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MEASUREMENTS AND ANALYSES OF LATERAL ACCELERATION IN TRAFFIC OF VEHICLES

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Subject review

Accelerations and braking are needed in traffic to allow a vehicle to travel from one place to another. Also present during the drive are lateral accelerations, which are active in curves. The accelerations and braking active during the drive are usually in the range of one fifth to one third of maximum value. In critical and unexpected situations, the accelerations and braking are increased up to maximum values. Maximum values of acceleration and braking depend on roughness of ground, type of ground, quality of tires, quality of vehicle brakes, etc. Because of critical and unexpected situations, there are many accidents on the roads. In these cases, accelerations or braking reach their limit values and many times the vehicle becomes uncontrollable. In this paper the system for measurement and analyses of accelerations and braking in traffic of vehicles is presented. These systems are necessary for analyses of different accidents in traffic and to define maximal longitudinal accelerations, maximal lateral accelerations and maximal braking in different situations. Also presented in this article are practical measurements and analyses of maximal accelerations and braking for selected cars, which were measured on a straight road, and comparisons of these measurements with the producer data and accelerations and braking measured on a racetrack.

Keywords: *accelerations, analyses, braking, lateral acceleration, longitudinal acceleration, measurement*

Mjerenje i analiza bočnog ubrzanja u prometu vozila

Pregledni članak

Ubrzanja i kočenja su potrebna u prometu kako bi se omogućilo vozilu da putuje iz jednog mjesta na drugo. Tijekom vožnje prisutna su bočna ubrzanja, koja djeluju u zavojima. Ubrzanja i kočenja prisutni tijekom vožnje su obično u rasponu od jedne petine do jedne trećine maksimalne vrijednosti. U kritičnim i neočekivanim situacijama, ubrzanja i kočenja se povećavaju do maksimalne vrijednosti. Maksimalne vrijednosti ubrzanja i kočenja ovise o hrapavosti tla, tipa tla, kvalitete guma, kvalitete kočnice vozila, itd. Zbog kritičnih i neočekivanih situacija, postoje mnoge nesreće na cestama. U tim slučajevima, ubrzanja ili kočenja dostižu granične vrijednosti i mnogo puta vozilo postaje nekontrolirano. U ovom radu prikazan je sustav za mjerenje i analizu ubrzanja i kočenja u prometu vozila. Ti sustavi su neophodni za analize različitih nesreća u prometu i definiranju maksimalnih ubrzanja, maksimalnih bočnih ubrzanja te maksimalne vrijednosti kočenja u različitim situacijama. U ovom članku su također prikazana praktična mjerenja i analize maksimalnog ubrzanja i kočenja za odabrane automobile, koje su izmjerene na ravnoj cesti, te usporedbe tih mjerenja s podatcima proizvođača i ubrzanja i kočenja izmjerenih na pisti.

Ključne riječi: *analize, bočno ubrzanje, kočenje, mjerenja, ubrzanja, uzdužni ubrzanje*

1 Introduction
Uvod

Accelerations and braking of vehicles can be measured and analyzed with different systems and software. In our case, we used the system G-Tech Pro Performance Meter RR w and Performance Analysis System Software (PASS). This system enables measurements of longitudinal accelerations, lateral accelerations and braking. PASS software has two options, the first is Drag Runs, which is designed for the analyses of acceleration and braking on a straight road with 400 m for acceleration and a part for braking. The second option is Road Race Sessions, which is designed for the analyses of accelerations and braking of drive. Second option enables the analyses of longitudinal accelerations, lateral accelerations and braking.

