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# COMPARISON OF BRAKING PROPERTIES OF SELECTED VEHICLE WITH DIFFERENT METHODS

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## Abstract

The aim of this article was to perform a practical measurement of the braking properties of a selected Škoda Yeti vehicle on a wet and dry asphalt road and then evaluate and compare the measured data using a decelerograph and a mobile application mSTK. It is a new application for measuring driving dynamics, which was developed for the needs of technical inspection stations in Slovakia. The subject was the intensive braking of a Škoda Yeti passenger car with a fully compressed service brake from different velocities and on different surfaces. A total of 18 measurements were performed, of which 9 on the dry and 9 on the wet surface. This is a new alternative method for recording vehicle driving dynamics. The developed application in conjunction with modern smartphones can thus compete with the current decelographer, both in terms of technical parameters, measurement accuracy (total average deviation 2.11%) and ease of use. The results and data processed in this way are presented in the final part of the paper.

**Keywords:** braking; dynamics; full braking deceleration; braking distance; smartphone; application mSTK; XL MeterTM Pro; dry; wet; road surface

## 1. Introduction

With the growth of the automotive market [6] and increasing vehicle velocity, the requirements for efficient and reliable wheel brake systems are constantly tightening. Increased vehicle production and increased traffic require improved braking mechanisms.

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The brake system is the most important part of a car in terms of active safety. This system has a decisive influence on the driving safety of the car. The early studies [7] investigated the brake force characteristics. The main functions are stopping, maintaining velocity while driving, parking the vehicle on a level or sloping road and securing against the movement of a parked vehicle [9]. In order for the car to stop, slow down or remain locked, a braking force is required which is created by the action of the braking system and acts against the movement, as a result of which braking occurs. There is a wide set of studies focusing on the various types of vehicles e.g. [5, 11, 18] and also electric vehicles [12] which are nowadays trending in the usage due to environmental aspects.

The functionality and reliability of the brake system is one of the most important things concerning the safety of the crew and the safe driving of the car [4]. There are various approaches investigating the behaviour of vehicles on the different road surface [19]. Some authors use the simulation methods [25]. Other studies [9, 10, 13] verify the brake intervention time according to various road friction factors, the simulation scenario reflected the vehicle velocity and road curvature radius. The novel approach of this research paper consists in the testing with the smartphone and the decelographer to verify the possibility to use the smartphone as the research measurement tool in various areas [20].

# 2. Methodology

The aim of the practical measurement was to find out the difference between the braking properties of the selected motor vehicle using **the XL metro** and **the mobile application mSTK** [14], which is a novelty and is used at technical inspection stations.

## 2.1. Vehicle characteristics

The Škoda Yeti passenger car, year of manufacture 04/2010 (see Figure 1), was used as a test vehicle for the measurement, with a four – cylinder petrol engine with a displacement of 1197 cm$^3$, 4x2, and an output of 77 kW in the Ambition version.

The vehicle contained Michelin summer tires in dimensions 215/60 R16 and a tread depth of approximately 5 mm. The vehicle has hydraulically operated disc brakes front with a diameter of 280 mm and rear with a diameter of 255 mm. The vehicle was in a fault-free condition. At the time of measurement, the tires were inflated to the pressure specified by the manufacturer. The vehicle was loaded by two people during the experiments.

Fig. 1. Škoda Yeti passenger car with used tires. Source: authors

## 2.2. The used technics and application

**XL Meter™ Pro decelograph** and **mSTK smartphone** were used as measuring and recording devices during intensive braking.

### 2.2.1 XL MeterTM Pro a SW XL Vision

**XL Meter™ Pro** is a battery-powered universal device with an alphanumeric LCD display that measures acceleration or deceleration (see Figure 2). From a technical point of view, the measuring instrument consists of three parts. The main unit contains an electronic part with an LCD display, a vacuum suction cup and an articulated arm. The articulated arm allows zero level calibration when placing the main unit using a vacuum suction cup on the vehicle windshield. The whole measuring device is integrated on one accelerometric chip, which contains a miniature acceleration sensor with signal circuits for quality measured results.

Fig. 2. The location of the measurement tool (XL MeterTM Pro – left; smartphone – right). Source: authors

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The measurement tool automatically captures the logs of output signal voltage, with the sampling rate of 200 Hz. At the same time, the device records the course of acceleration within a span of 80 seconds, starting from the turning on. Table 1 depicts the basic specifications.

