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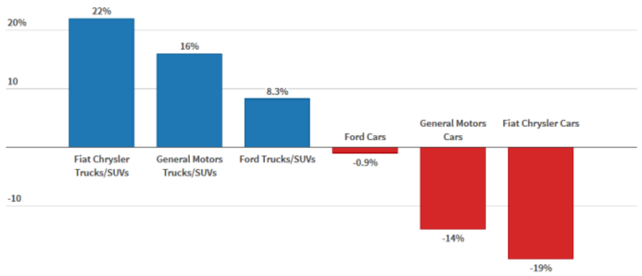
THE INFLUENCE OF THE HIGH ENERGY BRAKE APPLICATIONS ON THE DISC BRAKE PERFORMANCE – ESTABLISHED BY INERTIA BRAKE DYNAMOMETER TESTING

Article describes the dangers resulting in improper brake components choice and using them in an incorrect way. It shows the results of the tests conducted on the Brake Dynamometer test station on three different Sport Utility Vehicles.

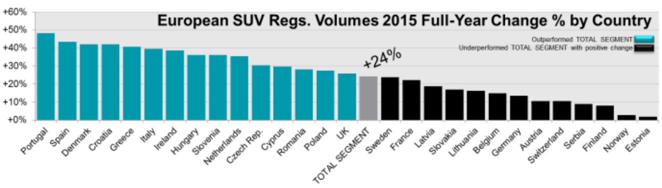
INTRODUCTION

The modern age vehicle users have changed their approach to a passenger family car. Nowadays people are looking for cars that are big, comfortable, spacious, fast, good looking, have nice interior, have powerful drivetrain, have a lot of load space in the boot and are good to look at. Perhaps also the one that is good off-road. The only vehicle type currently made that can join those functions together are the "Sport Utility Vehicles", commonly known as SUVs. SUVs are becoming to be quite popular all over the world, in fact the sales of Trucks and SUVs in the United States of America has increased rapidly over last years. Graph 1 shows the percentage increase of number of Trucks/SUVs sold in the USA and the percentage decrease of sales of normal family cars over last two years.



Graph. 1. *Percentage car sales in the USA in 2014 and 2015. [1]*

Also in Europe the market for Sport Utility Vehicles has grown over last years, in case of some countries the overall increase in SUVs sales increased by nearly 50%. Graph 2 shows the increase in SUVs sales in European countries in 2015.



Graph. 2. *Percentage increase of SUVs sales in European countries in 2015. [2]*

But uniting so many vehicle traits on one base has its drawbacks. Rising the car body has a dramatic effect on the vehicle centre of gravity which is located much higher compared to other passenger car types. Also SUVs have larger wheel base, suspension, steering system, engine, gearbox, body, brakes and interior elements which causes the vehicle mass to be bigger as well and because of the larger space in the cabin and a larger boot space the overall gross weight of the car is much more bigger than of conventional vehicle types. All this means that the SUV type of vehicles had a large mass and a high centre of gravity which meant they have to be fitted with larger brakes in order to stop them in time. Modern SUVs brake systems are much bigger than in normal family saloon or hatchback car and they are exposed to much more heat and load. The purpose of this article is to check if the brake systems of modern Sport Utility Vehicles can cope with breaking conditions they have to face on and off public roads.

1. THE TEST

1.1. The test objects

The tests were conducted on front disc brakes from three selected Sport Utility Vehicles: The BMW X6, Volvo XC-60 and Mercedes-Benz ML500. The choice was based on finding the vehicles with large permissible weight and top speed, so the chosen versions of the cars have large and powerful petrol engines. The basic data of the selected vehicles comparison is shown in the table number 1.

Tab. 1. *Test vehicles.*

Make	BMW	Volvo	Mercedes-Benz
Model	X6 I (E71)	XC60	ML500 (W164)
Year	2008-2014	2010-	2007-
Version	50i XD	3.2 AWD	ML 500
Engine	4.4 litres V8	3.2 litres R6	5.5 litres V8
Power [kW/km]	300/406	179/243	285/388
Torque [Nm]	600	320	530
Vmax [km/h]	250	210	250
Gross weight [kg]	2 840	2 430	2 830
Rolling radius	364	360	369
Inertia [kg·m^2]	149	128	148

For every tested brake, three different friction material was used, the Original Equipment and two Aftermarket compounds. The Original Equipment will be referred to as "OE" and the Aftermarket ones will be marked as "AM1" and "AM2".