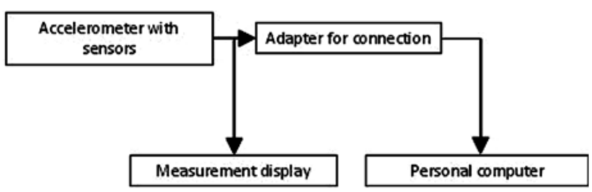

Figure 1 *Scheme of the measuring chain for the measurement system G-Tech Pro Performance Meter RR w*
Slika 1. *Prikaz mjernog lanca u mjernom sustavu G-Tech Pro Performance Meter RR w*

Before starting to measure, the system has to be properly installed in a vehicle. The system can be installed with a special holder on the windshield or on the dashboard

Figure 2 *Measurement system G-Tech Pro Performance Meter RR w and PASS software with all necessary equipment (holders, charging equipment, equipment for connection to personal computer, etc.)*
Slika 2. *Mjerni sustav G-Tech Pro Performance Meter RR w i PASS softver sa svom potrebnom opremom (držači, punjači, oprema za spajanje na osobno računalo, itd.)*

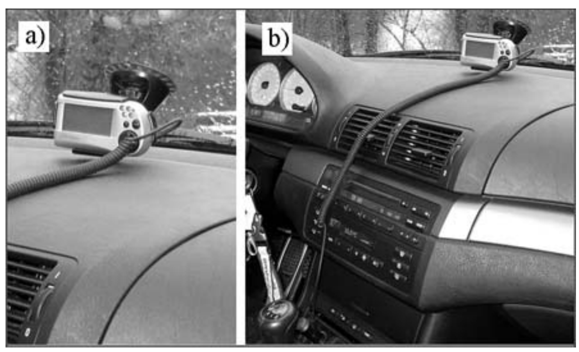

Figure 3 *Mounted measurement system G-Tech Pro Performance Meter RR w in vehicle, a) the system with holder on the windshield, b) the system with charging equipment*
Slika 3. *Instalirani sustav za mjerenje G-Tech Pro Performance Meter RR w u vozilu, a) sustav s nosačem na vjetrobranskom staklu, b) sustav s opremom za punjenje*

with an inflexible holder. The latter holder is more rigid, therefore, it enables better mounting of the measurement system and more precise adjustment of zero bases. After mounting the measurement system has to be calibrated, all shown accelerations on the measurement system should be on standing position of vehicle equal to zero, also revolutions per minute (RPM) of engine have to be equal to the shown RPM on measurement system.

Fig. 1 presents a scheme of the measurement chain, in Fig. 2 is a measuring system with all the necessary equipment and in Fig. 3 is an example of installation of the measuring system in a vehicle.

When finished with the measurements, it is possible to check the results on the measurement system or download them to a personal computer with serial connection. Measurements can be analyzed with the software PASS. This software can show graphs of different data like accelerations, braking, velocities, lengths, times, horsepower (HP), torque (TQ), etc. and different calculations which are shown in the tables.

2 Measurements and analysis with drag runs option
Mjerenja i analize s opcijom prikupljanja pokreta

Option Drag Runs in software PASS is designed for analyses of acceleration and brake on straight road. This option has the possibility to represent different graphs and data. It is also possible to represent data in different units (US mode or metric mode). Different possibilities of option Drag Runs are:

- reaction, time to drive a defined distance (20 m, 100 m, 300 m), time and achieved speed at the defined distance (200 m and 400 m) and time to accelerate from 0 km/h to 100 km/h,
- HP and TQ vs. RPM (graph, maximum HP and maximum TQ at RPM),
- HP vs. time,
- RPM vs. time,
- speed vs. time (graph, acceleration (0÷40 km/h,…, 0÷240 km/h), passing (40÷80 km/h,..., 100÷140 km/h and zero-speed-zero (0÷100÷0 km/h, 0÷160÷0 km/h and 0÷MAX÷0 km/h)),
- acceleration vs. time,
- travelled distance vs. time,
- braking (graph (speed vs. distance), braking distances (20÷0 km/h,…, 260÷0 km/h) and braking distance intervals (80÷40 km/h,…, 140÷100 km/h).

