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Low-cost system for monitoring road friction properties

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Abstract

The knowledge of the friction conditions on driving surfaces on the public road network is a major factor in providing traffic safety. Whenever the specialised measurement equipment is used, it is difficult or even impossible to quickly perform the measurements on all sensitive locations during emergency events. By installing moderately priced and easy to control yet still accurate enough devices for measuring the longitudinal deceleration during braking onto the vehicles that travel over the road network performing their everyday assignments, the friction measurements are available quickly and with minimal additional cost. We present a prototype of a low-price device, which can be installed in the vehicles that traverse the roads on a daily basis. Its application quickly and effortlessly provides the braking-test-based friction data on the critical location on the road surface and their conveyance to the road administration authorities as the basis for taking measures for condition improvement.

Keywords: road friction, skid resistance, braking deceleration, single board computer, database, connected system

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1. Introduction

The forces between a wheeled vehicle and the driving surface are only transferred by adhesion on the contact patch formed between the tyres and the roadway. The adhesion properties on the contact patch determine the driving behaviour of the vehicle and thereby the driver's ability of safe control in longitudinal and lateral direction. For an assessment of the traffic safety on a particular location on a road network it is thus important to be able to quantify the friction properties of the contact between the vehicle tyres and the roadway they are driving on.
Several procedures have been developed and standardised for such quantification (Wallman et al. 2001, Mataei et al. 2016). These procedures assess the quality of contact based on the measured values of various physical quantities and mathematical models, which describe the conditions more or less accurately.
The method, which is the closest to directly measuring the tangential force on the contact patch, is measuring the braking deceleration of the vehicle. The friction force between the skidding vehicle and the roadway is directly related to the friction coefficient between its tyres and the driving surface as follows:

$$F_t = G_v \cdot \mu = m_v \cdot g \cdot \mu, \tag{1}$$

where F_t represents the friction force between the vehicle tyres and the driving surface, G_v the vehicle weight, μ the friction coefficient between the vehicle tyres and the driving surface, m_v the vehicle mass and g the acceleration due to Earth gravity.
Assuming the vehicle mass is constant during braking, the average friction coefficient can be expressed as follows:

$$\mu = \frac{a}{g} \tag{1}$$

where a represents the average longitudinal deceleration of the vehicle during braking and g the acceleration due to Earth gravity.
Knowing the full time series of the vehicle deceleration, we can also determine the time series of the friction coefficient and its relation to the way the tyres skid over the roadway. This is especially important to determine the conditions which cause the tyres to, skid as the parameters of safe driving in a particular vehicle-roadway system depend on them.
From the measured deceleration time series it is also possible to calculate other standardised quantities for friction conditions assesment, such as the Medium Fully Developed Deceleration (Regulation No 13 of the ECE, 2016).

2. Prototype device design

The main goal in designing the prototype device was achieving the performance comparable to calibrated accelerometers in "vehicle performance computers". The other important goal was to integrate the prototype using readily available components and minimising the costs. In the early phase of the design important requirements are also a flexible software platform and interchangeability of hardware components.
The first step of the prototype design included defining the requirements. The most important among them are the possibility of mounting to any vehicle, battery power supply with at least a few hours of autonomy, deceleration time series acquisition and storage with sampling frequency of at least 100 samples per second, and geographical location acquisition before every measurement. Additionally, the device has to have a simple and intuitive user interface that enables accurate control of its functions without hindering the driver's control of the vehicle. This is most efficiently achieved with movable physical buttons and single-point light indicators.
The next design step involved the concept synthesis and preparation of morphological matrices (Ambrož et al. 2019). These were then used to select the most appropriate concept regarding technical end economical criteria.
Seeing the rapid expansion of affordable and powerful single board computers in many science and engineering fields (Ambrož et al. 2019, Andria et al. 2016, Virant and Ambrož 2016, Ambrož 2017) prompted us to consider using one as the base of the prototype system. The concept selected for the production of the prototype includes a Raspberry Pi Zero W single-board computer (Raspberry Pi Foundation, 2019), to which an inertial measurement system (consisting of a 3-axial accelerometer and a 3-axial gyroscope) and a global positioning system are connected. An additional power supply circuit provides three different operation regimes: powering from the built-in battery without external power, powering only on external power (vehicle on-board socket), or powering from the built-in battery while simultaneously charging it from the external power. The prototype device block diagram is shown in Fig. 1. The device components are mounted in an enclosure that can be equipped with different