1.2. The testing equipment

The tests were performed on an Inertia brake Dynamometer LINK model M3000. The Dyno is shown on picture 1.

Picture. 1. *The LINK M3000 Inertia Brake Dynamometer.*

The dynamometer allows to test the drum and disk brake systems in real scale in range of functional tests and durability:

- friction material: brake pads and shoes
- brake drums
- solid and ventilated brake discs of each type and material.

The test bench is adapted to test:

- Conventional hydraulic systems
- Electro-hydraulic systems (SBC)
- Electro-mechanical systems (EBM)
- Hybrid brakes

Technical specification and capabilities of the Dyno are shown in table 3.

Tab. 3. *The LINK M3000 specification.*

DC Drive Motor Power	186 kW
Speed range	0 ÷ 2500 rpm
Maximum braking torque	5650 Nm
Minimum simulated inertia	5 kgm^2
Minimum mechanical inertia	42,7 kgm^2
Maximum mechanical inertia	128 kgm^2
Maximum simulated inertia	250 kgm^2
Maximum brake pressure	200 bar
Maximum pressure ramp rate	1000 bar/sec

1.3. The test procedure

The purpose of the test was to put disc brakes under influence of high energy brake applications to check the influence on their performance. The test procedure was similar to “High Load Test” from UN ECE regulation No. 90 [3]. For every test vehicle, each friction material compound was subjected to a series of 20 brake cycles with test parameters shown in table 1. Before the test every brake pad and disc set was properly burnished, the burnish procedure contained 200 brake application from 80 kph to 20 kph with the deceleration of 2 m/s^2 with initial brake temperature approximately 100°C. This burnish procedure guarantees the friction contact area between brake disc and pad of about 90 – 95%.

Tab. 2. *Test parameters.*

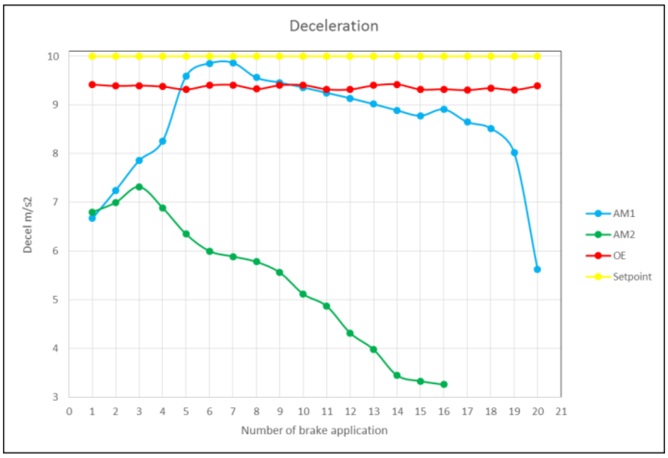
Parameter	Value
Number of cycles	20
IBT (Initial brake temperature)	100°C
FBT (Final brake temperature)	open
Initial speed	Vmax
Final speed	10 km/h
Deceleration	10 m/s^2 (1g)
Cooling air speed	0,33 * Vmax
Cooling air temperature	15°C +/- 2°C

For every test cycle the following signals were measured: Braking torque, rotational speed of the brake disc, temperature of the disc and the pressure in the brake system. Based on those signals and on the geometry of the brake disc and the brake calliper the friction coefficient was also calculated. Also the wear of the brake pads was measured. There was a brake fluid pressure limit set to 160 bar, because it is hard to get more in a normal car.

2. THE TEST RESULTS

2.1. Deceleration

The results are in form of graphs, the yellow line shows the required by the test deceleration value (set point), the results for the first Aftermarket parts are shown in blue, Aftermarket 2 in green and red for the Original Equipment. The results of the tests for the BMW X6 are shown on graph 3.



