

## Vpliv lastnosti cestišča na zavorne lastnosti avtomobila

### The Influence of Road Surface on an Automobile's Braking Characteristics

Edgar Sokolovskij - Robertas Pečeliunas  
(Vilnius Gediminas Technical University, Lithuania)

*V prispevku smo opisali rezultate raziskave zavornih lastnosti avtomobilov, opremljenih s protiblokirnim zavornim sistemom (ABS) in brez njega. Predstavili smo vrednosti zaviranja avtomobila, od trenutka zaviranja do konca zaviranja, na suhi asfaltno-betonski površini, ki je bila nespremenjena med raziskavo. Prikazali in dokazali smo odvisnost zaviranja avtomobilov, opremljenih z ABS in brez njega, od začetne hitrosti vožnje. Predstavili smo tudi rezultate preizkusov zaviranja avtomobilov, opremljenih z ABS in brez njega, v zimskih razmerah, na ledu in snegu. Opisali smo tudi stične lastnosti in zaviranja avtomobilov pri zaviranju na drugih površinah cestišča.*

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**(Ključne besede: avtomobili, parametri zaviranja, ABS, dinamika zavor)**

*The present paper describes the results of an investigation into the braking parameters of automobiles equipped with an antilock brake system (ABS) and without an ABS. The values of the automobile deceleration, the time of the deceleration increase and the time of disbraking, while braking on a dry asphalt-concrete surface, which has been fixed in the course of the experimental investigation, are presented. The dependence of the deceleration of the automobiles, equipped with an ABS and without an ABS, upon the primary driving speed is reflected and substantiated. The results of the investigation of the braking of the automobiles, equipped with an ABS and without an ABS, in winter conditions, i.e., on ice and snow, are presented. The cohesion characteristics and the automobile decelerations while braking on other road surfaces are presented.*

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**(Keywords: automobiles, braking parameters, ABS, dynamics)**

#### 0 INTRODUCTION

It is usual for the values of braking parameters, fixed for earlier models of automobiles, to be specified in reference sources [1]; however, these values are not usually appropriate for modern automobiles. The values of the braking parameters for automobiles specified in some sources do not match the modelling of the automobiles' movement. For example, the values for the deceleration of automobiles, specified by the manufacturers of automobiles and tires, are usually fixed for the phase of the most efficient braking, having not evaluated certain constituents of the braking process, as a result of which larger values are obtained. These values are, nevertheless, good for advertising and a comparison of products. However, for modelling the automobiles' movement (for example, for an examination of traffic accidents), values of the average, settled deceleration are necessary ([1] and [2]). Moreover, in the course of the in-

vestigation of the braking process, the deceleration of vehicles and the braking track are usually fixed; however, other parameters, such as the time of the deceleration increase and the time of disbraking, are also important when examining road-traffic accidents.

Recently, issues associated with antilock brake systems (ABSs), installed in automobiles, have frequently been considered, both in the scientific and popular references ([3] to [9]). However, so far not all the issues have been solved. The results of the investigation of the braking parameters and the peculiarities of the automobiles equipped with ABS, and of the automobiles without an ABS, are specified below [10].

#### 1 METHODS AND CONDITIONS OF THE EXPERIMENTAL INVESTIGATION

The experimental investigation was carried out under the following conditions:



- cars, equipped with an ABS and without it, which were produced in the years 1986 to 2000 were used for the investigation;
- the cars were in a good mechanical condition and equipped with their factory (non-substituted) brake systems;
- two people served as the load in the tested cars, i.e., the driver and the "passenger", who was taking care of the measuring device (the decelerometer);
- the same person drove the car during all the tests;
- the cars were equipped with tires of the size that is recommended for the particular type of model; the depth of the protector notch was not less than 3 mm. The cars, equipped with summer tires, were tested on the dry surface of an asphalt road, whereas the cars equipped with the winter "non-prickly" tires were tested in winter conditions (on snow and ice);
- the air pressure of the tires was nominal for the particular model of car and its load;
- the tests were carried out on a horizontal strip of a "non-rough" asphalt road, where there was no traffic, by calculating the mean number later;
- the tests were carried out in both directions – not less than three tests in each case, by calculating the mean number later;
- in the course of the investigation of the dependence of the deceleration on the car's primary speed, the tests on the dry surface of the asphalt road were carried out with the cars equipped with the ABS, which were driven at a primary speed of 60 km/h, 80 km/h and 100 km/h, and with the cars without the ABS, which were driven at a speed of 30 km/h, 50 km/h and 80 km/h (for the sake of safety, the tests with the cars without the ABS were carried out at the lower primary speed);