mounting devices, such as suction cup for windscreen mounting or a handlebar clamp for motorcycle mount. The enclosure has been produced by FDM 3D-printing based on the prepared 3D model as shown in Fig. 2. Fig. 3 and 4 show the actual prototype with the components built into the enclosure.

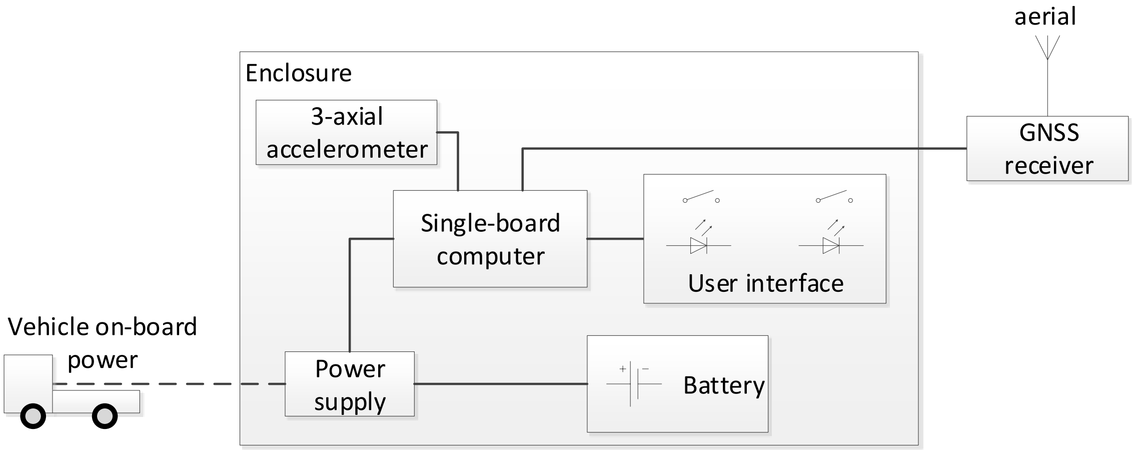

Fig. 1 Prototype device block diagram

Table 1. List of components used for prototype.

Component	Characteristics	Approximate Unit Cost
Tri-axial accelerometer with IMU	I2C/SPI interface, 16-bit resolution, 2–16 g range	15.00€
USB GNSS receiver	Simultaneous receive of up to 3 GNSS, 2.5 m accuracy, up to 10 Hz update rate	28.00€
Raspberry Pi Zero W	1 GHz ARM CPU, 512 MB RAM, 802.11 b/g/n WLAN, 8 GB micro SD card for OS and storage	12.00€
18650 Li-ion battery	3.7 V, 3000 mAh	10.00€
Power module	5 V 1 A load-sharing power supply, simultaneous battery charging and power output	19.90€
Two buttons with built-in LED (red, green)	Momentary switch with pull-up resistor and LED with series resistor	6.00€
Custom case for components	3D-printed from PLA, mounts and openings for built-in components	4.00€
Suction cup mount	Adjustable arm angle, rubber suction cup	2.50€
	Total cost of material per prototype unit	97.40€