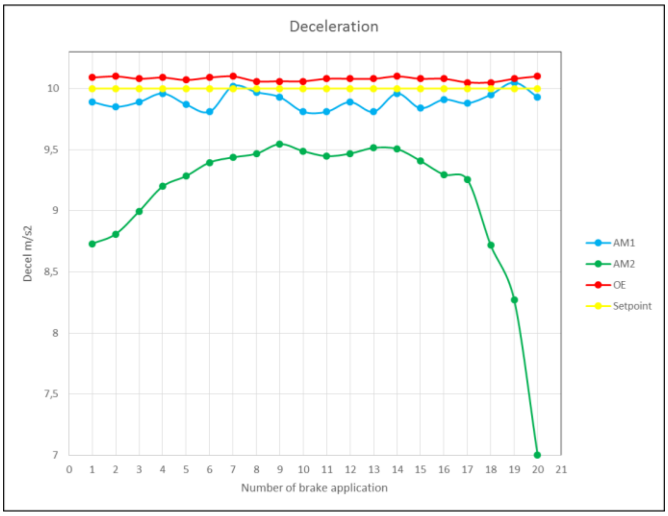
Graph. 3. *The results of the measured deceleration for BMW X6.*

The first Aftermarket brake pads needed a few cycles to reach the required by the test deceleration level. Unfortunately they have done only 4 cycles within that range, from then their performance began to decrease slightly up to the point when they have reached 8m/s^2 , at this point the performance dropped rapidly to about 5,5m/s^2 because the pads were at the end and reached the glue layer.

The second Aftermarket pads did not cope well with the test conditions. They started up with reaching about 7m/s^2 for about 4 cycles, but from then the performance was fading dramatically up to cycle number 16 on which the deceleration level has dropped to 3,2 m/s^2 which is 68% less that the required deceleration level of 1g. The pads were completely worn out at this stage and could not continue the test to reach the required 20 test cycles.

The Original Equipment brake pads performance was very stable and efficient. These pads have reached about 9,5m/s² in pretty much every test cycle. It was less than the required 1g but it was very consistent.

The results of testing the Volvo XC60 are shown on graph 4.



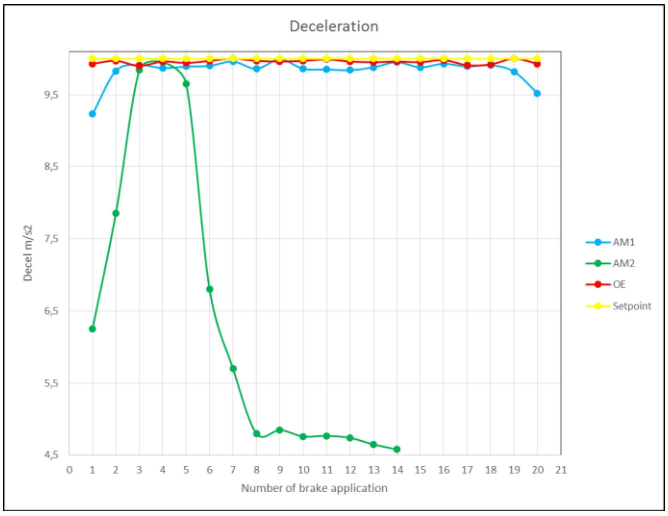
***Graph. 4.** The results of the measured deceleration for Volvo XC60.*

The first Aftermarket friction material was nearly reaching the required deceleration level, but it was a bit unstable.

The second Aftermarket friction compound begun the test from 8,7m/s² with increasing braking torque up to reaching about 9,5m/s². At this moment it has stabilised for 8 test cycles up until reaching cycle number 17 when the performance has decreased rapidly reaching 7m/s², the pads were nearly at the end when the test finished.

The Original Equipment pads have performed perfectly. They have reached 10,1m/s² in every test cycle showing perfect stability and consistency.

The results of testing the Mercedes-Benz ML500 are shown on graph 5.