- for the sake of safety, in the course of the investigation of the influence of the ABS's functioning on the car's deceleration in winter conditions, the cars driven at the primary speed of 30 km/h were tested in winter conditions (on the snow and ice).

Measurements were taken with the help of an electronic device that measures the deceleration, i.e., a VZM 100 decelerometer.

## 2 RESULTS OF THE EXPERIMENTAL INVESTIGATION

At first, the dependence of the deceleration of the vehicles without the ABS on the primary speed was investigated. The results of the investigation are presented in Fig. 1.

As we can see, the deceleration of the vehicle without the ABS decreases with the increase of the primary speed.

An analogous investigation was carried out with vehicles equipped with the ABS. The results of these investigations are presented in Fig. 2.

It must be stated that in the course of the testing the average settled deceleration of all the vehicles equipped with the ABS on the dry surface of the asphalt road was not less than  $8 \text{ m/s}^2$  – it was within the range from  $8 \text{ m/s}^2$  to  $8.8 \text{ m/s}^2$ . The vehicle's deceleration at the stage of the most efficient braking in most cases exceeded  $9 \text{ m/s}^2$ , sometimes it reached the value of the acceleration due to gravity ( $9.81 \text{ m/s}^2$ ).

In the course of the investigation it was observed that during the braking of the vehicles equipped with the ABS, it was sometimes difficult to observe the traces of braking of the wheels (especially in certain lighting conditions). However, in most cases the length of the remaining traces is shorter than the length of the braking path.

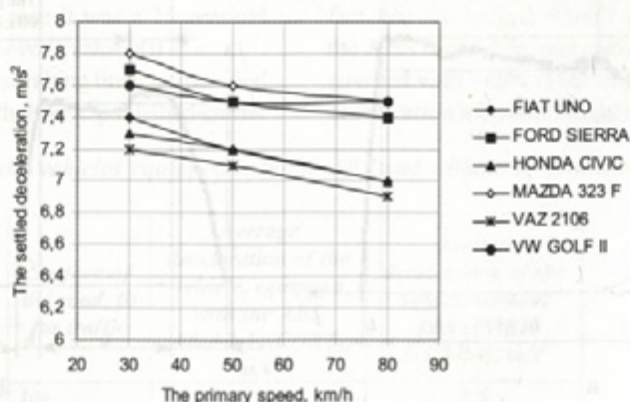


Fig. 1. Dependence of the deceleration on the primary speed during the braking of vehicles without the ABS

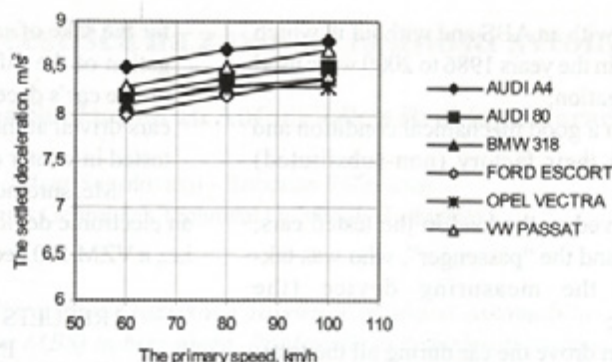


Fig. 2. Dependence of the deceleration on the primary speed during the braking of vehicles equipped with the ABS

It was ascertained that during the braking of the vehicles equipped with the ABS, the deceleration does not decrease; it even increases with the increase of the primary speed of the vehicle. In order to explain this situation, we will compare the braking diagrams in both cases (Fig. 3).