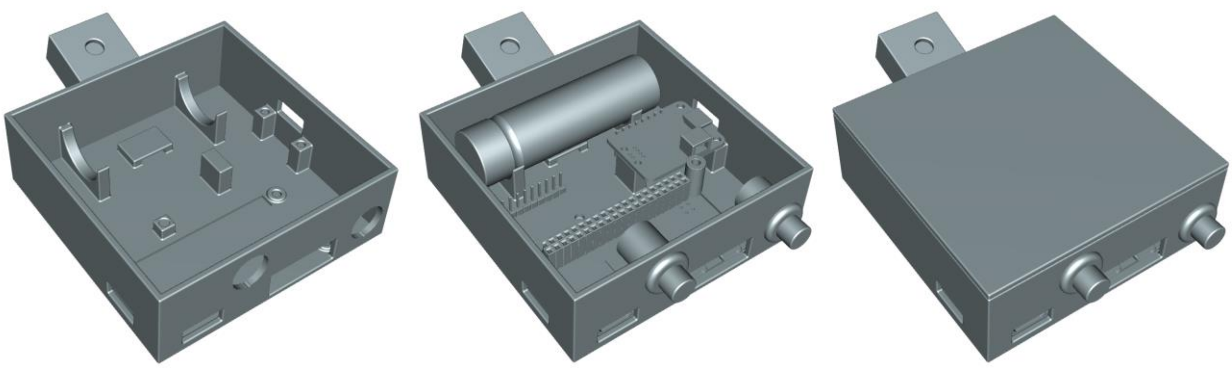

Fig. 2 3D model of the prototype device enclosure showing the component layout

The total cost of the material required for one copy of the prototype device is just under 100 €, which is less than 10% of the retail price of the basic version of a specialised device for measuring braking deceleration (Vericom LLC, 2019).