**Tab. 1. Basic specifications. Source: processed by the author on the basis [19, 24]**

| Technical Data | Features |
|---|---|
| · Number of measurements: **3, 6 or 8** | · Measures Longitudinal – and Lateral acceleration |
| · Storage capacity*: **3x80 s + 5x40 s** | · Extra fast, strong installation, easy handling |
| · Acquisition Frequency: **200 Hz ... 25 Hz** | · Brake pedal input and trigger output |
| · Acceleration Measurement **($a_x$, $a_y$)** | · On the spot service brake performance evaluation |
| · Longitudinal – and Lateral acceleration | · On the spot acceleration performance evaluation |
| · Range: **(± 5.0–± 20.0) m/s²** | · Modular system architecture |
| · Resolution: **0.005 m/s²** | · Selectable acceleration direction |
| · Display: **16x2 PLED** | · Remote Control |
| · PC interface: **RS-232, USB**** | · Optional display language |
| · Dimensions (HxWxL): **(50x97x110) mm** | · **80 hours** continuous operation with one battery-set |
| *for 200 Hz, ** only with additional accessory | |
| **Applications** | |
| · Service brake performance evaluation | · Substitute for Roll Brake Test Bench |
| · Retarder brake performance evaluation | · Technical condition survey |
| · Tram brake performance evaluation | · Drag racing, tuning |
| · Accident reconstruction | · Vehicle dynamics measurement |
| · Vehicle diagnostics measurement | · **(0-100) km/h, (0-1/4) mile etc. speed-up tests** |

At the end of the measurement, the **XL Meter™ Pro** screen displays the individual values of mean fully developed deceleration (MFDD), the braking distance ($s_0$), the initial velocity ($v_0$), and the intensive braking time ($t_{br}$).

According to ECE Regulation 13, the mean fully developed deceleration (MFDD) is calculated as the mean deceleration with respect to the distances travelled in the interval $v_b$ to $v_e$ according to the formula:

$$\mathrm{MFDD} = \frac{v_b^2 - v_e^2}{25.92 * (s_e - s_b)} \tag{1}$$

where:

- MFDD – mean fully developed deceleration [m/s²],
- $v_b$ – vehicle velocity at 0.8 $v_o$ [km/h],
- $v_e$ – vehicle velocity at 0.1 $v_o$ [km/h],
- $v_o$ – the starting vehicle velocity [km/h],
- $s_b$ – distance between $v_o$ and $v_e$ [m],
- $s_e$ – distance between $v_o$ and $v_b$ [m] [15, 16].

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**XL Vision™** – it is a program designed for the transmission and evaluation of measured data from the measuring device **XL Meter™ Pro** and contains an ever-increasing number of functions (Figure 3).

Once the software is installed on the PC, data transfer between the computer and the XL Meter™ Pro is secured using a standard USB cable [17]. The goal of the XL Vision™ program is to offer full-fledged computer evaluations of the acceleration and deceleration of various vehicles.

XL Vision™ is not only an extension of the XL Meter™ Pro to visualize measured data, but also allows you to accurately determine time, distance, instantaneous velocity, acceleration / deceleration, as well as average acceleration calculation [23]. Documentation and archiving of measured data are also very easy with XL Vision™. The measurement results can be printed in the form of a measurement report, which contains important information [8, 24].

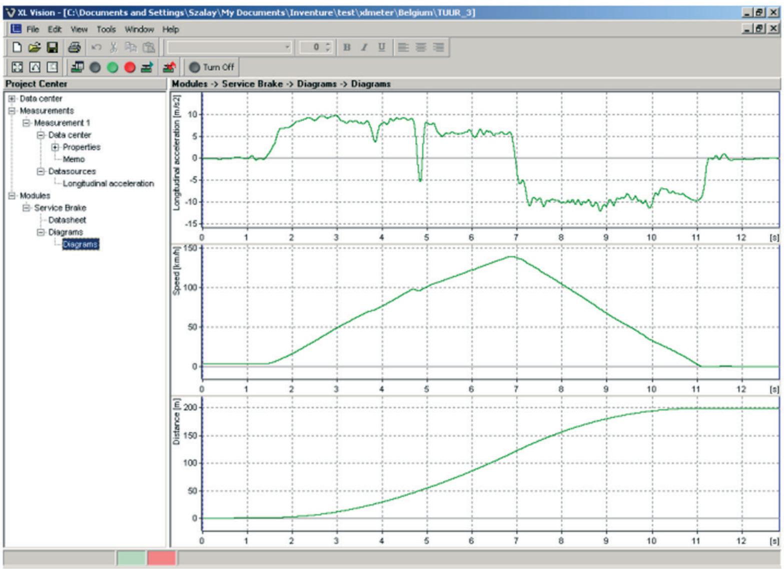


**Fig. 3. The progress of the measurement in the graphical display in the program XL VisionTM. Source: output from XL Vision software, authors**

### 2.2.2 Smartphone and the smartphone app

In addition to **the XL Meter™, a Samsung Galaxy A70 smartphone** and **the mSTK mobile application** [1] were used to measure braking performance (Figure 4).