As it is clear from the braking diagram that the deceleration of the vehicle without the ABS, which is in a good mechanical condition, reaches its peak at the very beginning of braking, during which time the vehicle's wheels continue to rotate. When the wheels become locked, the deceleration decreases to a certain extent because the braking of a locked wheel is less efficient (Fig. 3, b). Thus, in the course of braking for the vehicle without the ABS, when the vehicle is driven at a lower speed, the above-mentioned peak of deceleration makes a larger part of the whole process of braking and in contrast the peak makes up a smaller part of the process of braking when the vehicle is driven at a higher speed

and the process of braking takes a longer time. In addition, the other factors, such as the heating of the tire compound of the blocked wheel of the automobile in the contact zone, etc., are also significant. The deceleration decrease, typical of the vehicles that are driven at the increasing primary speed, can be explained by this fact. It should be noted that it was not always the "classic" diagrams of braking, reflecting the peak in the maximum deceleration, when starting to brake that were obtained in the case of braking for the automobiles without the ABS.

In the course of braking for the vehicles equipped with the ABS (according to the principle of the ABS the wheels remain unlocked during the whole period of braking), there is no deceleration peak at the beginning of braking. On the contrary, in the course of braking for the vehicles equipped with the ABS, when the wheels interact with the surface of the road (the ABS controls the situation and prevents the wheel slip from exceeding a certain value –

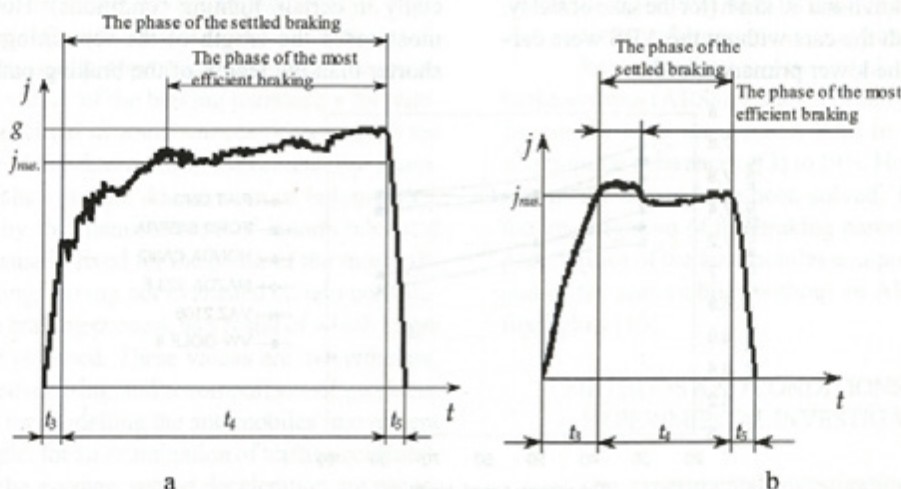


Fig. 3. The diagrams of braking: a – the vehicle equipped with the ABS, b – the vehicle without the ABS



Table 1. The time of deceleration increase,  $t_p$ , and the time of disbraking,  $t_d$ 

Vehicle	ABS	Time of deceleration increase $t_p$ , s	Time of disbraking $t_d$ , s
AUDI A4	+	0.1	0.1
AUDI 80	+	0.15	0.1
BMW 318	+	0.15	0.1
FIAT UNO	-	0.2	0.15
FORD ESCORT	+	0.15	0.15
FORD SIERRA	-	0.2	0.1
HONDA CIVIC	-	0.25	0.15
MAZDA 323 F	-	0.2	0.1
OPEL VECTRA	+	0.15	0.15
VAZ 2106	-	0.3	0.2
VW GOLF II	-	0.2	0.1
VW PASSAT	+	0.1	0.1

usually, approximately 20%), the deceleration continues to increase insignificantly in the course of further braking after the phase of increase for the deceleration. Thus, slightly smaller deceleration values are reached at the beginning of braking, whereas the largest values are usually reached when the process of braking becomes stable at the end of braking. The deceleration increase with the increase of the primary speed of the vehicle equipped with the ABS can be explained by this fact (Fig. 3, a).

Furthermore, the values of the time of the deceleration increase,  $t_p$ , and of the time of disbraking,  $t_d$ , were determined in the course of the investigation. The obtained results are presented in Table 1.