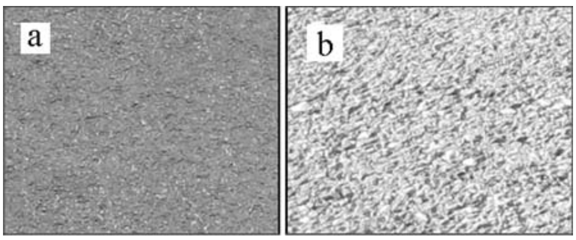

Figure 4 *a) The asphalt on which maximal acceleration and braking were measured (average grain size 5 mm), b) the asphalt on which acceleration and braking were measured (average grain size 11 mm)*
Slika 4. *a) asfalt na kojem su mjerena maksimalna ubrzanja i kočenja (prosječna veličina zrna 5 mm), b) asfalt na kojem su mjerena ubrzanja i kočenja (prosječna veličina zrna 11 mm)*

2.1 Practical measurements, analysis of longitudinal accelerations and comparison with the producer data
Praktična mjerenja, analiza uzdužnih ubrzanja i usporedbe s podacima proizvođača

The tested vehicle had summer tyres Pirelli P Zero Corsa. Front 225/45 ZR 18, rear 255/40 ZR 18. The asphalt was dry (Fig. 4).

Data for tested vehicle

Tested vehicle was 2001 BMW E46 M3.

Table 1 *General data*
Tablica 1. *Opći podaci*

Make	BMW
Model	2001 E46 M3
Power Train Layout	Front Engine / RWD

RWD (rear wheel drive)

Table 2 *General engine data*
Tablica 2*. Opći podaci o motoru*

Configuration	Inline 6
Valve Train	DOCH, 4 valves / Cyl.
Displacement	3246 cm^3
Power	343 hp at 7900 rpm
Torque	365 Nm at 4900 rpm

Table 3 *Chassis and body*
Tablica 3. *Karoserija i tijelo*

Engine Location	Front
Engine Alignment	Longitudinal
Steering	Rack and Pinion / Power Assist
Turning Circle	11 m
F / R Wheels	8J x 18 / 9J x 18
F / R Tyre Sizes	225/45 ZR 18 / 255/40 ZR 18
Brake Types	Vented Disc / Vacuum Assist / ABS
F / R Brake Size	325 mm / 328 mm

F / R (front / rear),
ABS (anti-lock braking system)

Table 4 *Performance*
Tablica 4 *Svojstva*

0÷60 mph	4,8 s
0÷100 km/h	5,2 s
0÷100 mph	11,5 s
Standing ¼ Mile	13,4 s @ 107 mph
Standing 1 km	23,7 s @ 224 km/h
Top Speed	249 km/h
Lateral Acceleration	0,91 g
Fuel Consumption	17,8/8,4/11,9 l/100 km Urban / Extra Urban / Overall
CO_2 Emission	287 g/km

2.1.1 Measurements and analysis of longitudinal accelerations
Mjerenja i analiza uzdužnih ubrzanja

The longitudinal acceleration of the vehicle depends on available drive force and the force between wheel and ground.

Maximal drive force F_d depends on maximal available instantaneous torque T_{emax}, gear ratio i_{gi}, final drive ratio i_0, transmission efficiency μ_t and dynamic radius of tyre r_d (1).

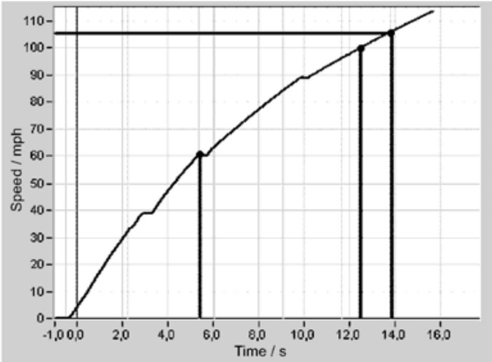

Figure 5 *Graph of speed (mph) vs time (s) for the test vehicle*
Slika 5 *Grafikon brzina (mph) u odnosu na vrijeme (s) za test vozilo*

