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Comparative Insights on Vehicles' Deceleration Measurements

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Abstract: This paper investigates the possibilities of measuring vehicle deceleration using modern devices based on GPS (Global Positioning System) and MEMS (Micro Electro Mechanical System) technologies, with the aim of replacing traditional inertial devices. The experiments were carried out on a passenger vehicle and a construction machine, using three different measuring devices: an inertial decelerometer, a GPS device (Racelogic DriftBox) and a MEMS accelerometer. The measurement results show good mutual agreement between recorded results from devices used for this paper, with an emphasis on the precision and ease of use of modern devices. The conclusion emphasizes the justification of using GPS and MEMS devices in testing the dynamic characteristics of vehicles due to their high frequency of data acquisition, simple processing, absence of the need for calibration, and greater practicality. This research suggests that such devices will be increasingly used in the future to analyse vehicle dynamics.

Keywords: construction machine; deceleration; GPS; MEMS; vehicle

1 INTRODUCTION
1.1 Background

Deceleration is an important dynamic characteristic of a vehicle that provides information about its ability to change speed in a certain time interval. It is often used as a measure of vehicle performance and safety when stopping the vehicle.

When braking is considered, deceleration is the rate at which a vehicle can reduce its speed after applying the brakes. Effective deceleration is key to safe driving, as it allows the driver to control the vehicle and adjust speed to changing road conditions. Investigation of various dynamic characteristics of the vehicle, among which is the deceleration, was most often performed with devices that are demanding and complex to handle. In recent times, devices based on GPS (Global Positioning System) and MEMS (Micro Electro Mechanical System) technologies have been increasingly introduced to test the dynamic characteristics of vehicles.

1.2 Objectives

The aim of this paper is to investigate the possibility of measuring deceleration using modern devices based on GPS and MEMS technology, which should replace inertial devices. To justify the use of these devices on all types of vehicles, the measurement was carried out on a passenger vehicle and a construction machine to compare the matching results between individual devices. The obtained results of this research show the justification of using devices based on GPS and MEMS technologies for measuring the dynamic characteristics of vehicles, both passenger and heavy construction machines.

The use of devices based on GPS and MEMS (Micro-Electro-Mechanical Systems) technologies for measuring the dynamic characteristics of vehicles brings significant advantages. GPS technology enables highly precise real-time tracking of vehicle positions, which is crucial for analysing vehicle movement and routes. When GPS is combined with MEMS sensors, which provide detailed information on acceleration, velocity, and other dynamic parameters, a comprehensive and accurate information of the vehicle's dynamic behaviour can be obtained. These sensors are compact, energy-efficient, and relatively inexpensive, making them ideal for widespread application in the automotive industry. By using these technologies, researchers can better understand vehicle performance, optimize design, and improve safety features, thereby contributing to the enhancement of efficiency and safety in traffic.