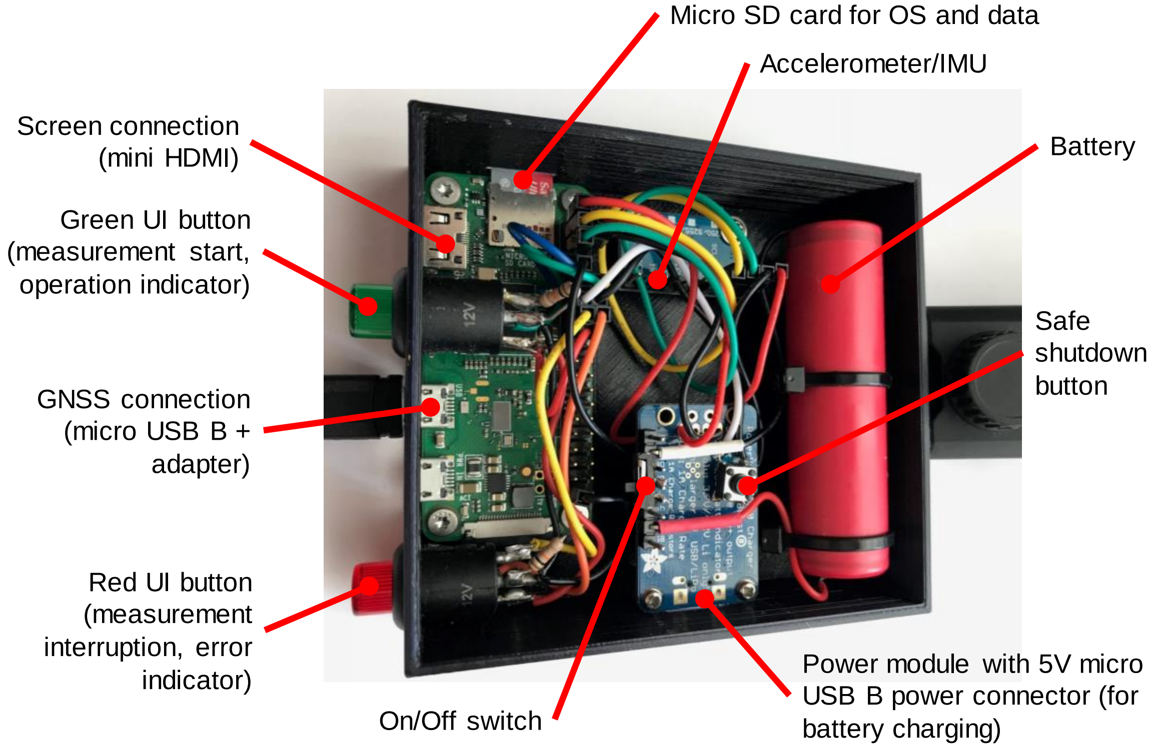

Fig. 3 Components built into the prototype device enclosure

Fig. 4 Mounting of the prototype device on the test vehicle windscreen

3. Prototype device testing and results

The device was first tested as a circuit built on a proto-board (Fig. 5, left), consisting of the single-board computer, the IMU, the GNSS receiver and a physical button acting as a simplified user interface. The first set of tests was conducted with the device stationary in order to separately test the performance of the accelerometer and the GNSS receiver. The tests were done with the prototype software, which included the routines for data acquisition, storage and control by the one-button user interface. The start and the end of measurement was initiated by a physical switch. This test confirmed the proper operation of the connected hardware.

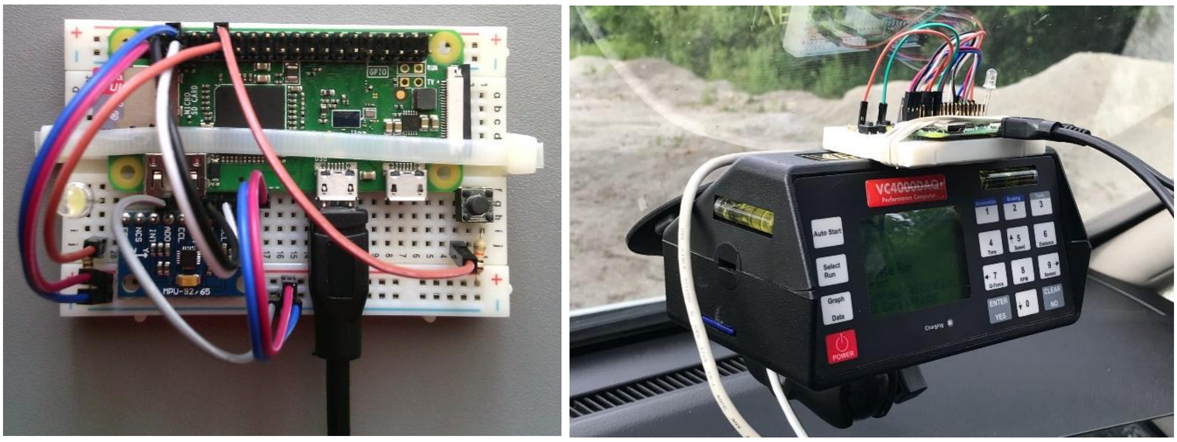

Fig. 5 Proto-board version of the initial device prototype (left) and its mounting on top of the VC4000 (right)

The second part of testing included dynamical testing during braking of a vehicle. The prototype device was mounted on the inside of the vehicle windscreen together with the VC4000 vehicle performance computer (Fig. 5, right). With this setup 11 tests were done, including different driving and braking modes. All the available measured quantities were acquired and stored on both devices. The test parametres are summarised in Table 2.

Table 2. Summary of testing parameters.

No.	Type of test
1	free drive on the polygon perimeter, counter clockwise, duration ~90 s
2	free drive on the polygon perimeter, counter clockwise, duration ~90 s
3	braking on tarmac ~50 km/h, ABS
4	braking on tarmac ~50 km/h, ABS
5	braking on tarmac ~50 km/h, ABS
6	braking on tarmac ~50 km/h, ABS
7	braking on tarmac ~50 km/h, ABS
8	braking on tarmac ~50 km/h, ABS
9	braking on gravel ~30 km/h, without ABS
10	braking on gravel ~30 km/h, without ABS
11	braking on gravel ~30 km/h, without ABS

3.1. Preliminary test results

The measured data acquired from both devices during the tests have been written into comma-separated-values text files, which were subsequently transferred to a personal computer for analysis. The analysis included an evaluation of the signal shape and characteristics. Fig. 6 shows a sample measurement with unfiltered accelerometer output. Based on the analysis of the signal and the noise present in it, the filtering parameters were selected and tested. After the suitable filters were applied, the measured acceleration curves were compared between the prototype device and the VC4000 as shown in Fig. 7. The comparison shows a good agreement between the two curves. The correlation between the measured signals was also quantified and verified by computing the Pearson coefficients (Ambrož et al. 2019), which were consistently over 0.8 for the subsequent tests.