Acceleration				
0-30	2,060s	----	----	----
0-40	3,400s	----	----	----
0-50	4,282s	----	----	----
0-60	5,354s	----	----	----
0-70	6,981s	----	----	----
0-80	8,427s	----	----	----
0-90	10,383s	----	----	----
0-100	12,480s	----	----	----
0-110	14,793s	----	----	----

Figure 6 *Results of measurement of longitudinal acceleration (0÷60 mph and 0÷100 mph)*
***Slika 6**. Rezultati mjerenja uzdužnih ubrzanja (0÷60 mph 0÷100 mph)*

Reaction	
60 ft	2,238s
330 ft	6,047s
1/8 mi	9,086s @ 84,27mph
1000 ft	11,652s
1/4 mi	13,810s @ 104,99mph
0-60	5,354s

Figure 7 *Results of measurements of reaction (standing 1/4 mile)*
***Slika** 7. Rezultati mjerenja reakcije (stojeći 1/4 milje)*

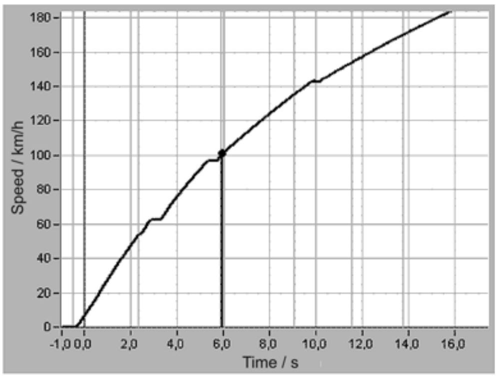

Figure 8 *Graph of speed (km/h) vs. time (s) for the test vehicle*
***Slika 8**. Grafikon brzina (km/h) u odnosu na vrijeme (s) za test vozilo*

Acceleration				
0-40	1,623s	----	----	----
0-60	2,734s	----	----	----
0-80	4,255s	----	----	----
0-100	5,909s	----	----	----
0-120	7,624s	----	----	----
0-140	9,533s	----	----	----
0-160	12,366s	----	----	----
0-180	15,259s	----	----	----

Figure 9 *Results of measurement of longitudinal acceleration (0÷100 km/h)*
***Slika 9.** Rezultati mjerenja uzdužnih ubrzanja (0÷100 km/h)*

Reaction	
20 m	2,355s
100 m	6,027s
200 m	9,056s @ 135,30km/h
300 m	11,540s
400 m	13,761s @ 170,04km/h
0-100	5,906s

Figure 10 *Results of measurements of reaction*
***Slika 10.** Rezultati mjerenja reakcije*

$$F_{\mathrm{d\,max}} = \frac{T_{\mathrm{e\,max}} \cdot i_{\mathrm{gi}} \cdot i_0 \cdot \eta_{\mathrm{t}}}{r_{\mathrm{d}}}. \qquad (1)$$

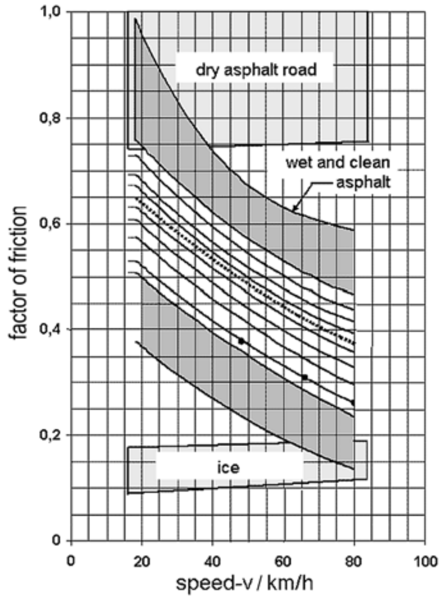

Figure 11 *Factor of friction for different ground vs. speed*
***Slika 11.** Faktor trenja za različita tla u odnosu na brzinu*