1.3 Literature Review

Apart from GPS and MEMS devices, other types of devices are also used, as shown in [1]. A wireless accelerometer mounted on the inner rim of the wheel was used here. It has been shown that this method can be used to monitor the condition of the screw joints that hold the wheel to the hub. In the paper [2], a triaxial accelerometer based on MEMS technology was used to analyse the obstacles on the road. Along with a smartphone camera and a model based on neural networks, a new model was created to analyse these phenomena. In a study [3], the application of MEMS accelerometers for evaluating the dynamics of cargo securing on road vehicles is investigated. Safety is a crucial aspect of successful cargo transport, particularly in road traffic, where the dynamics of a vehicle during routine events such as braking, steering, and evasive manoeuvres vary at different locations within the vehicle. The authors developed a smartphone-based system utilizing a dual acquisition method capable of capturing images of road surface anomalies and measuring the vehicle's acceleration upon their detection. The study highlights the importance of MEMS accelerometers in monitoring accelerations and related forces acting on cargo during transport. The use of MEMS accelerometers provided reliable data for assessing the impact of dynamic events on cargo, enabling adjustments to cargo packaging, securing methods, and even modifications to transport routes. The results emphasize that MEMS devices play a crucial role in enhancing transport safety by providing valuable insights into the dynamics of securing the cargo on road vehicles. The research presented in the paper [4] focuses on the accuracy assessment of three selected devices used for distance measurement in dynamic vehicle tests: accelerometer (XL meter), a global position measurement device (VBOX), and a constructed 5th wheel providing precise measurements of distance, speed, and acceleration. The experiments involved attaching all three devices to the vehicle during various driving conditions. Results indicated that GPS-based devices, such as VBOX, outperformed accelerometers, particularly in locations with a clear view of the sky. Another application of GPS based measuring accelerometers can be seen in [5]. Here the authors investigated the influence of various suspension configurations regarding comfort in N2 type vehicles. Vehicles safety in traffic with regards to proper functioning is ensured through periodic technical inspections. As vehicles are increasingly complex for traditional inspection, sophisticated test equipment must be used. An example of the analysis of the periodical technical inspection of vehicles in Slovakia is presented in [6]. Here, it was pointed out that the previously used inertial decelerometers are being replaced with modern triaxial accelerometers. These accelerometers are able to perform remote reading of the vehicle braking parameters, i.e. deceleration. Various examples of recent investigation into possibility of using triaxial accelerometers for the vehicle dynamics investigations can be seen as an example in [7, 8]. Research [9] shows that sensors have indeed become a reality in modern construction machines. This paper addresses the challenges of modelling construction machine dynamics, while also considering their low velocities and unique operating conditions. The proposed vehicle model, tailored for construction machines, is validated using experimental data obtained from a series of tests. The dynamic model includes considerations for vehicle and wheel dynamics, weight transfer, and the transmission system. It effectively models wheel slip behaviour, especially crucial for low-speed systems typical in construction machinery. Experimental validation, conducted using a range of sensors, including triaxial accelerometers, demonstrates a close match between the system model and collected data. Additional examples of the use of sensors to analyse construction machines are presented in [10, 11]. Paper [12] investigates the application of sensor-based technology to improve safety management on construction sites. Given the complexity of construction sites and the increased amount of information, traditional safety management faces challenges. Sensor based technology provides efficient ways to collect, identify and process information, thus enabling the creation of a new generation of methods to improve safety management in the construction sector. The paper reviews various sensor-based technologies that have been applied to safety management on construction sites, including location-based technologies, visual recognition, and wireless sensor networks. Among others, it emphasizes the importance of triaxial accelerometers as essential elements for future analysis of the processes that construction machines are subjected to.

Previous research indicates the presence of triaxial accelerometers as sensors to test the dynamic characteristics of vehicles, along with all the other phenomena related to movement and performance of work using vehicles. It has been proven several times that triaxial accelerometers based on MEMS technology are relevant devices for measuring vibrations on internal combustion engines and vehicles or for road profile investigations [13-15].

1.4 Structure of the Paper

The paper is composed of four chapters. In the first chapter, an introduction to the topic of the paper is given, the relevant literature is reviewed, and the aim of the paper is set. The second chapter presents the measurement method and the devices that were used for measurement. The third chapter presents the measurement results and a comparison between individual types of devices for both tested vehicles. The fourth chapter is the conclusion of the paper, where the research is summarized and an assessment of the possibility of using these devices is given. At the end, references are listed.

2 MEASUREMENT METHOD AND DEVICES

2.1 Overall Approach

To compare the deceleration measurements on two different types of vehicles, an experimental deceleration measurement was performed on one passenger vehicle and one construction machine.

To measure the vehicle's deceleration, it is necessary to provide an area where it can be done safely, while respecting the safety of other road users. The length of the test track should be at least 75 m for a passenger vehicle and 50 m for a construction machine. The minimum velocity at the moment of braking start should be 40 km/h for a passenger vehicle. For a construction machine, a velocity of at least 40% of its maximum velocity should be achieved. When the desired velocity is reached, it is necessary to press the service brake pedal and maintain the pressure evenly until the vehicle comes to a complete stop. Deceleration is recorded using the selected deceleration measuring device. The tested vehicles are shown below.

2.2 Passenger Vehicle

The Škoda Kamiq passenger vehicle, shown in Fig. 1, was used to measure deceleration. The tested vehicle is powered by a turbocharged otto engine, with a volume of 1498 cm^3, maximum power 110 kW which is achieved from 5000 to 6000 min^{-1} and a torque of 250 Nm which is achieved from 1500 to 3500 min^{-1}. The engine is paired with a seven-speed DSG automatic transmission. The vehicle curb weight is 1279 kg, and the maximum speed is 215 km/h. The braking system is a double circuit hydraulic system with self-ventilating discs on all wheels. The vehicle is equipped with modern active safety systems (ABS, ESP, ASR, etc.).