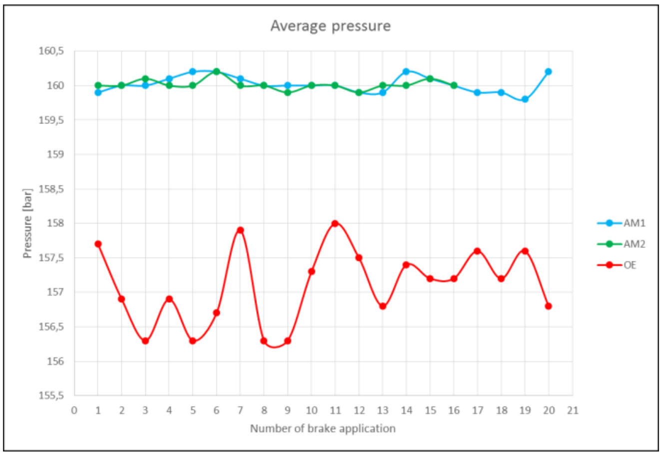


***Graph. 5.** The results of the measured deceleration for Mercedes-Benz ML500.*

The OE friction material has performed ideally, matching the required deceleration level in every brake cycle. The Aftermarket friction material number 1 has also performed really good. It only had slight deviation from the setpoint on the beginning and at the end of the test. As for the AM2 material, it has burned itself completely during the course of the test and after reaching the set point value for 3 cycles the performance has dropped rapidly and significantly up to around 4,5m/s² .This brake torque level is dangerously low and it might cause a seriously dangerous situation on the road if it was fitted to an actual road vehicle.

2.2. Brake Fluid Pressure

The results are shown in graphs, the results for the first Aftermarket pads are shown in blue, Aftermarket 2 in green and red for the Original Equipment. The results of the tests for the BMW X6 are shown on graph 6.

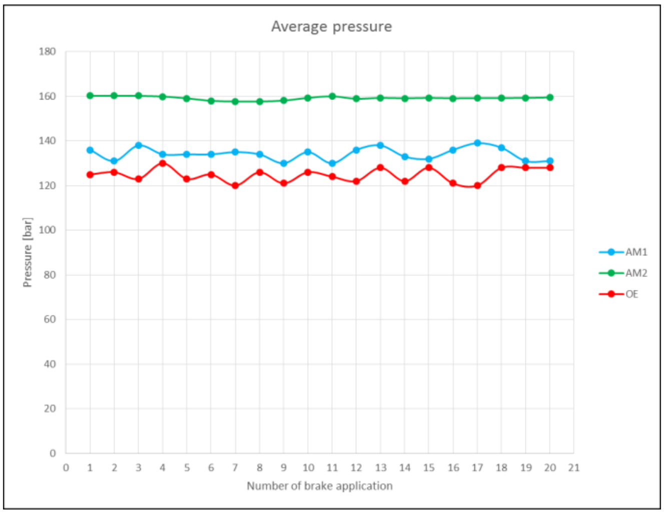


***Graph. 6.** The results of the measured brake fluid pressure for BMW X6.*

Both Aftermarket brake friction material have reached the maximum 160 bar of brake fluid pressure that the Dynamometer brake servo was limited to, and it was for all of the test cycles. That means they have difficulties with reaching the required deceleration values.

For the OE Brake pads the pressure is below the 160 bar limit fluctuating between 156 and 158 bar.

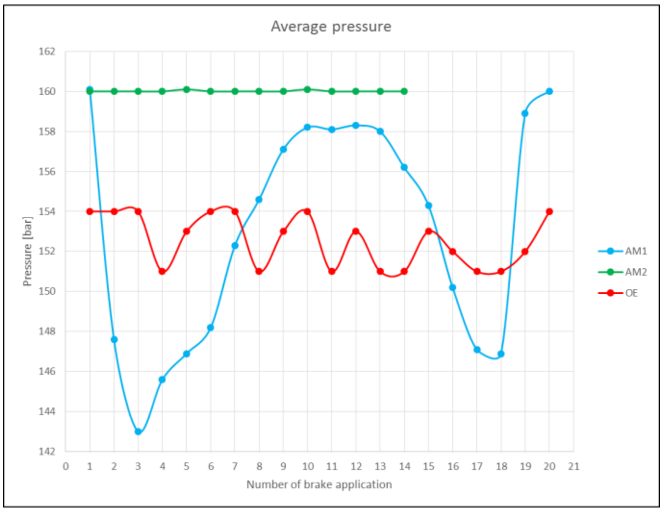
The results of the tests for the Volvo XC60 are shown on graph 7.