As we can see, the values of the time of deceleration increase,  $t_p$ , for all the vehicles that were investigated did not exceed 0.3 s. This value was typical for the VAZ 2106 automobile. The values of the time of deceleration increase,  $t_p$ , for most of the Japanese and western vehicles did not exceed 0.2 s and remained within the limits of 0.1 to 0.2 s. The only exceptions were very old-fashioned vehicles. In this case it was a 15-year-old HONDA CIVIC, which achieved a value of 0.25 s.

The values of the disbraking time,  $t_d$ , specified in certain written sources that were published earlier

were not proven (for the hydraulic brake system  $t_d = 1.5$  s). The values of the time of disbraking, obtained in the course of the investigation did not exceed the values of the time of deceleration increase and were within the limits of 0.1 to 0.15 s, except for the VAZ 2106, with the time of disbraking equal to 0.2 s.

Braking tests were also carried out in winter conditions, i.e., on ice and snow. For this we used a FORD ESCORT (equipped with the ABS) and a FORD SIERRA (without the ABS). The obtained results are presented in Table 2.

In the course of the investigation it was determined that a slightly higher deceleration was typical for the vehicle equipped with the ABS (FORD ESCORT) when braking on the ice.

Slightly different results were obtained when braking with vehicles equipped with the ABS and without it on a snowy road surface, fit for traffic. In this case a slightly higher deceleration was typical for the vehicle without the ABS (FORD SIERRA). Such unexpected results can be explained by the fact that the locked wheels of the vehicle without the ABS contact the wet surface of the asphalt road, covered with a thin layer of snow, thus causing the deceleration increase. In addition, the locked wheels

Table 2. Deceleration of the vehicles equipped with the ABS and without it, in winter conditions

Surface of the road, fit for traffic	Average deceleration of the vehicle, equipped with the ABS (FORD ESCORT), $m/s^2$	Average deceleration of the vehicle without ABS (FORD SIERRA), $m/s^2$
Ice	2.0	1.8
Snow	2.6	3.0



push and thicken the snow in front of them. Thus, the area of the wheel pressure increases and the effect, similar to the braking of the vehicle on a soft surface (for example, soft soil) reveals itself.

The wheels of the vehicle equipped with the ABS remain unblocked. Thus, they do not contact the wet surface of the asphalt road and the deceleration is lower. However, it should be stressed that in any case, including the case when braking the vehicle on the snow (though in this case the deceleration of the vehicle equipped with the ABS was a bit lower), the ABS has a significant positive influence on the operation of the vehicle as the possibility to drive the vehicle remains. This is very important for traffic safety as most traffic accidents occur because it is not possible to correctly operate the vehicle.

### 3 COHESION CHARACTERISTICS AND AUTOMOBILE DECELERATION WHILE BRAKING ON THE DIFFERENT ROAD SURFACES

A vehicle is driven along various road surfaces. Sometimes a situation occurs when there are places on the road fit for traffic where the coefficient

of cohesion of the surfaces with the wheels is different ([11] to [18]). For example, the surface of the road, fit for traffic, is covered with sand or slush, is coated with ice in certain places, etc. Furthermore, the values of the deceleration of the vehicles and the cohesion coefficients of their wheels while braking on different road surfaces in each definite case will be submitted. Such data are necessary while analysing and modelling the vehicle's movement under various road conditions, while restoring the course of traffic accidents and while carrying out an examination of traffic accidents.

The diversity of road surfaces is vast in winter conditions. For example, the statement that a stretch of the road, fit for traffic, is covered with snow points to almost nothing. It may mean snow that has just fallen; snow that is churned up; snow that is covered with a layer of ice; churned up snow that is covered with sand, etc. Accordingly, the coefficient of cohesion of the wheels with the road surface is different in each case.