Figure 1 Passenger vehicle – Škoda Kamiq

2.3 Construction Machine

The second vehicle that was tested, shown in Fig. 2, is a Caterpillar 444 combined construction machine powered by a diesel engine with a volume of 3600 cm^3 and a power of 82 kW. The vehicle curb mass is 9500 kg, and the maximum speed is 40 km/h.

Figure 2 Construction Machine – Caterpillar 444

2.4 Measurement Equipment and Setup

As a part of this experiment, three devices were used to measure deceleration. The first device is of the inertial type, which until now has been most often used for these purposes. The device with its characteristics is shown in Fig. 3. The other two devices are based on modern technologies of GPS (Global Positioning System) and MEMS (Micro Electro Mechanical System) accelerometers. These two devices with their characteristics are shown in Figs. 4 and 5.

Deceleration measurement range	0 – 10 m/s^2
Force on the pedal range	0 – 1000 N
Pressure range	0 – 20 bar
Measurement accuracy	± 1%
Power supply	230 V/15V AC
Battery	6 V / 1.2 Ah
Weight	1.1 kg
Dimensions	120 x 65 x 245 mm

Figure 3 Inertial decelerometer [16]

The goal of the measurements is to investigate:

- The possibility of using devices based on MEMS and GPS technology instead of inertial devices for measuring vehicle deceleration and
- Flexibility of measuring devices on different types of vehicles.

Measurement range	0 – 4g
Measurement resolution	0,01g
Measurement accuracy	± 1%
GPS accuracy	± 5 m
GPS frequency	10 Hz
Memory type	SD card
Battery	6 – 28 V, 100 mA
Mass	0.266 kg
Dimensions LxWxH	113x63x96 mm

Figure 4 DriftBox GPS measurement device [17]

The set goal is important because of the measurement of the efficiency of the braking system in all types of vehicles, which cannot be tested on the inspection lines of the vehicle technical inspection stations. The most important value that needs to be determined is the maximum deceleration and matching of the character of the results obtained by measurements with these devices. The results of measuring deceleration with devices based on GPS and MEMS technology are compared to the results obtained by measuring on an inertial device.

Measurable range of acceleration	± 100G
Frequency of data acquisition	100 ÷ 20000 Hz
Possible data records	up to 4 10^9 points
Weight	65 g
Dimensions	76.2 x 29.8 x 15 mm
Temperature work range	- 40 ÷ 80 °C
Type of PC connection	USB
Battery lifetime (with one charge)	5.5 ÷ 15.5 h
Measurement accuracy	± 5%

Figure 5 MEMS accelerometer [18]

The measurement setup in a passenger vehicle, for the purpose of measuring deceleration, is depicted in Fig. 6.

Figure 6 Measurement setup in a passenger vehicle

The measurement setup in the construction machine had to be adapted to the specific construction of the machine cabin. Fig. 7 shows measurement setup of these devices in the cabin of the construction machine.

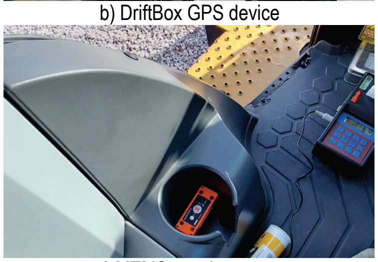
The decelerations measured by the mentioned devices were collected and processed using appropriate software programs developed by the manufacturers of these devices. The results are presented on common diagrams, where along with the display of the deceleration, the change in the velocity of the vehicle and the distance travelled during the braking are also given. The data recording frequency of the Racelogic DriftBox device was 10 Hz, and the MEMS accelerometer was 150 Hz.

3 RESULTS AND DISCUSSION

Several measurements were performed on both vehicles. The measurements were performed on the test track, which is isolated from the rest of the traffic, to ensure safety when conducting the experiments. After the setup of the measuring devices from Figs. 6 and 7, several test measurements were conducted to check the accuracy of the measuring devices. The device in Fig. 3 is an inertial device and printed data on the measured deceleration were obtained on it, which were then processed in digital form.