The mobile application called mSTK is intended exclusively for the purpose of performing technical inspections at technical inspection stations, its use is therefore linked to the national information system of technical inspections [2]. The aim of the development of the mobile application was, in addition to accurately measuring the course of the longitudinal

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acceleration of the vehicle and evaluating the brake test, to simplify the use of this meter in comparison with commercial deceleration meters (decelographers) used at roadside control stations [1, 3].

Using the accelerometer built into the smartphone, the mobile application measures the acceleration components from the x, y, and z axes, from which it calculates the total longitudinal acceleration of the vehicle. To achieve an accurate measurement of the longitudinal acceleration of the vehicle, it is necessary to fasten the smartphone firmly to the vehicle using a mobile phone holder. The advantage is that there is no need to additionally correct and calibrate the smartphone for the correct position as with the XL Meter™ Pro [21], this position correction will take place automatically as soon as the measurement is started. The smartphone can thus measure correctly in any position. Another advantage is the low price, easy availability (including the necessary hardware, which is a common mobile device), as well as simple operation.

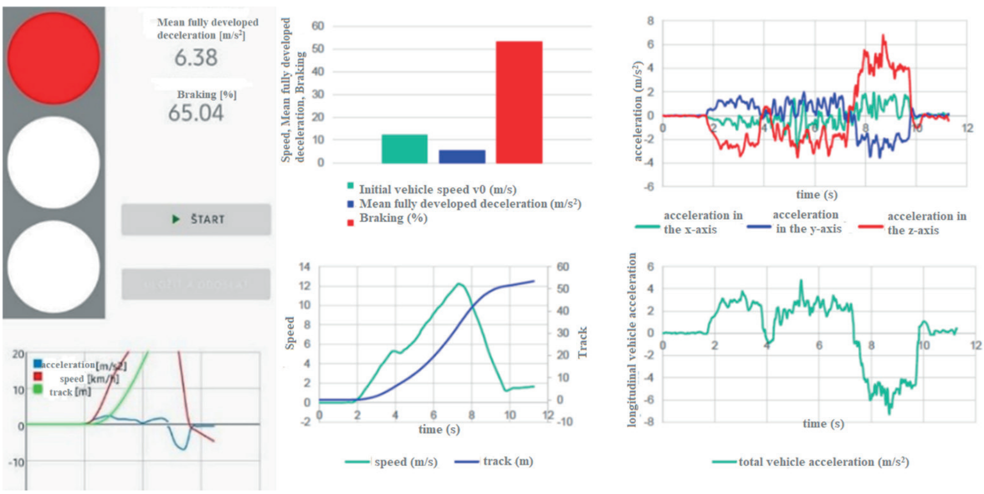


**Fig. 4. The outputs of the mSTK app (left) with graphical outputs (right) in Slovak.**

**Source: authors**

Immediately after the measurement, the mobile application calculates the results of the brake test, namely mean fully developed deceleration as defined by ECE Regulation No. 13, as well as the braking rate, which is defined by:

$$Z = \frac{MFDD}{g} \tag{2}$$

where:

- Z – braking rate [%],
- MFDD – mean fully developed deceleration [m/s²],
- g – gravitational acceleration [m/s²] [12].

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From the measured results, we can also find out the course of the path, velocity and acceleration during the measurement, the increased inclination of the road or an unattached smartphone in the holder, or the specific position of the mobile device during the measurement using GPS coordinates.

## 2.3. Steps of measurement

The experiment was performed on 12 May 2021 on both dry and wet surfaces. The measurement was made possible in one day due to the sunny weather in the morning and the subsequent storm and rain in the early evening. The measurement took place in the town of Čadca in the Milošová suburbs with an altitude of 492 height over sea. The weather conditions are shown in Table 2.