Graph. 7. The results of the measured brake fluid pressure for Volvo XC60.

Due to difficulties with reaching the required deceleration level the Aftermarket 2 pads are using all available pressure therefore reaching the limit of 160 bar. The AM1 material requires about 135 bar in order to achieve the setpoint. OE friction material uses 125 bar. The AM1 and OE are quite stable with pressure usage.

The results of the tests for the Mercedes-Benz ML500 are shown on graph 8.

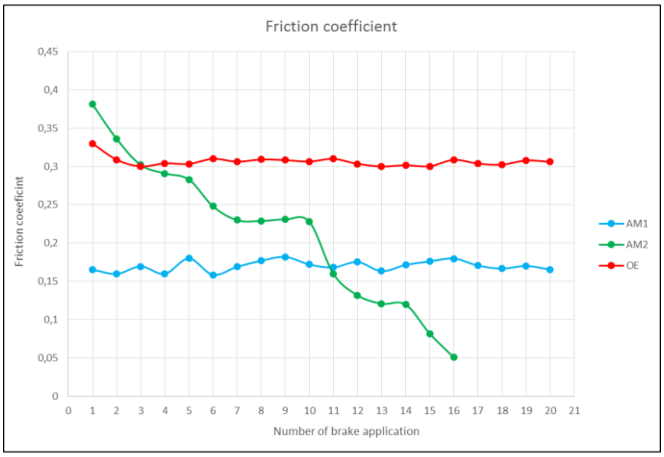


Graph. 8. *The results of the measured brake fluid pressure for Mercedes-Benz ML500.*

The Aftermarket 2 material is once again reaching the brake fluid pressure limit at 160 bar for all test cycles. The Aftermarket 2 brake pads have very irregular brake fluid pressure curve, at first stage it is dropping by about 18 bar then it rises to about 158 bar and stabilises for a couple of cycles then it decreases again and rises at the end of the test. The OE pads have quite stable brake fluid pressure, oscillating from 151 to 154 bar.

2.3. Friction coefficient

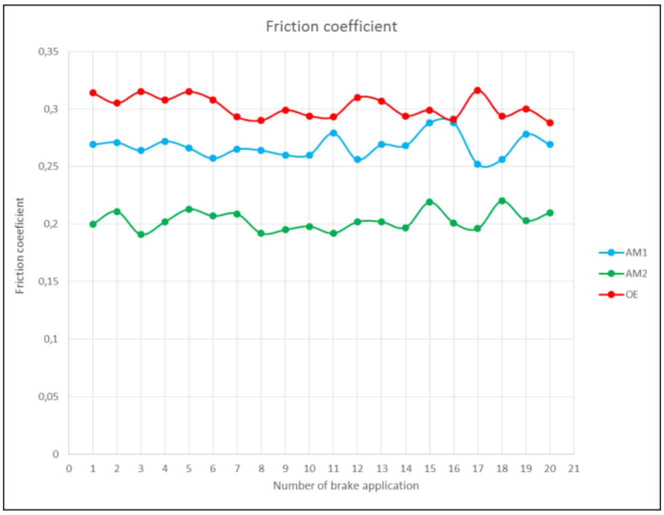
The friction coefficient results are shown in graphs below, the results for the first Aftermarket pads are shown in blue, Aftermarket 2 in green and red for the Original Equipment. The results of the tests for the BMW X6 are shown on graph 9.



Graph. 9. *The results of the friction coefficient for BMW X6.*

The first AM pads has quite stable friction coefficient but their values are low, around 0,17, considering it is at the pressure limit and that for the most of the test cycles it is struggling to achieve the required deceleration level the performance of this brake pads is considered to be not good at all. The Aftermarket 2 friction material is beginning with the highest friction coefficient of all but it is dropping quite fast to an alarming value of 0,05 for which it has reached only 4,5 m/s^2 and that is far from setpoint. The Original Equipment brake pads have very consistent friction coefficient values, also the average is the highest of all three. The performance of those pads is very high.