Some values of deceleration in winter conditions are included in Table 2. However, sometimes cases that have not been described in the literature

Table 3. *Coefficient of cohesion on snow and ice*

Road surface	More detailed description of the surface condition	Coefficient of cohesion, $\varphi$
Churned up snow	Snow, churned up by vehicles, which does not make a compounded layer of snow and ice	0.24 to 0.37
Non churned snow	Snow that has just fallen on the asphalt and that is not churned up with the wheels of vehicles – the first drive	0.15 to 0.42
Snow and ice, covered with the snow that has just fallen	Churned up snow and ice, covered with a layer of snow (thickness – up to 10 cm), which has just fallen and is not churned up	0.18 to 0.45
Snow and ice, mixed with sand and slush	Churned up snow and ice, mixed with sand and slush, the particles of which are 3 to 6 mm in diameter	Depending upon the quantity of slush (little – much) 0.15 to 0.45
Snow and ice	Entire layer of snow, churned up to reveal the icy surface	0.12 to 0.39
Snow and ice before crossroads	Snow, which first was melted by the motors of the standing vehicles and then frozen to produce a smooth surface	0.09 to 0.22
Deep snow	Deep and non-touched snow when the vehicle "seats itself on the bottom"; however, it does not stick	0.92 to 0.95
Dry asphalt in winter conditions	Dry asphalt (uncovered with anything) in winter conditions	0.59 to 0.72
Asphalt, covered with hoar-frost	White cover on the asphalt, which is observed by the driver and easily recognized as hoar-frost	0.48 to 0.58
Smooth ice	Thick layer of frozen water, not penetrated by spikes and chains	0.054 to 0.19
Ice and tires with chains	Thick non-penetrated layer of frozen water, penetrated by wheels equipped with steel chains	0.12 to 0.18
"Black" ice	Thick ice layer that looks like a wet, black stretch of road, which is fit for traffic, but which is not easily noticed by the driver	0.12 to 0.26



Table 4. Values of deceleration for a vehicle while braking on various non-typical surfaces ([10], [13] to [16])

Road surface	Deceleration
Churned up soil	(0.6 to 0.65) g
Grass	(0.35 to 0.54) g
Sand, gravel (loose – compounded)	(0.4 to 0.7) g
Edge of the road (non-asphalted)	(0.35 to 0.4) g
Slush on a wet surface	(0.2 to 0.3) g

Remark: g is the acceleration due to gravity, m/s<sup>2</sup>.

occur in practice. The values of the coefficient of cohesion on the snow and ice are listed in Table 3. These values pertain to universal tires.

It is a common case that the values of the coefficient of cohesion that are listed in the literature for such cases differ, or their limits are too wide. It is like this because the conditions of the investigation, the type of tires, the model, etc., significantly influence the obtained values. It is known that the snow and ice change their qualities depending upon the temperature. Thus, this fact influences the obtained results.

The values of the deceleration of vehicles while braking along various non-typical surfaces, which are specified in the literature ([10], [13] to [16]), are listed in Table 4.

Sometimes, very unusual surfaces, which are not typical for normal traffic, occur. However, practically (for example, while carrying out the examination of traffic accidents), such data, that may be applied to individual cases, are necessary as well. Thus, Table 5 reflects the deceleration of a vehicle with ABS while braking on wet asphalt, which is covered with grain [17]. The deceleration was measured exactly on the wet asphalt because, from the point of view of traffic safety, such a case is more dangerous because at that time a significant reduction in the deceleration is observed (similar to the braking on the asphalt, which is covered with slush).

Table 6 reflects the deceleration of the automobile while braking on the asphalt, which is covered with motor oil or resin ([11], [13] to [16]).

Table 5. Deceleration of a vehicle with ABS while braking on a wet asphalt surface, covered with a layer of grain [17]

Road surface	Deceleration, m/s <sup>2</sup>
Wet asphalt, covered with a "dry" layer of grain	3.3
Wet asphalt, covered with a "wet" layer of grain	2.9

Interesting results were obtained while investigating the deceleration of a vehicle while braking on a stretch of road, fit for traffic, on which petrol was spilt ([11] and [18]). The dependence of the deceleration on the time (when the surface was drying) was investigated. The results of the investigation prove that the spilt petrol immediately starts to react chemically with the asphalt and creates a very slippery surface, which later dries and acquires the previous coefficient of cohesion. The surface of the stretch of the road, fit for traffic, being wet with water in the place where the petrol was spilt has a slightly smaller coefficient of cohesion. The results of the investigation are listed in Table 7.

