas the following actions are necessary:

– comparison of braking characteristics of cars with and without studded tires, evaluation of the car longitudinal deceleration a_x for braking on the wet clean asphalt road surface;

– carrying out these experiments also braking cars on the road surface covered with wet muddy snow. Such research is aimfull because of lack of deceleration data namely for braking in the mentioned conditions;

– examination of influence of the braking system construction (with or without ABS) on braking in urban conditions (i.e., for a slight speed).

2. Experimental research

During this research experiments were carried out with 23 cars (aged 10–12 years) in good working order which were exploited in Lithuania (Tables 2, 3). These experiments were carried out on the horizontal even not roughened asphalt road surface. All cars were with winter tires (studded or not studded) and with different braking systems (with or without ABS).

Table 2. Experimental data for cars, braked on wet cleaned asphalt

Car, year of production, ABS	Tires	Initial speed, v_a, km/h	Deceleration samples, a_x, m/s^2	Average deceleration, $\bar{a}_x$, m/s^2
1. BMW 318i, 1995, with ABS	185/65 R15, not studded	33,4	6,5	6,6
		40,8	6,6	
		38,3	6,6	
2. VW Caddy, 2005, with ABS	195/65 R15, not studded	40,8	6,6	6,5
		39,4	6,5	
		37,5	6,5	
3. RENAULT 19, 1992, without ABS	175/70 R13, studded	44,3	5,9	6,0
		43,0	6,2	
		42,5	5,8	
4. VW Golf II, 1984, without ABS	155/70 R13, not studded	31,3	5,9	6,5
		32,7	7,3	
		33,1	6,3	
5. Peugeot 406, 2001, with ABS	195/65 R15, not studded	44,2	6,5	6,7
		41,6	6,8	
		37,0	6,7	
6. Nissan Sunny, 1991, without ABS	175/70 R13, not studded	36,2	5,9	6,1
		38,4	6,1	
		36,8	6,4	
7. Audi A4, 1996, with ABS	195/60 R15, not studded	40,6	6,8	6,4
		41,0	6,4	
		38,5	6,1	
8. Nissan Primera, 1991, without ABS	175/65 R14, studded	38,2	5,8	5,7
		36,5	5,7	
		36,0	5,7	
9. Audi 100, 1984, without ABS	175/75 R14, studded	35,2	5,8	6,1
		34,6	6,3	
		32,4	6,1	
10. Toyota Celica, 1990, with ABS	175/75 R13, studded	38,2	6,1	6,3
		38,1	6,5	
		39,5	6,3	
11. Audi 80, 1988, without ABS	185/75 R14, not studded	33,2	6,7	6,6
		34,1	6,5	
		35,0	6,6	
12. Hyundai Sonata, 1995, with ABS	195/65 R15, not studded	40,5	6,3	6,5
		42,0	6,6	
		41,6	6,6	
13. Mazda 323F, 1996, with ABS	175/75 R13, studded	39,3	6,1	6,3
		36,1	6,5	
		37,8	6,4	

Continuation of Table 2. Experimental data for cars, braked on wet cleaned asphalt

14. Opel Astra, 1997, with ABS	175/65 R14, studded	33,2	6,0	6,4
		33,4	6,5	
		31,3	6,6	
15. Mazda 626 Coupe, 1988, without ABS	195/65 R14, studded	36,3	6,1	5,9
		34,9	5,9	
		34,2	5,8	

Table 3. Experimental data for cars, braked on asphalt, covered with wet snow

Car, year of production, ABS	Tires	Initial speed, v_a, km/h	Deceleration samples, a_x, m/s^2	Average deceleration, $\overline{a}_x$, m/s^2
1. Audi A4, 1996, with ABS	195/65 R15, not studded	30,3	2,8	2,9
		34,3	2,9	
		34,8	3,0	
2. Nissan Terrano, 1995, without ABS	185/65 R15, not studded	23,9	1,9	1,9
		22,7	1,8	
		25,7	1,9	
3. Ford Galaxy , 1996, with ABS	195/65 R15, studded	28,8	2,2	2,2
		29,7	2,1	
		30,4	2,3	
4. Audi A3, 1999, with ABS	195/65 R15, studded	33,9	3,0	3,0
		28,6	3,0	
		31,4	2,9	
5. Audi 80, 1992, without ABS	175/70 R14, not studded	27,3	3,2	3,0
		29,3	2,8	
		29,8	2,9	
6. Mazda 626, 1993, with ABS	185/70 R14, studded	32,2	2,7	2,8
		29,3	2,8	
		28,8	3,0	
7. Audi A4, 1996, with ABS	195/65 R15, not studded	23,8	3,4	3,5
		25,3	3,4	
		27,7	3,8	
8. Honda Accord, 2005, with ABS	205/55 R16, not studded	19,9	3,1	3,2
		23,1	3,1	
		24,4	3,3	