**Tab. 2. The weather conditions during the measurement. Source: authors**

| Day | Dry road | Wet road |
|---|---|---|
| | 12.05.2021 | 12.05.2021 |
| Air temperature [°C] | 25.5 | 16 |
| Velocity of wind [km/h] | 6 | 13 |
| Humidity [%] | 26 | 59 |
| Surface temperature [°C] | 38.3 | 18.9 |

The measurement of the braking properties of the Škoda Yeti motor vehicle took place on wet and dry asphalt roads at three different velocities, using the Michelin 215/60 R16 summer tires. Specifically, the velocities were 30 km/h, 50 km/h and 70 km/h. A detailed picture of the dry and wet road surface is shown in Figure 5.

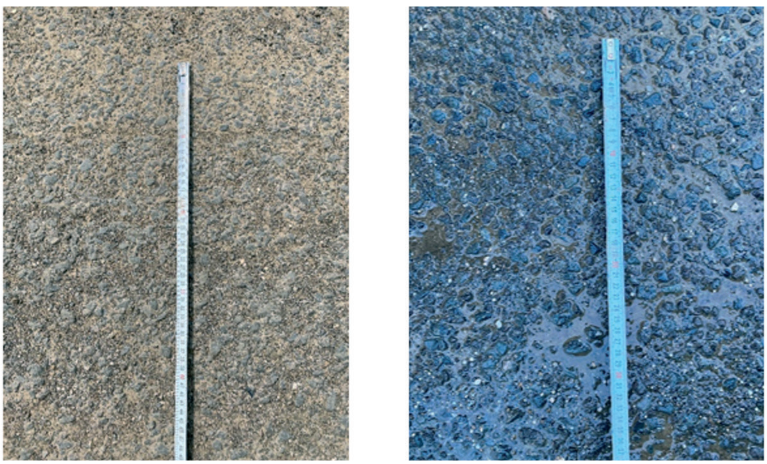

**Fig. 5. The detail of dry and wet road surface. Source: authors**

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We focused mainly on determining the full braking deceleration, braking distance, and braking time at selected velocities.

The measurement procedure was as follows:
1) warm up the brakes and tires to operating temperature,
2) install the XL Meter™ Pro and smartphone on the inner windshield using vacuum suction cups,
3) setting and calibration of both devices,
4) acceleration, achievement and stabilization of the required vehicle velocity,
5) intensive braking of the test vehicle,
6) complete stop of the test vehicle,
7) storage of measured data.

**The results of the measurements**

The values obtained from the measurement of the braking properties of the Škoda Yeti passenger car are given in Tables 3 and 4, depending on the surface. The tables depict the velocities at the beginning of full braking deceleration ($V_0$), braking times ($t_{BR}$), braking distances ($s_0$), and the values for full braking deceleration (b). In addition to the above data, we have added data such as average full braking deceleration during individual velocities ($b_{V0}$) and the total average full braking deceleration ($b_{average}$).

**Dry surface**

The following Table 3 shows the calculated values for measuring braking performance on a dry surface. The values of the total average deceleration evaluated by XL Meter™ Pro (8.33 m/s²) and smartphone (8.31 m/s²) are almost the same (deviation 0.10 m/s², i.e., 1.27%).

The highest value of full braking deceleration 8.96 m/s² was recorded by the application mSTK at a velocity of 52.01 km/h (*trial 6*) and the lowest value 7.36 m/s² at a velocity of 34.70 km/h (*trial 1*). The application also calculates the braking rate, which is lowest in the first measurement with a value of 75.02% and highest in the sixth measurement with a value of 91.37%. The highest value measured with XL Meter™ Pro was 8.91 m/s² (trial 6) and the lowest 7.5 m/s² (*trial 8*).

**Tab. 3. Measured and processed data for a Škoda Yeti on a dry asphalt road. Source: authors**

| Trial | XL Meter™ Pro | | | | | Smartphone with app. mSTK | | | Difference to XL Meter™ Pro | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $V_0$ [km/h] | s0 [m] | $t_{BR}$ [s] | b [m/s²] | $b_{V0}$ [m/s²] | b [m/s²] | $b_{V0}$ [m/s²] | braking rate [%] | b [m/s²] | b [%] |
| 1 | 34.70 | 7.01 | 1.39 | 7.70 | | 7.36 | | 75.02 | 0.34 | 4.62 |
| 2 | 36.38 | 7.27 | 1.38 | 8.05 | 8.03 | 8.12 | 7.91 | 82.77 | 0.07 | 0.87 |
| 3 | 38.90 | 7.83 | 1.39 | 8.33 | | 8.25 | | 84.09 | 0.08 | 0.97 |
| 4 | 48.21 | 12.00 | 1.69 | 8.89 | | 8.85 | | 90.24 | 0.04 | 0.45 |
| 5 | 54.34 | 14.87 | 1.86 | 8.80 | 8.87 | 8.94 | 8.92 | 91.13 | 0.14 | 1.59 |
| 6 | 52.01 | 13.33 | 1.77 | 8.91 | | 8.96 | | 91.37 | 0.05 | 0.56 |