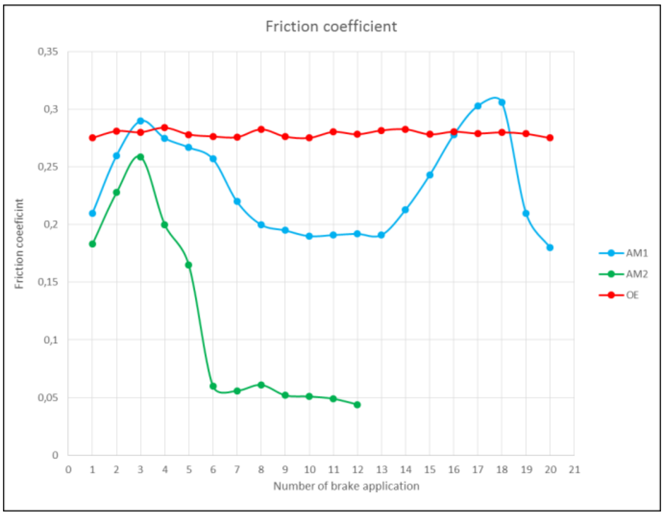
The results of the tests for the Volvo XC60 are shown on graph 10.



Graph. 10. *The results of the friction coefficient for Volvo XC60.*

For the Volvo XC60 all of the pads have quite stable friction coefficient but their values are different. The AM1 pads are in the middle reaching the average friction coefficient 0,275. AM2 are reaching the average of about 0,2. The best results were obtained on the Original Equipment brake pads reaching about 0,3.

The results of the tests for the Mercedes-Benz ML500 are shown on graph 11.

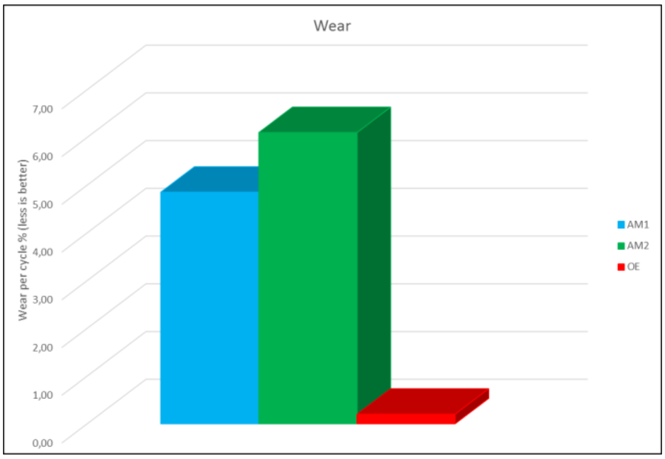


Graph. 11. *The results of the friction coefficient for Mercedes-Benz ML500.*

Aftermarket 1 pads have very irregular friction coefficient changing within 20 cycles by about 0,12. Aftermarket 2 samples are reaching 0,26 for one cycle at the beginning of the test only to drop rapidly to about 0,05 for the most of the test. This figure I alarmingly low. The best result was obtained on OE pads. The friction coefficient values are very stable and reaching an average of about 0,28.

2.4. The influence on Wear

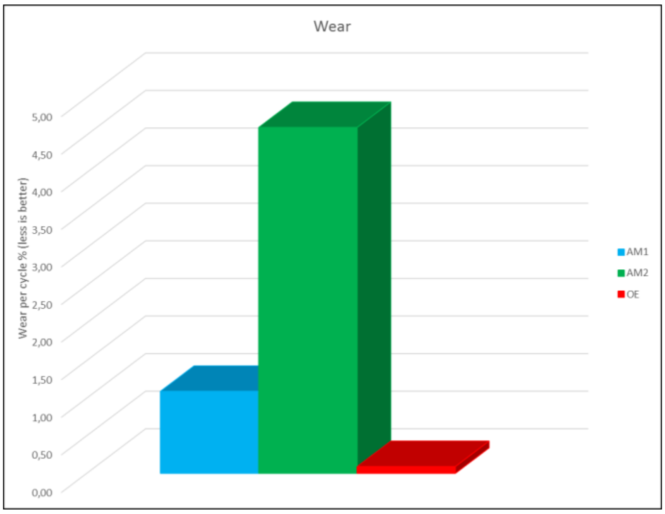
The wear measurement of the pads are shown below, the results for the first Aftermarket pads are shown in blue, Aftermarket 2 in green and red for the Original Equipment. The results of the tests for the BMW X6 are shown on graph 12.