Carrying out and conditions of the experimental research:

1. Measuring were carried out with the portable decelerometer XL Meter Pro Beta (Fig. 1).

Fig. 1. The portable decelerometer XL Meter Pro Beta, arranged in the working position

This device indicates the average deceleration as well as initial speed, braking time, braking distance, all of which are necessary for further calculations with the obtained experimental data by use of a process software pack (mathematical statistics, see section 3). Tests were carried out 3 times with each car. We think, that there existed one valuable feature – cars were driven by their own drivers, so it can be said, that braking characteristics of every car were measured in complex manner including also the human factor.

2. Cars were tested at 30 km/h and 40 km/h initial speed, measured by the car speedometer (speed was defined more exactly in final processing of the experimental data). In every case, when the desired speed was reached, sudden braking was realized by the service brake (wheels of cars without ABS were locked during braking), the service brake pedal was held pressed down till the car full stop.

The first test was carried out on the wet asphalt road surface (Table 2) with 15 cars (average value of the car initial speed $v_a = 40$ km/h).

The second test was carried out with 8 cars, braked on wet asphalt, covered with wet snow (Table 3). The initial speed in this test was slightly less ($v_a = 30$ km/h), if compared with the first test.

Graphs in Fig. 2 and Fig. 3 illustrate dependence of dissipation of deceleration values on the initial speed before braking.

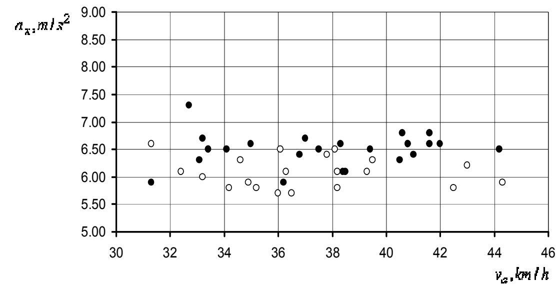

Fig. 2. Dissipation of deceleration a_x values as they depend on initial speed v_a . Braking on wet cleaned asphalt: ○ – studded tires, ● – not studded tires

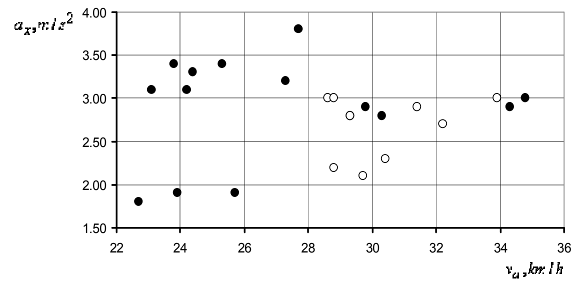

Fig. 3. Dissipation of deceleration a_x values as they depend on initial speed v_a . Braking on asphalt covered with snow: ○ – studded tires, ● – not studded tires

Fig. 2 shows, that deceleration of cars with not studded tires is slightly higher than that of cars with studded ones. Fig. 3 shows some greater dissipation of deceleration values comparing with the case of car braking on wet cleaned asphalt. But the tendency remains similar – deceleration of cars with not studded tires is higher than cars with studded tires.

Fig. 4 and Fig. 5 present graphs, which illustrate influence of the car braking system construction (with or without ABS) on dissipation of deceleration values in correspondence with the initial speed before braking.