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**Tab. 3. Measured and processed data for a Škoda Yeti on a dry asphalt road. Source: authors; cont.**

| Trial | XL Meter™ Pro | | | | | Smartphone with app. mSTK | | | Difference to XL Meter™ Pro | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $V_0$ [km/h] | s0 [m] | $t_{BR}$ [s] | b [m/s²] | $b_{V0}$ [m/s²] | b [m/s²] | $b_{V0}$ [m/s²] | braking rate [%] | b [m/s²] | b [%] |
| 7 | 75.92 | 28.73 | 2.66 | 8.65 | | 8.77 | | 89.43 | 0.12 | 1.39 |
| 8 | 71.54 | 28.95 | 2.83 | 7.50 | 8.09 | 7.48 | 8.10 | 76.31 | 0.02 | 0.27 |
| 9 | 74.12 | 30.24 | 2.82 | 8.11 | | 8.05 | | 82.12 | 0.06 | 0.75 |
| | $b_{average}$ | | | **8.33** | | **8.31** | | | **0.10** | **1.27** |

There was also the difference in measured data of standard deviation of full braking deceleration. The XL Meter™ Pro captured the value 0.49 m/s², the mSTK app 0.58 m/s².

### Wet surface

Also in this case, 9 measurements were performed using measuring instruments, the measured data of which are given below in Table 4. The values of the total average braking deceleration evaluated by XL Meter™ Pro (7.13 m/s²) and smartphone (7.21 m/s²) are almost the same. The average difference between the full braking deceleration values on the wet asphalt road of the mSTK application and the XL Meter™ Pro is 0.21 m/s², i.e., 3.00%.

The highest value of full deceleration 7.66 m/s² was recorded by the application mSTK at a velocity of 73.73 km/h (*trial 8*) and the lowest value 6.75 m/s² at a velocity of 32.35 km/h (*trial 1*). The application also calculates the braking, which is lowest in the first measurement with a value of 68.83% and highest in the eighth measurement with a value of 78.17%. The highest value measured with XL MeterTM Pro was 7.92 m/s² (*trial 8*) and the lowest 6.6 m/s² (*trial 1*).

**Tab. 4. Measured and processed data for a Škoda Yeti on a wet asphalt road. Source: authors**

| Trial | XL Meter™ Pro | | | | | Smartphone with app. mSTK | | | Difference to XL Meter™ Pro | |
|---|---|---|---|---|---|---|---|---|---|---|
| | $V_0$ [km/h] | s0 [m] | $t_{BR}$ [s] | b [m/s²] | $b_{V0}$ [m/s²] | b [m/s²] | $b_{V0}$ [m/s²] | braking rate [%] | b [m/s²] | b [%] |
| 1 | 32.35 | 6.62 | 1.39 | 6.60 | | 6.75 | | 68.83 | 0.15 | 2.27 |
| 2 | 32.90 | 6.78 | 1.37 | 7.27 | 6.86 | 7.49 | 7.06 | 76.38 | 0.22 | 3.03 |
| 3 | 36.52 | 8.60 | 1.59 | 6.71 | | 6.95 | | 70.89 | 0.24 | 3.58 |
| 4 | 53.05 | 16.78 | 2.18 | 6.68 | | 6.91 | | 70.49 | 0.23 | 3.44 |
| 5 | 52.69 | 16.27 | 2.14 | 7.34 | 7.02 | 7.52 | 7.17 | 76.68 | 0.18 | 2.45 |
| 6 | 55.94 | 18.32 | 2.28 | 7.04 | | 7.08 | | 72.48 | 0.04 | 0.57 |
| 7 | 71.79 | 27.86 | 2.72 | 7.53 | | 7.23 | | 73.71 | 0.30 | 4.15 |
| 8 | 73.73 | 30.01 | 2.79 | 7.92 | 7.50 | 7.66 | 7.41 | 78.17 | 0.26 | 3.39 |
| 9 | 75.53 | 33.43 | 3.06 | 7.05 | | 7.34 | | 74.82 | 0.29 | 4.11 |
| | $b_{average}$ | | | **7.13** | | **7.21** | | | **0.21** | **3.00** |

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There was also the difference in measured data of standard deviation of full braking deceleration. The XL Meter™ Pro captured the value 0.41 m/s², mSTK app: 0.29 m/s².