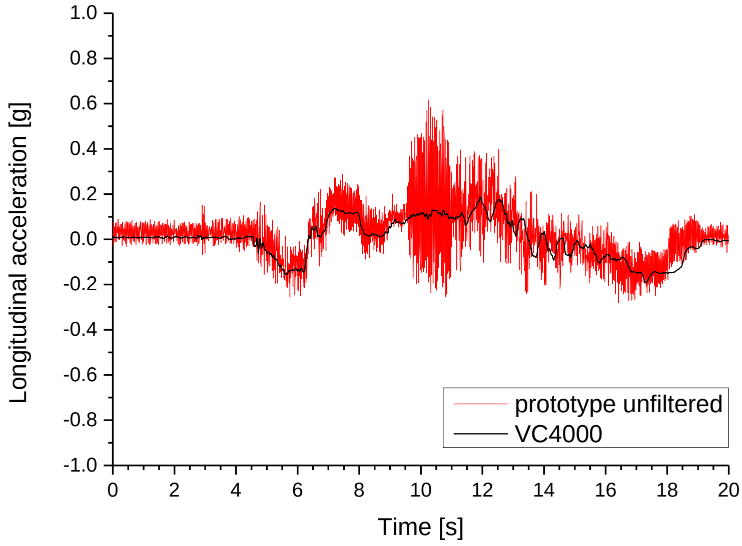

Fig. 6 Sample preliminary measurement acceleration curve with unfiltered output

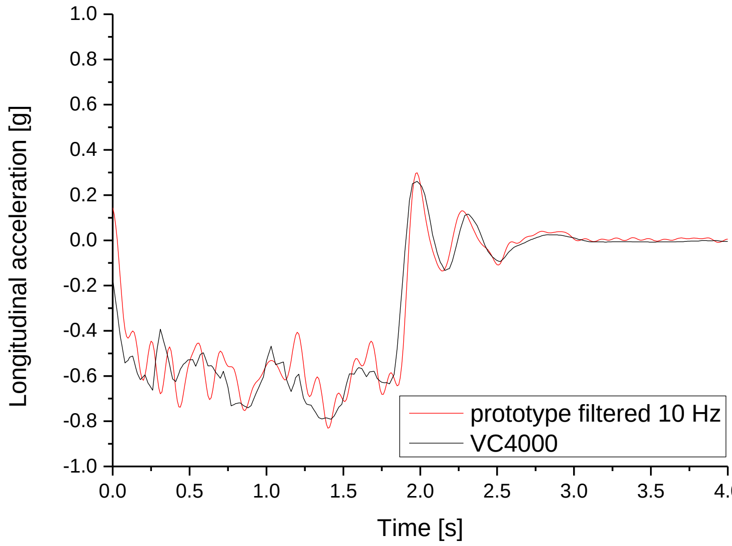

Fig. 7 Sample measurement acceleration curve after applying hardware 10 Hz low pass filter on accelerometer

3.2. Design modifications

Based on the findings from the preliminary tests the software on the prototype device was adjusted to apply the hardware 10 Hz low pass acceleration filtering and add automatic sensing of the thresholds for starting and ending the measurement during a brake test. The data acquisition routines were optimised to ensure stable sampling with the required frequency of 100 samples per second.

The modified design was further tested together with the VC4000 on a tilt device (Fig. 8) to make sure the measured values and triggering thresholds are comparable between both devices. Fig. 9 shows the acceleration time curves from one such test. It can be observed that the start measurement triggering at negative 0.2 g occurs simultaneously on both devices, as does the acceleration change of sign at the end of the measurements. The subsequent tests proved that the differences in the recording time among over 20 brake tests never exceeded 3%.