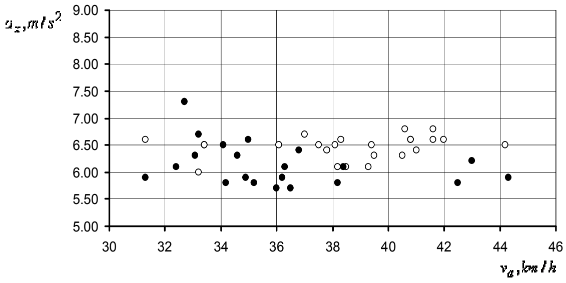

Fig. 4. Dissipation of deceleration a_x values as they depend on initial speed v_a . Braking on wet cleaned asphalt: ○ – cars with ABS, ● – cars without ABS

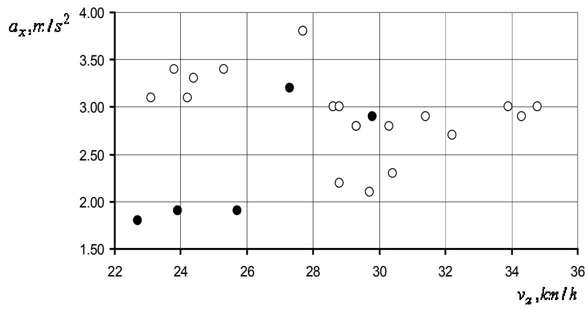

Fig. 5. Dissipation of deceleration a_x values as they depend on initial speed v_a . Braking on asphalt covered with snow: ○ – studded tires, ● – not studded tires

As it is seen from the presented graphs, influence of ABS on the braking efficiency is small for not great speed (especially for braking on the wet asphalt surface). For the second test (braking on the snow-covered asphalt) influence of ABS on braking is hardly determinable because of high dissipation of values (Fig. 5).

3. Application of regressive analysis for prognosis of car braking parameters

After the experimental research the obtained data of deceleration a_x values was processed by the „SPSS“ software pack of mathematical statistics. There were created models based on mathematical statistics for prognosis of average deceleration a_x [4]. Below there are presented two models of simulation, which were mentioned before.

1) Cars are braked on the wet cleaned asphalt road surface. The average value of deceleration $\overline{a}_x$ can be prognosed (calculated) by use of the following equation (evaluating cars with and without studded tires at speed $v_a = 40\, km/h$):

$$\overline{a}_x = 0.164 \cdot v_a(STUDDED) + 0.170 \cdot v_a(NOT\ STUDDED) + e(a_x), \qquad (1)$$

here: „ $STUDDED$ “, „ $NOT\ STUDDED$ “ – variables of the regression equation, describing type of car tires; $e(a_x)$ – regression standardized residual of $\overline{a}_x$ of the created model. Its average value approximately equals to 0.080 .

In accordance with this model we obtain (apply equation (1)), that average car deceleration $\overline{a}_x$ for $v_a = 40$ km/h and tires not studded is slightly greater if compared with the studded car tires, – $\overline{a}_x = 6.88\,\text{m/s}^2$ and $\overline{a}_x = 6.64\,\text{m/s}^2$ correspondingly (difference of these values equals to 3.6% approximately).

According to the statistical information (Table 4), obtained by the „SPSS“ software pack, there was found, that the created model sufficiently

Table 4. Results of tests and simulation of car braking on the wet asphalt surface ($v_a = 40\,\text{km/h}$) using the „SPSS“ software pack

Number of tests	Average experimental value of deceleration, $\bar{a}_x$, m/s^2	Average value of deceleration, obtained by simulation, $\bar{a}_x$, m/s^2	R	R^2	Standard deviation of the $\bar{a}_x$ value, m/s^2		
					±σ	±2σ	±3σ
45	6.31	6.26	0.995	0.989	0.615	1.29	1.85

precisely describes the data, obtained by the experiments which were described in the last section.

The correlation coefficient R, expressing correspondence between the existing and prognosed values of a_x indicates high correspondence and equals approximately 0.995. The same can be said also about proportions of deviations of a_x values if compared with the regression model. Its value is $R^2 \approx 0.989$.

2) Cars are braked on asphalt covered with snow. The average value of deceleration $\bar{a}_x$ can be prognosed (calculated) by use of the following equation (evaluating cars with and without studded tires at speed $v_a = 30\,\text{km/h}$):

$$\bar{a}_x = 8.776 \cdot 10^{-2} \cdot v_a(STUDDED) + 0.105 \cdot v_a(NOT\ STUDDED) + e(a_x), \qquad (2)$$

here: $e(a_x) \approx 0.048$.