## 2.4. Evaluation of measurements on wet and dry asphalt roads

The following Figure 6 clearly shows the results obtained during braking on a Škoda Yeti passenger car on both dry and wet surfaces. Here we can notice the high accuracy of the results achieved by the smartphone with the mSTK app compared to the XL Meter™ Pro decelograph. Also of interest are the relatively high values of full braking deceleration on a wet surface compared to a dry surface.

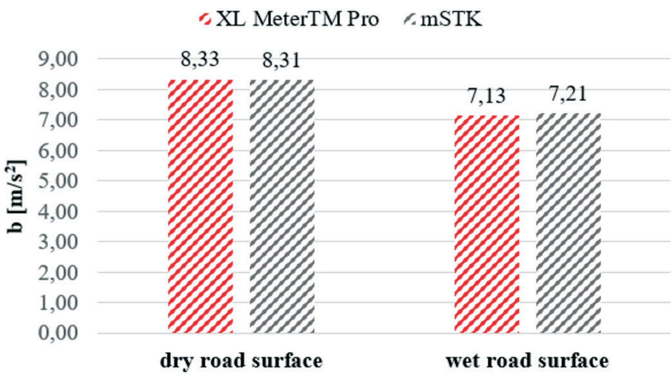


**Fig. 6. Average full braking deceleration for wet and dry roads on both surfaces. Source: authors**

The measurements were performed simultaneously on two measuring devices, namely on the XL Meter™ Pro measuring device and the Samsung Galaxy A70 smartphone with the mSTK application installed and calibrated. The calibration was performed by a professionally authorized organization, which is in charge of the calibration of equipments of authorised vehicle testing stations. The mSTK application was chosen to replace the XL MeterTM Pro meters with effect from 01.01.2021, when all STKs had to start using different smartphones to perform driving tests. A comparison of the percentage deviations of measuring instruments is shown in Table 5.

**Tab. 5. Average deviation of measuring deceleration of measuring instruments XL Meter™ Pro and mSTK app [%]. Source: authors**

| average deviation of brake deceleration measurement [%] | |
|---|---|
| average deviation in velocity measurement 30 km/h | 2.56 |
| average deviation in velocity measurement 50 km/h | 1.50 |
| average deviation in velocity measurement 70 km/h | 2.27 |
| **total deviation in velocity measurement** | **2.11** |

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The total average percentage deviation of the measured data was found by comparing the results measured by the measuring instruments. The percentage deviation was 2.11%, which was determined by calculation from the mSTK application and the XL Meter™ Pro meter. The overall average deviation did not take into account velocity, whether it was a dry or wet asphalt road.

## 3. Conclusion

The experiment consisted of 18 measurements of the braking characteristics of the Škoda Yeti, of which 9 on a wet and 9 on a dry surface.

**The decelograph XL Meter™ Pro** was used as a measuring and recording device during heavy braking with a sampling frequency of 200 Hz. We processed data from it using XL Vision programs. In addition to the **XL Meter™ Pro**, we also used a **Samsung Galaxy A70 smartphone** and **the mSTK mobile application.**

This is a new alternative method for recording vehicle driving dynamics. The developed mobile application in conjunction with modern smartphones can thus compete with the current decelographer, both in terms of technical parameters, measurement accuracy (total average deviation 2.11%) and ease of use.

There are many factors affecting the process of braking. For instance, the braking distance length and the full braking deceleration value. It is necessary to point out, that the driver´s reaction time was not considered. This is planned in the future including the bigger size of vehicle fleet. The results from this study are possible linked to the research of car suspension system [22]. There is also possible to add the environmental research related to the air pollution from braking [10]. Also important issue is related to the forensic investigation of car accidents [1].

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# 5. Nomenclature

**cm$^3$** cubic centimeter
**GPS** Global Positioning System
**Hz** Hertz
**kW** kilowatt
**LCD** Liquid Crystal Display
**mm** millimetre
**s** second
**USB** Universal Serial Bus

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