Graph. 12. *The results of wear for BMW X6.*

Both AM1 and AM2 have ware out completely during the course of the test, while the Original Equipment pads were barely worn. Aftermarket 1 pads have achieved 4,85% of wear per single test cycle which after 20 cycles gives a complete wear of 97%. AM2 pads have achieved 6,1% of wear per one brake application which after 16 cycles gave 97,6% of overall pad wear, for that reason the pads could not proceed and therefore the test was finished. The best wear result was obtained on the OE pads which have achieved only 0,2% of wear per single brake application therefore during the whole test the OE pads have worn only by 4%.

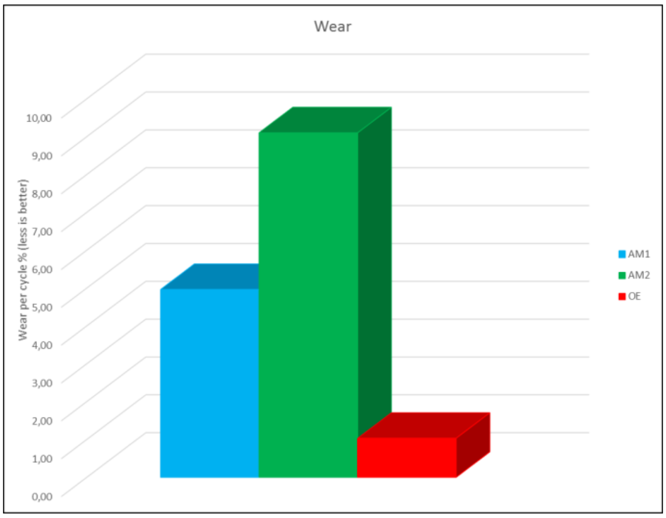
The results of the tests for the Volvo XC60 are shown on graph 13.



Graph. 13. *The results of wear for Volvo XC60.*

During testing the Volvo XC60 brake the only friction material that have worn totally was the Aftermarket 2 pads. They have reached 4,6% of wear per one cycle giving 92% of overall wear. Aftermarket 1 pads have achieved 1,09% of wear per one brake application which results in 21,8% pad wear. The OE material again resulted the best in test, scoring only 0,09% of wear per cycle for overall wear of 1,8%.

The results of the tests for the Mercedes-Benz ML500 are shown on graph 14.



Graph. 13. *The results of wear for Mercedes-Benz ML500.*

The OE has once again resulted much better that the Aftermarket friction compounds, with 1,03% of wear per cycle it has resulted in 20,6% of overall wear. Aftermarket 1 has achieved 4,96% of wear which gave 99,2% of total wear. AM2 have done 7,1% of wear per single brake application giving for 14 cycles the total wear of 99,4%. The AM1 and AM2 have wear out entirely.

2.5. The results summary

The Original Equipment brake friction material was the best performing compound. It did not have many difficulties to achieve the required deceleration level in pretty much all of the tests. While testing BMW X6 it had the average of 9,4 m/s^2 which is a very satisfying result while in case of testing other two vehicles it has reached the required 1g easily. Despite achieving 10m/s^2 in pretty much every test brake application the OE brake pads did not required much of the brake fluid pressure. For BMW X6 the average was 157 bar, for Volvo XC60 – 125 bar and for the Mercedes-Benz ML500 about 152 bar. Friction coefficient is stable and consistent during all of the tests and the average values are higher than the other two compounds. The biggest advantage of the OE brake pads is the wear which is the smallest in every test, and a lot smaller. When AM compounds are achieving 1 – 9% of wear per cycle, the OE has only 0,09 – 1% of wear per single brake application. After the tests the OE pads were worn only in about 1 to 20% when Aftermarket pads were usually worn out entirely. The Original Equipment brake pads are unquestionably the best tested friction material in every way.