In accordance with this model we obtain (apply equation (2)), that average car deceleration $\bar{a}_x$ for $v_a = 30\,\text{km/h}$ and tires not studded is greater if compared with the studded car tires. For not studded tires we obtain $\bar{a}_x = 3.20\,\text{m/s}^2$ and for studded ones we obtain $\bar{a}_x = 2.70\,\text{m/s}^2$ (difference of these values is about $15.6\,\%$).

According to the statistical information (Table 5), obtained by the „SPSS“ software pack, there was found, that the created model sufficiently precisely describes the experimental data.

The correlation coefficient R, expressing correspondence between the existing and prognosed values of a_x in this case equals to $R = 0.981$. The same can be said also about proportions of deviations of a_x values if compared with the regression model. Its value is $R^2 \approx 0.963$.

On the ground of the experimental results and statistical data processing we established, that braking characteristics of cars with not studded tires, when braking takes place on the wet cleaned or covered with snow asphalt are better, than for cars with studded tires. We suppose, that for the case of cleaned road surface it can be so because of better contact of not studded tires with the road surface (for the rubber tire cap surface neighbouring upon to studs in essence does not contact with the road surface).

Influence of ABS on the braking efficiency was low. From the technical view it can be explained because of low enough speed during the tests. Therefore in technical examination of road accidents which take place in settlement areas existence of ABS system can be ignored.

4. Conclusions

After the experimental car braking research in winter conditions and after creation of models, based on linear regression method of mathematical statistics there can be formulated the following conclusions:

1. Braking of cars having not studded tires is more effective in comparison with cars having studded tires. Difference of average values of their decelerations equals to approximately 3.6 %, if braking is going on the wet cleaned asphalt and approximately 15.6 % if it is going on asphalt covered with wet snow.

2. There were established the following average values of deceleration:

– for cars with not studded tires $\bar{a}_x \approx 6.88\,\text{m/s}^2$ if braking goes on the wet cleaned asphalt and $\bar{a}_x \approx 3.20\,\text{m/s}^2$ if it goes on asphalt covered with wet snow;

Table 5. Results of tests and simulation of car braking on asphalt covered with snow ($v_a = 30\,\text{km/h}$) using the „SPSS“ software pack

Number of tests	Average experimental value of deceleration, $\bar{a}_x$, m/s^2	Average value of deceleration, obtained by simulation, $\bar{a}_x$, m/s^2	R	R^2	Standard deviation of the $\bar{a}_x$ value, m/s^2		
					±σ	±2σ	±3σ
24	2.80	2.78	0.981	0.963	0.344	0.668	1.03

– for cars with studded tires $\overline{a}_x \approx 6.64\,\text{m/s}^2$ if braking goes on the wet cleaned asphalt and $\overline{a}_x \approx 2.70\,\text{m/s}^2$ if it goes on asphalt covered with wet snow.

3. There were created models, based on linear regression for the mentioned cases of braking. By use of this models a sufficiently precise prognosis of average deceleration value $\overline{a}_x$ can be found (calculated) for fixed values of a given speed v_a. Analysis of $\overline{a}_x$ values, calculated from experimental data and found by simulation results in the following differences:

– for braking on the wet asphalt – $a_x \approx 0.05\,\text{m/s}^2\,(\approx 0.8\%)$;

– for braking on asphalt covered with wet snow – $a_x \approx 0.02\,\text{m/s}^2\,(\approx 0.7\%)$.

4. The presented methods can be used for examination of road accidents in winter conditions. Besides the mentioned values $\overline{a}_x$, evaluation of limits of their errors of calculations is of great importance. Assuming, that presented models describe 95% values of deceleration a_x („2σ“ rule), we will obtain the following limits of $\overline{a}_x$ errors:

– for braking on the wet asphalt ($v_a = 40\,\text{km/h}$) – $\pm 1.2\,\text{m/s}^2\,(\pm 20\%)$;

– for braking on asphalt covered with wet snow ($v_a = 30\,\text{km/h}$) – $\pm 0.7\,\text{m/s}^2\,(\pm 25\%)$.

5. As there was established, influence of the anti-lock brake system (ABS) on braking efficiency is rather small for small speed ($v_a = 30\,\text{km/h}$). But synonymous description of this is difficult because of the relatively wide data spread (especially in the case of braking on the road covered with wet snow.

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