a) Inertial decelerometer

b) DriftBox GPS device



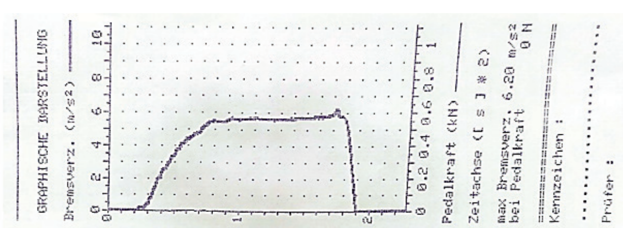
c) MEMS accelerometer

Figure 7 Measurement setup in a construction machine

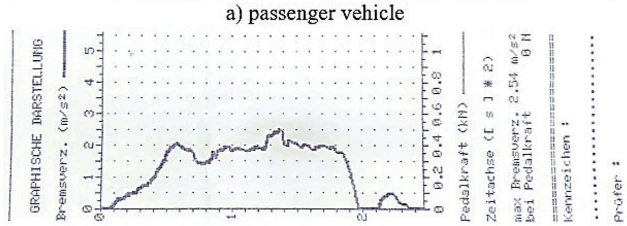
3.1 Measurement Results

The first measured set of decelerations of the passenger vehicle was measured from the initial velocity of 55 km/h, and the of the construction machine from 20 km/h. Fig. 8 depicts the results of deceleration measurements, for both vehicles, obtained in printed form from the inertial decelerometer shown in Fig. 3.

In Fig. 8, the time axis is given with a factor of 2. Therefore, for the exact time axis, the time from the axis on the diagram should be multiplied by 2.



a) passenger vehicle



b) construction machine

Figure 8 Results obtained from inertial decelerometer

It has already been pointed out that along with the measurement of deceleration by means of an inertial device, the measurement was also performed with two other devices, shown in Figs. 4 and 5. Fig. 9 depicts the results of measuring the deceleration of a passenger vehicle with the devices, while the results for the construction machine are depicted in Fig. 10.

In addition to deceleration, the Racelogic DriftBox device can record other kinematic parameters when the vehicle is moving, so that in addition to the results of the deceleration, the change in speed and the distance travelled while the vehicle is being stopped are also obtained.

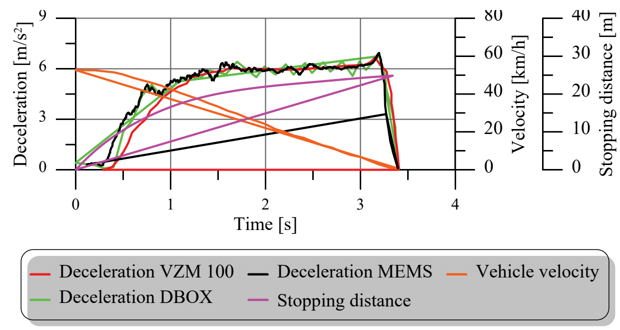


Figure 9 Deceleration results for passenger vehicle, first set

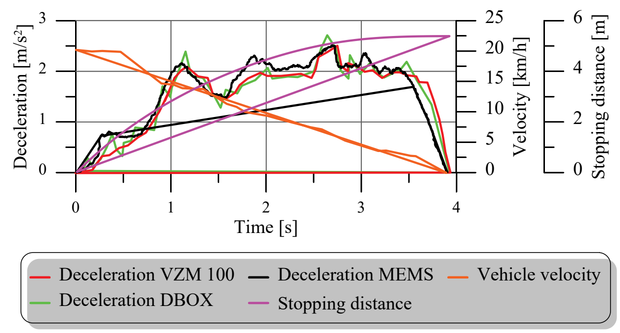


Figure 10 Deceleration results for construction machine, first set

3.2 Evaluation

Based on the obtained results of vehicles' deceleration measurements depicted in Figs. 9 and 10, it can be concluded that all three measuring devices for both vehicles match well when it comes to the nature or character of the measurement results. It is clearly seen that devices based on GPS and MEMS technology work at higher data acquisition frequencies than the inertial decelerometer. That is why they can be used to measure data that are of dynamic nature. This is especially depicted in construction machines. Oscillation of the recorded results with the construction machine (Figure 10) is a consequence of the rigid construction of the machine, its mass and the performance of the suspension system.

Another important parameter obtained by measurements are the values of the maximum decelerations of the given vehicles. Tab. 1 shows the results of the measured maximum deceleration for all three measuring devices, for the first set of measurements from Figs. 9 and 10. In addition to these values, the percentage deviations of the deceleration measured with MEMS and GPS devices in relation to the deceleration measured with an inertial device, as a reference measuring device, were also calculated.