The Aftermarket 1 brake pads compound is coping with the tests rather good, but has its problems. The deceleration level is satisfying in most of the test cycles, only for BMW X6 it is struggling at the beginning and at the end of the test, but it is still acceptable. But AM1 needs a lot more brake fluid pressure to achieve required deceleration level. While testing the BMW X6 the pressure was reaching the limit at all times. In other two tests it was quite near the limit. The friction coefficient is stale in most cycles but the overall values are lower than OE pads. In the BMW X6 test the friction coefficient values are almost half of those achieved on the OE compound. During the Mercedes-Benz ML500 test the friction coefficient is very chaotic which shouldn't happen because at every brake application the brake requires different brake pressure to achieve the same level of deceleration, which may be confusing for the vehicle driver. The Aftermarket 1 pads were worn completely after every test except the Volvo XC60 test when it has reached about 22% of overall wear. The overall performance of the compound is quite good in comparison with the OE.

Aftermarket 2 is the friction material that has the most confusing behaviour. It is struggling heavily to achieve the required by the test specification deceleration level, it has dropped to 3,2 m/s^2 in the BMW X6 test which is alarmingly low considering the required 10m/s^2 setpoint. The performance in the Volvo XC60 is a bit better, the pads have achieved the 9,5m/s^2 marker but only for 8 cycles and then it is fading rapidly. The worst performance by AM2 was in Mercedes-Benz ML500 test during which the pads have achieved the 10 m/s^2 for only 2 brake applications to fade dramatically after up to about 4,5m/s^2. The AM2 pads are constantly using all available brake fluid pressure which is 160 bar for this test, this means it requires more to gen near the setpoint decel. Friction coefficient was stable only while testing the Volvo XC60, but the average level was disturbingly low, about 1,2 lover then the OE and about 0,7 lover than AM1. For other two tests the friction coefficient is rapidly decreasing from the beginning of the test until reaching around 0,05. This value is unacceptably low, and probably dangerous in an actual car. The wear is also the weak point of the AM2 brake pad. It has wear out entirely in every test, in some cases it did not even reach 20 test cycles, achieving 16 cycles for the BMW and only 14 for Mercedes-Benz for which the wear per cycle was the largest – 7,1%. The overall performance of this friction material is very low. Compared to other two it is significantly worse in every test point.

SUMMARY

The conducted tests aim was to check how the brake applications with high deceleration level influence the performance of different friction compounds and how they can affect the safety of the public road users. The tested Original Equipment and the Aftermarket 1 parts have coped with the test conditions quite well and in most conditions can assure the vehicle driver and passengers their safety. As for the Aftermarket 2 compound, the results are really disturbing. It does not achieve the desired deceleration level and when it does it is fading rapidly and dramatically, then it needs a very high pressure values which can be hardly achieved in an actual vehicle. Friction coefficient is very low at most times and they wear out almost immediately. This pad compound is very sensitive to high load and temperature and can be easily destroyed. The conducted tests have proved that the brake can be brought to a condition that it simply will stop decelerating the vehicle. Also the performance of this friction material is dropping back so rapidly that it can totally catch the driver by surprise. This situation might be very dangerous for the vehicle driver, passengers and other public roads users. And because the Sport Utility Vehicles are getting more popular with every day the problem might become serious in the near future.

BIBLIOGRAPHY

1. http://www.ibtimes.com/
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3. UN ECE Regulation No. 90. , *Uniform provisions concerning the approval of replacement brake lining assemblies, drum brake linings and discs and drums for power driven vehicles and their trailers,* Geneva 2011.

Wpływ hamowania z dużą energią na hamulec tarczowy – określone poprzez badania na stanowisku dynamometrycznym do badań hamulców

Artykuł opisuje zagrożenia związane z niewłaściwym doborem komponentów hamulca oraz z użytkowania hamulców w niewłaściwy sposób. Pokazuje wyniki badań hamulców z trzech pojazdów samochodowych typu SUV wykonanych na stanowisku dynamometrycznym do badań hamulców.

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