Fig. 8 Tilt device for testing the measuring values and triggering (left in horizontal position, right in vertical position)

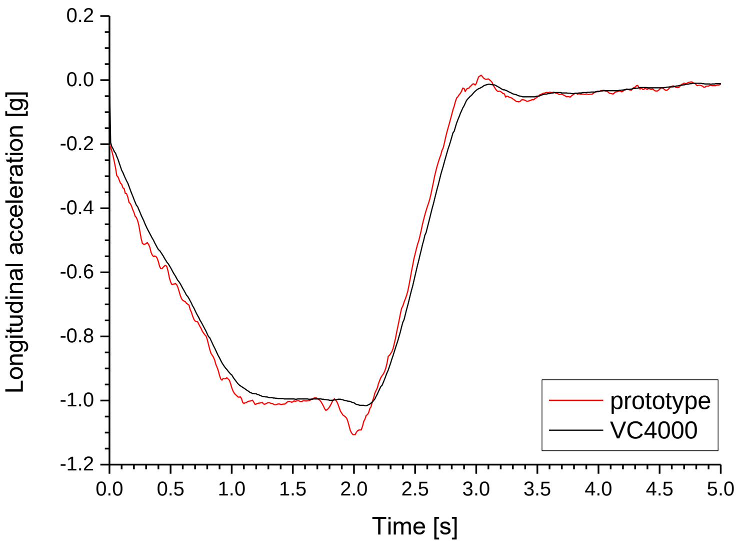

Fig. 9 Comparison of longitudinal acceleration time curves during a test on the tilt device

3.3. Testing the final prototype

The final prototype was tested during a set of braking tests with two different vehicles on different surfaces and with different initial velocities. The prototype device was mounted on the inner side of the vehicle windshield together with the VC4000. Both devices were aligned with the vehicle longitudinal axis in its horizontal plane and set up to trigger the measurement upon reaching the deceleration of 0.2 g. After the tests were completed, the measurement data files were transferred to a computer and analysed for matching between the two devices. The results are summarised in

Table 3, where $\bar{a}$ denotes the average acceleration during the entire braking manoeuvre, t_{m} denotes the measuring time between the two automatic trigger events – measurement start and stop, and $\Delta\bar{a}$ denotes the relative difference between the average measured acceleration values between the prototype device and the VC4000.

Table 3. Results from braking tests.

No.	Vehicle, surface, initial velocity	$\bar{a}$ (g)	t_m (s)	$\Delta\bar{a}$ (%)
1	Opel Zafira on tarmac, 60 km/h	−0.74	2.57	1.64
2	Opel Zafira on tarmac, 65 km/h	−0.67	2.88	0.36
3	Opel Zafira on tarmac, 60 km/h	−0.71	2.65	1.07
4	Opel Zafira on tarmac, 60 km/h	−0.68	2.61	1.36
5	Opel Zafira on gravel, 40 km/h	−0.52	2.21	0.23
6	Opel Zafira on gravel, 48 km/h	−0.49	2.79	−0.02
7	Opel Zafira on gravel, 38 km/h	−0.50	2.21	0.81
8	Renault Clio on wet skid pad, ~40 km/h	−0.41	3.02	3.22
9	Renault Clio on wet skid pad, ~40 km/h	−0.41	3.04	3.33
10	Renault Clio on wet skid pad, ~40 km/h	−0.42	2.99	3.50
11	Renault Clio on wet skid pad, ~40 km/h	−0.45	2.74	4.45
12	Renault Clio on wet skid pad, ~40 km/h	−0.42	2.85	4.53
13	Renault Clio on wet skid pad, ~40 km/h	−0.41	2.80	4.26
14	Renault Clio on dry tarmac, ~50 km/h	−0.80	1.43	5.46
15	Renault Clio on dry tarmac, ~50 km/h	−0.78	1.51	4.91
16	Renault Clio on dry tarmac, ~50 km/h	−0.81	1.50	3.77
17	Renault Clio on dry tarmac, ~50 km/h	−0.79	1.34	3.59
18	Renault Clio on dry tarmac, ~50 km/h	−0.80	1.40	4.94
19	Renault Clio on dry tarmac, ~50 km/h	−0.80	1.41	4.17
20	Renault Clio on wet skid pad, ~40 km/h	−0.30	3.38	1.86

Figures 10 and 11 show the comparison of two sets of acceleration time curves acquired during two of the braking tests. For each pair of curves the basic statistics have been computed in order to assess the level of match between the two devices.