Maximum force between wheel and ground F_{wmax} depends on the wheel load Q_1 and factor of friction μ_{f} [2].

$$F_{\mathrm{w\,max}} = Q_1 \cdot \mu_{\mathrm{f}}. \qquad (2)$$

2.1.2
Comparison of measurements and producer data
Usporedba mjerenja i podataka proizvođača

Between the data measured in this experiment (longitudinal acceleration and reaction) and the data provided by the producer there are relatively small differences. The relative difference is smaller if it is necessary to achieve higher speed. In reaction (standing ¼ mile), producer data for achieved speed is 107 mph, while measured speed was 104,99 mph, where relative difference is less than 2 %. All absolute and relative differences are shown below in Tab. 6.

Table 5 *Provided producer data and measurements of longitudinal accelerations*
***Tablica 5**. Podatci proizvođača i mjerenja uzdužnih ubrzanja*

	Producer data	Measurements
0÷60 mph	4,80 s	5,35 s
0÷100 km/h	5,20 s	5,91 s
0÷100 mph	11,50 s	12,48 s
Standing 1/4 Mile	3,40 s @ 107,00 mph	13,81 s @ 104,99 mph

Table 6 Differences and relative differences of longitudinal accelerations
***Tablica 6.** Razlike i relativne razlike uzdužnih ubrzanja*

	Diff.	Relative Diff.
0÷60 mph	+0,55 s	+11,46 %
0÷100 km/h	+0,71 s	+13,65 %
0÷100 mph	+0,98 s	+8,52 %
Standing 1/4 Mile	+0,41 s @ −2,01 mph	+3,06 % @ −1,88 %

3 Measurements and analysis with the road race session option
Mjerenja i analize s opcijom sekcija ceste

The Road Race Sessions option in software PASS is designed for analyses of the drive longitudinal accelerations, lateral accelerations and braking. This option has the possibility to represent different graphs and data, such as RPM vs. driving time, different accelerations, collective accelerations, etc. The collected data can be represented in different units, US mode or metric mode. It is also possible to compare different measurements, maximum two.

Measurements were carried out on a racetrack with dry asphalt. A comparison was also made with two measurements provided by equal measurement systems, which were measured at the same time.

3.1 Model of lateral acceleration margin
Model granične vrijednosti bočnog ubrzanja

It is supposed that the speed choice strategy of drivers in curves is based on dynamically adjusting the safety margin of lateral acceleration. When entering the given curve, the driver reduces the initial speed to avoid reaching some maximum value in lateral acceleration inside the curve. This maximum lateral acceleration, Γ_{max}, is estimated subjectively by individual drivers, depending on their own driving experience, the road handling performance of their vehicle, road and weather conditions, and a personal level of acceptable risk. The safety margin is taken in case any unexpected deviation in the trajectory should be necessary (e.g., because of steering errors, obstacles, or sudden increase in road curvature). The level of possible course deviation is again estimated by individual drivers in accordance with their own steering skills, dynamic behaviour of their vehicle, and their anticipation of the road layout. This parameter corresponds to a path curvature variation, ΔC_{max}, which the driver accepts when negotiating a curve, and is considered herein as independent of the road curvature [1].