Table 1 Measurement results – first set

Measurement device	Passenger vehicle			Construction machine		
	v = 55 km/h			v =20 km/h		
	a (m/s^2)	r (%)		a (m/s^2)	r (%)	
DriftBOX GPS	6.25	0.8	-	2.60	2.3	-
Inertial device	6.20		0.95	2.54		0
MEMS acc.	6.26	-		2.54	-	

In Tab. 1, a is the measured maximum deceleration of the vehicle, while r is the deviation between the measured acceleration values for the two devices (DriftBOX – Inertial, Inertial – MEMS) and is calculated as the quotient of the difference between the measured deceleration values from the two devices ($a_{\max}$, $a_{\min}$) and the larger value of those two ($a_{\max}$) multiplied with 100:

$$r = \frac{a_{\max} - a_{\min}}{a_{\max}} \cdot 100\ (\%). \tag{1}$$

In addition to the previously discussed deceleration measurements on both vehicles for the specified conditions, two more measurements were performed for different velocities of the vehicles at the moment of braking process start. Tab. 2 shows the measurement results for the other two velocities for both vehicles.

Table 2 Measurement results – second and third set

Measurement device	Passenger vehicle			Construction machine		
	v = 45 km/h			v =25 km/h		
	a (m/s^2)	r (%)		a (m/s^2)	r (%)	
DriftBOX GPS	6.99	0	-	3.27	1.2	-
Inertial device	6.99		0	3.31		0.6
MEMS acc.	6.99	-		3.29	-	
Measurement device	Passenger vehicle			Construction machine		
	v = 65 km/h			v =35 km/h		
	a (m/s^2)	r (%)		a (m/s^2)	r (%)	
DriftBOX GPS	7.54	0.53	-	3.92	2	-
Inertial device	7.5		1.31	4.00		0.25
MEMS acc.	7.6	-		3.99	-	

3.3 Interpretation

If the results of both vehicles are summed up, there is clear justification in using modern devices based on MEMS or GPS technology for several reasons:

- the measurement results match, both in the character of the signal and maximum deceleration values,
- the deviations of the measured maximum deceleration values are within the limits prescribed by the device manufacturer, i.e. according to the device accuracy,
- data acquisition and processing are more simplified than with inertial devices,
- there is no need for their laboratory calibration as in the case of an inertial device,
- by working with a higher frequency of data acquisition, they are suitable for sensitive measurements in a range of dynamic loads,
- they are easier to handle and transport.

It is important to note that, since the displayed devices are properly calibrated, and their accuracy is clearly declared by the manufacturer, the measurement error between the values of individual decelerations is minimal. This is clearly seen from Figs. 9 and 10, where the measured deceleration results match very well in character and obtained values.

4 CONCLUSIONS

The aim of this paper was to investigate whether measuring devices based on GPS and MEMS technology are suitable for use when researching the dynamic characteristics of construction machines travel, with emphasis on deceleration. To investigate this, a deceleration measurement experiment of a construction machine was carried out. Deceleration was measured with a traditional Maha VZM 100 inertial decelerometer, as well as with modern Racelogic DriftBOX measuring devices and a triaxial accelerometer manufactured by Mide Technologies. The other two devices are based on GPS and MEMS technologies respectively. The recorded results of the deceleration of the construction machine showed good matching of the three devices, and a very small deviations in measured maximal decelerations for each vehicle at different stopping velocities. This concludes that modern devices can be successfully used to determine the dynamic characteristics of construction machines travel. This is important when analysing the performance of these vehicles, their load and predicting operating modes. To prove that these devices are universal when it comes to testing the dynamic characteristics of vehicles, in addition to testing a construction machine, measurements were also performed on a passenger vehicle. The measurement methodology is the same for both vehicles. Also, as for the construction machine, the obtained results showed that the measuring devices match well. Although research dealing with the same topic is very scarce, the ones available showed good results in the use of GPS or MEMS devices for determining the dynamic characteristics of vehicles [3, 19, 20]. This shows that the experiments and research results in this paper justified the use of GPS and MEMS devices. From all the above and the results presented, it is reasonable to expect that devices based on GPS and MEMS technology will be increasingly represented in the testing of dynamic characteristics of all types of vehicles in the future. With the very development of the ADAS Systems (Advanced Driver Assistance System) and further integration into vehicles, it can be expected that devices based on GPS and MEMS technologies will be a standard part of the vehicle's equipment for monitoring the dynamic characteristics of the vehicle. These measuring devices can be used in automated vehicles for logistics and transport of goods, so that the dynamics of the movement of such vehicles can be monitored [19]. Further research will be focused on these systems. Although the results obtained by this research are very good, current GPS and MEMS devices still have certain limitations. Some limitations are the strength of the GPS signal, the need to use special software to process and analyse the results, the sensitivity of the device and the expertise required to operate them.

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