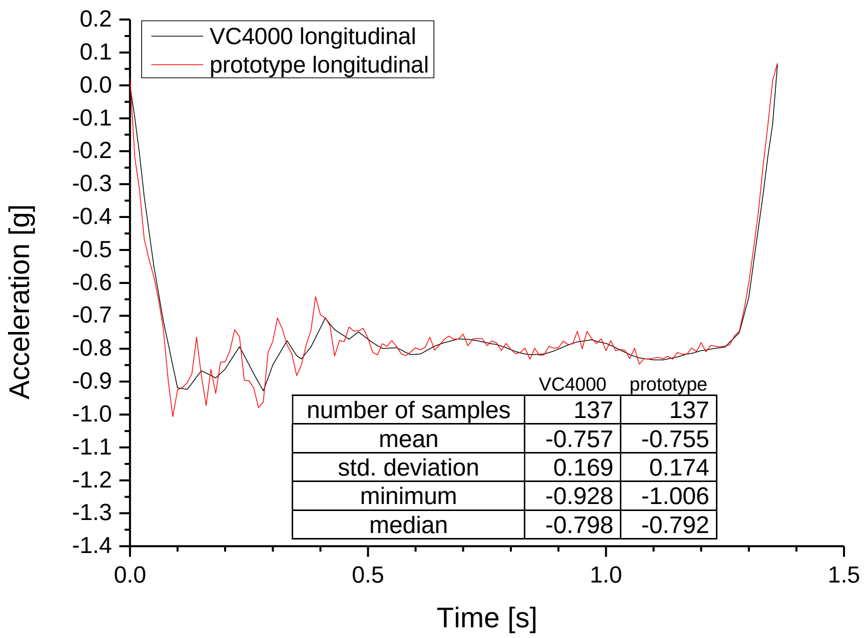

Fig. 10 Measured acceleration during braking (passenger car on dry tarmac, initial speed 40 km/h).

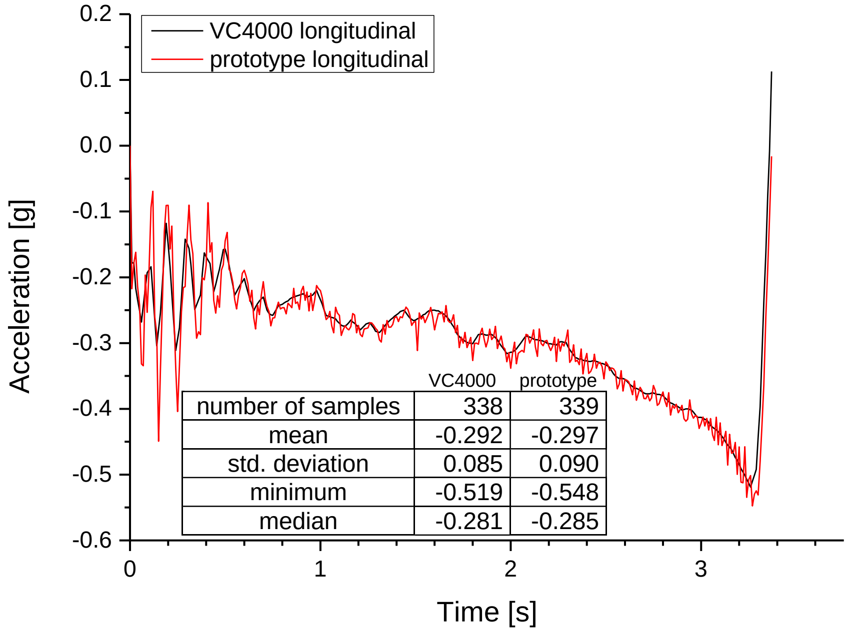

Fig. 11 Measured acceleration during braking (passenger car on wet skid pad, initial speed 40 km/h).