The investigation proves that the deceleration of the vehicle with the up-to-date tires when the wheels slide in the transversal direction is close to the value of deceleration while braking on the same surface [19].

#### 4 CONCLUSIONS

1. In the course of braking for vehicles equipped with the ABS, on the dry surface of an asphalt road, the average settled deceleration was within the limits from 8 m/s<sup>2</sup> up to 8.8 m/s<sup>2</sup>; in most cases the deceleration exceeded 9 m/s<sup>2</sup> in the phase of the most efficient braking. The values of the time of the deceleration increase,  $t_s$ , typical for the vehicles equipped with the ABS were within the limits 0.1 to 0.15 s. The values of the time of disbraking,  $t_d$ , did not exceed the time values of

Table 6. Deceleration of the vehicle while braking on asphalt covered with motor oil or resin ([11], [13] to [16])

Road surface	Deceleration
Wet, rough asphalt, on which oil is spilt	(0.25 to 0.3) g
Wet, smooth asphalt, on which oil is spilt	(0.05 to 0.12) g
Resin is spilt on the asphalt	(0.5 to 0.64) g



Table 7. Deceleration of a vehicle while driving across a petrol spill ([11] to [18])

Description of the surface and driving	Time	Deceleration
Driving along dry asphalt without a spill of petrol	—	0.8 g
Driving across the spill of petrol	After 10 s from the moment of spilling the petrol	0.22 g
Repeated driving across the trace	3 min after the spot became dry	(0.60 to 0.34) g (according to the direction of driving)
Repeated driving across the trace	6 min after the spot became dry	(0.80 to 0.54) g (according to the direction of driving)
Driving across the non-driven spill	9 min after the spot became dry	0.56 g
Driving across the completely dried spot	25 min	0.80 g
Driving on the wet asphalt without the spill	—	0.55 g
Driving across the spill of petrol on wet asphalt	50 min after the moment of spilling	0.45 g

the deceleration increase and were within the limits 0.1 to 0.15 s.

- The average settled deceleration of the vehicles without the ABS, while braking on the dry surface of an asphalt road, were within the limits from  $6.9 \text{ m/s}^2$  up to  $7.8 \text{ m/s}^2$ . The values of the time of the deceleration increase,  $t_p$ , were within the limits 0.2 to 0.3 s. The values of the time of disbraking,  $t_d$ , did not exceed the time values of the deceleration increase and were within the limits 0.1 to 0.2 s.
- It was determined that during braking for the vehicles equipped with the ABS the average settled deceleration increases with the increase of the primary speed of the vehicle, whereas in the case of braking for the vehicles without the ABS, it decreases (Figs. 1 and 2). This significant difference, typical of the vehicles equipped with the ABS and the vehicles without it, is reflected in the diagrams of braking (Fig. 3).
- After having carried out the experimental investigation in winter conditions, it was determined that the automobile equipped with the ABS

braked on the ice more efficiently (by approximately 10%). The vehicle without the ABS braked on the snow-covered surface of the road more efficiently (approximately 13%), because in this case the blocked wheels of the vehicle without the ABS contact the wet surface of the asphalt road, and so push and thicken the snow in front of them. However, in any case, the ABS plays a significant positive role in the control of the vehicle as the possibility to drive the vehicle remains.

- The cohesion characteristics and the automobiles' decelerations while braking on different road surfaces are presented. There is a possibility to model the vehicles' movement and to restore the course of the traffic accidents more precisely while carrying out the examination of the traffic accidents. However, it is necessary to use the fixed values of the braking parameters of automobiles while evaluating the technical condition of the particular automobile as in certain cases (for example, dealing with old automobiles) these values may be unsuitable.

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## Authors' Address:

Doc. Dr. Edgar Sokolovskij  
 Doc. Dr. Robertas Pečeliūnas  
 Vilnius Gediminas Technical University  
 Dept. of Automobile Transport  
 J. Basanavičiaus 28, LT-03224  
 Vilnius, Lithuania  
 edgar.sokolovskij@ti.vtu.lt  
 robertas.peceliunas@ti.vtu.lt

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