Given these parameters, the strategy of maximum speed choice may be expressed as follows. Inside a curve travelled at speed V, a deviation in path curvature ΔC_{max} would produce a modification of lateral acceleration $\Delta\Gamma = \Delta C_{max} \cdot V^2$ (because, by definition, $\Gamma = C \cdot V^2$). This variation $\Delta\Gamma$ should not exceed the margin $\Delta\Gamma_{max} = \Gamma_{max} - \Gamma$ to avoid reaching the maximum allowed lateral acceleration Γ_{max}. This translates directly into the following inequality [1]:

$$\Gamma < \Gamma_{max} - \Delta C_{max} \cdot V^2. \tag{3}$$

At lower speeds, though, this strategy is plausibly superseded by other physical constraints, such as the limit in steering wheel angle δ_{max}. The corresponding maximum curvature is $C_{max} = \delta_{max}/L$, where L is the wheelbase size of the car. At any given speed V, lateral acceleration is then limited to [1]:

$$\Gamma < \left(\frac{\delta_{max}}{L}\right) \cdot V^2. \tag{4}$$

Lateral acceleration is considered henceforth in right turns as positive and in left turns as negative [1].

3.2 Practical measurements of the drive and analysis with the Road Race Sessions option
Praktična mjerenja i analize pogona s opcijom sekcija

On the racetrack (Automotodrom Grobnik - Croatia) the maximum lateral accelerations, longitudinal accelerations and braking on the straight part of the racetrack and curves were measured. Lateral accelerations were more than three times higher than the prescribed lateral accelerations for usual roads. Next follow some graphs and data of drive measurement on the racetrack.

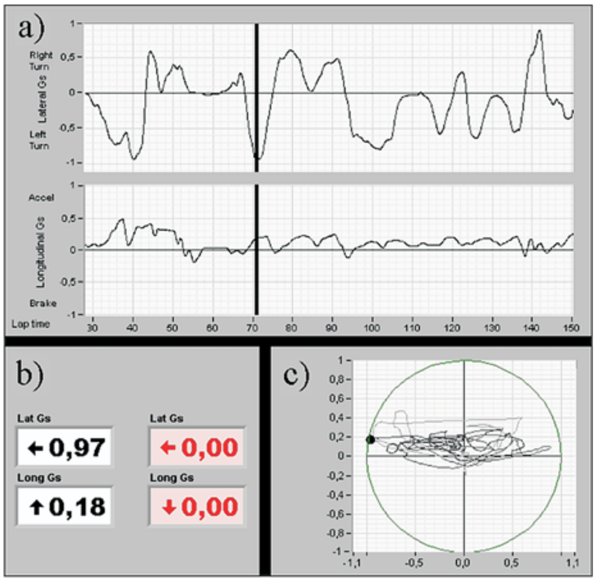

Figure 12 a) The graph of lateral accelerations, longitudinal accelerations and braking vs. driving time, b) data of longitudinal and lateral acceleration, c) the graph of collected acceleration
***Slika 12.** a) Graf bočnih ubrzanja, uzdužna ubrzanja i kočenja, u odnosu na vrijeme vožnje, b) podatci o uzdužnom i bočnom ubrzanju, c) graf prikupljenih ubrzanja*

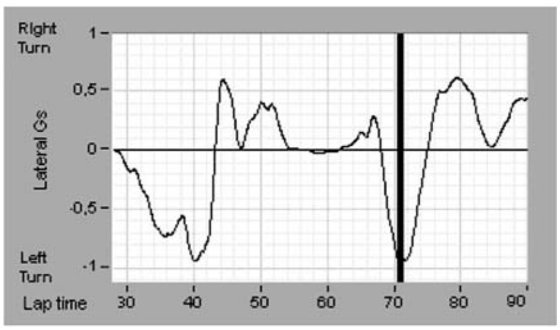

Figure 13 The graph of lateral accelerations vs. driving time
***Slika 13.** Graf bočnog ubrzanja u odnosu na vrijeme vožnje*

From the analysis we obtained the following results: maximal lateral acceleration equals 9,7 m/s^2, longitudinal acceleration equals 4,8 m/s^2 and braking equals 2,0 m/s^2.