3.4. Building the connected system

The connected system as outlined in the initial project target requires a framework for data transfer, storage and manipulation. To simplify the prototype device hardware and to save the cost of transferring data over metered connections using public mobile networks, we designed the prototype device to store the brake test data locally and transfer them to a server over Wi-Fi connection. For this to work, the server runs a software, which monitors the Wi-Fi connections and automatically initiates a data pull request to any of the known prototype devices appearing in the Wi-Fi range. This way the data is transferred from the devices to the server after each set of tests when the vehicles equipped with the prototype device return to the base.
As a proof of concept we have built and tested another copy of the prototype device, and connected it to the system. The system is currently being introduced within a small-scale pilot project employing six prototype device units in road inspector's vehicles.

4. Conclusions

Presented development of a low-cost device for measuring the roadway friction properties, manufacture of its prototypes and the measurement tests, prove that by careful design and component selection it is possible to design such a device and use it to obtain measurement results comparable to those from much costlier specialised measuring devices. The low cost of the material and open software enable manufacturing of several copies and their installation in vehicles that daily traverse the road network as part of their regular assignments. Such a setup will make it possible to measure the road friction properties even on locations where regular measurements are not done.
The prototype devices are connected to a server where the data from the measurement files are automatically stored into a database. The data is available on-line to the management authorities for analyses. Further development is planned and will include a GIS system for display of data on an interactive map and connection to the existing traffic data systems. The database of the measurements, which will accumulate by using the system over time, will provide an insight into the influence of various environment parameters on the friction properties of the roadway surfaces.
After the evaluation of the results we plan to continuously expand the system with new copies of the device and eventually enlarge the measurement area.

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References

Wallman, C.-G., Åström, H. Friction Measurement Methods and the Correlation between Road Friction and Traffic Safety. A Literature Review; Swedish National Road and Transport Research Institute: Linköping, Sweden, 2001.

Mataei, B.; Zakeri, H., Zahedi, M., Nejad, F.M. Pavement Friction and Skid Resistance Measurement Methods: A Literature Review. Open J. Civ. Eng. 2016, 6, 537–565.

Regulation No 13 of the Economic Commission for Europe of the United Nations (UN/ECE). Uniform Provisions Concerning the Approval of Vehicles of Categories M, N and O with Regard to Braking; UN/ECE, Geneva, 2016; Volume 194.

Ambrož, M., Hudomalj, U., Marinšek, A., Kamnik, R. Raspberry Pi-Based Low-Cost Connected Device for Assessing Road Surface Friction, Electronics 2019, 8, 341.

Andria, G.; Attivissimo, F.; Di Nisio, A.; Lanzolla, A.M.L.; Pellegrino, A. Development of an automotive data acquisition platform for analysis of driving behavior. Measurement 2016, 93, 278–287.

Virant, M.; Ambrož, M. Universal Safety Distance Alert Device for Road Vehicles. Electronics 2016, 5, 19.

Ambrož, M. Raspberry Pi as a low-cost data acquisition system for human powered vehicles. Measurement 2017, 100, 7–18.

Lewis, A.J.; Campbell, M.; Stavroulakis, P. Performance evaluation of a cheap, open source, digital environmental monitor based on the Raspberry Pi. Measurement 2016, 87, 228–235, doi:10.1016/j.measurement.2016.03.023.

Raspberry Pi Foundation: Raspberry Pi Zero W. https://www.raspberrypi.org/products/raspberry-pi-zero-w/ (accessed on 9 April 2019)

Vericom LLC. Motion Performance Instruments. https://www.vericomcomputers.com/products/ (accessed on 4 April 2019)