Figure 14 *Wear of the used tire after 45 min of driving*
Slika 14. *Istrošenje korištene gume nakon 45 min vožnje*

Prescribed accelerations and braking for usual roads [3]:

- longitudinal accelerations:
  - for a comfortable drive: $a_l \leq 2,65$ m/s^2
  - for an uncomfortable drive: $a_l \leq 3,45$ m/s^2
  - exceptional conditions for drive: $a_l \leq 4,25$ m/s^2
- lateral accelerations:
  - for a comfortable drive: $a_{lat} \leq 2,50$ m/s^2
  - for an acceptable drive: $a_{lat} \leq 3,00$ m/s^2
  - maximal lateral acceleration: $a_{lat\,max} \leq 3,50$ m/s^2
- braking:
  - for passive braking with engine: $a_b = 0,5 \div 0,82$ m/s^2
  - for active braking with brakes: $a_b = 2,94 \div 3,75$ m/s^2.

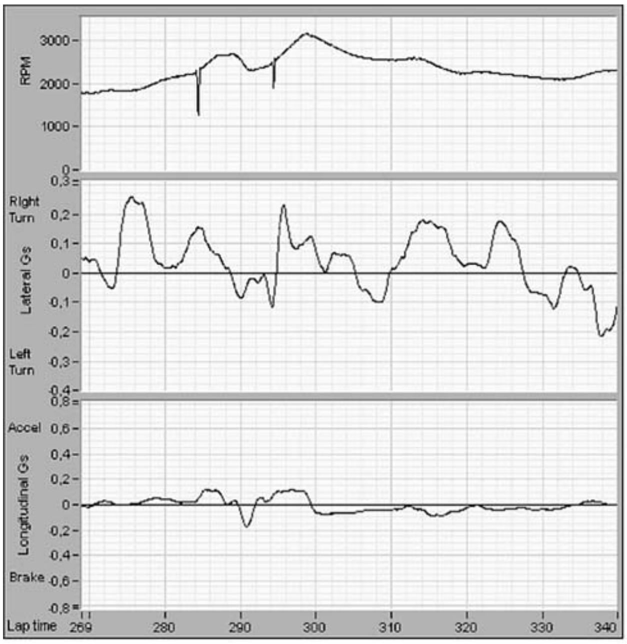

Figure 15 *Graph of RPM vs. driving time, lateral accelerations, longitudinal accelerations and braking of drive where speed limits were considered*
Slika 15. *Grafikon RPM vs vrijeme vožnje, bočna ubrzanja, uzdužna ubrzanja i kočenja promatrano na ograničenu brzinu*

Accelerations on the vehicle during driving where speed limits were considered were also measured in the experiment. Results are presented in Fig. 15. Maximal RPM of the drive was 3200, maximal lateral acceleration was 2,6 m/s^2, maximal longitudinal acceleration was 1,25 m/s^2 and maximal brake was 1,75 m/s^2. All measured data were within the prescribed range.

3.3 Practical measurements of the same drive with two equal measurement systems and comparison of analyses
Praktična mjerenja kod istog pogona s dva jednaka sustava mjerenja i usporedbe

In Fig. 16 below is presented a comparison of two analyses. The graph shows differences in measurements, which were done with two equal measurement systems at the same time. The differences here arise from bad mounting and calibration.

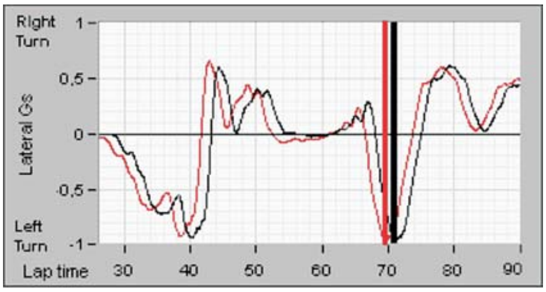

Figure 16 *Comparison of two lateral acceleration analyses*
Slika 16. *Usporedba analiza dvaju bočnih ubrzanja*

Figure 17 *Comparison of two lateral and longitudinal acceleration measurements*
Slika 17. *Usporedba mjerenja dva bočna i uzdužna ubrzanja*

Differences of measurements are in range of 5 %. In this case measurement systems were deliberately badly mounted and calibrated, because the purpose of this measurement was to acquire and define the differences. In other cases with rightly mounted and calibrated measurement systems, the differences would be less than 3 %.

Table 7 *Comparison of provided producer data and measurements of lateral accelerations*
Tablica 7. *Usporedba dostupnih podataka od proizvođača i mjerenja bočnih ubrzanja*

Producer data	Measurements
0,91 g	0,97 g
	0,93 g

Differences between provided producer data and measurements of lateral accelerations are in the range 2,2÷ 6,6 %.

3.4 Influence of calibration on measurements of accelerations
Utjecaj umjeravanja na mjerenja ubrzanja

Vibrations and calibration mistake affect the accuracy of acceleration measurements. First measurement system (red) was well calibrated. All shown accelerations on standing position were equal to zero. Second measurement system (black) was badly calibrated, because the left turn lateral acceleration on standing position was 0,04 g.

Table 8 *Differences of two lateral acceleration analyses, which were done with two equal measurement systems at the same time*
Tablica 8. *Razlike dva bočna ubrzanja, koja su učinjena s dva jednaka mjerna sustava u istom vremenu*

Point	Meas. (1)	Meas. (2)	Diff.	Turn
1	0,71 g	0,75 g	-0,04 g	right
2	0,70 g	0,74 g	-0,04 g	right
3	0,79 g	0,76 g	0,03 g	left
4	0,87 g	0,83 g	0,04 g	left
5	0,97 g	0,93 g	0,04 g	left
6	0,62 g	0,65 g	-0,03 g	right

Measurement analysis shows that average difference is the same as the mistake of calibration. In right turns the average difference is −0,04 g and in left turns the average difference is 0,04 g. Therefore in measurements of acceleration, the mistake of calibration is always presented as added difference.

$$a_{\mathrm{m}} = a_{\mathrm{t}} + \Delta a_{\mathrm{c}}. \quad (5)$$

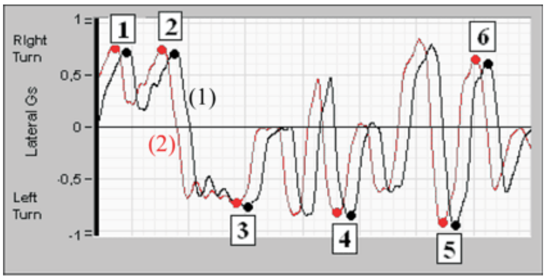

Figure 18 *Comparison of two lateral acceleration analyses*
Slika 18. *Usporedba dva bočna ubrzanja*

4 Conclusion
Zaključak

From the presented paper it is seen that the measurement system G-Tech Pro Performance Meter RR w and the Performance Analysis System Software (PASS) are useful for measuring and analyzing different data in the traffic of vehicles like lateral accelerations, longitudinal accelerations, braking, torque, power, different times and lengths. Measurement systems, as the ones used for these experiments, are suitable to define maximum performances for different vehicles, to define maximum power, torque, acceleration and braking for tuned cars, analyze traffic accidents and compare the drive in a race.

The presented analyses and results show the data for braking and longitudinal accelerations; this is a well-known-fact, which was already measured by other authors before us. For usual cars, braking can range up to 8,5 m/s^2 and the longitudinal accelerations can range up to 4,5 m/s^2. Our special contribution to this is the maximal lateral acceleration, here measured to be about 9,7 m/s^2. Therefore, it is necessary to understand that such a value of accelerations and braking can only be achieved in good conditions, such as rough and dry asphalt, good tires, braking on a straight section, etc. On regional roads, conditions are much worse and the prescribed accelerations and braking are lower.

5 References
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