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THE POSSIBILITIES OF UTILISING THE SKIDDOMETER T2GO FOR FORENSIC ENGINEERING

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Abstract. The aim of the paper is to verify the applicability of the T2GO skiddometer for measuring the coefficient of friction for forensic practice in accordance with the legislative framework of the Czech Republic. In the introduction, the article discusses the problem of friction coefficient measurement. The results of the comparison with dynamic measuring devices used in the Czech Republic and the determination of the mutual compliance rate with these devices, based on data obtained within the National Comparative Measurement Action, are presented. The article concludes with an interpretation and discussion of the results. In cases where no sufficient mutual compliance was found, an analysis and reasoning of these results is provided. Last but not least, based on the results, a procedure is proposed for future use of the T2GO skiddometer in practice within the legislative conditions of the Czech Republic.

Keywords: Forensic engineering, friction, walking speed measuring device.

1. Introduction

The assessment of the safety attributes of the road surfaces, airport surfaces, as well as pedestrian and cycling infrastructure surfaces is one of the most important ways to ensure an adequate level of surface safety, and therefore to reduce the societal losses caused by the inadequate quality of a particular surface. It is generally known that there is a relationship between the risk of an accident and the surface qualities, not only of the road surface, whereby as the skid resistance of the surface decreases, the braking distance increases and thus the risk of an accident increases [1, 2].

Currently, one of the most used methods for assessing the quality of surfaces is the measurement by continuous friction measurement equipment (CFME), which determine the coefficient of friction by rolling the measuring wheel on the surface. The disadvantage of most of these devices is the measuring speed, which corresponds to the speed of normal traffic on roads, with the associated complications such as the need to provide road closures to maintain a constant measuring speed, the impossibility of carrying out measurements in difficult conditions due to the need for adequate space to achieve the measuring speed, high consumption of water sprinkling, or the equipment's high operating costs. These disadvantages are eliminated by CFME devices such as the T2GO, with the ability to continuously measure the coefficient of friction of the surface at walking speed, which limits the measurement of this device over long distances, but on the other hand has the ability to measure in confined spaces, at local accident sites, or on sidewalks or pedestrian crossings. The T2GO can therefore work well as a complementary measuring device to standard dynamic meters for specific local investigations.

This article discusses the experiment of comparative measurement of the T2GO skiddometer with standard dynamic measuring devices, the aim of which is mainly to verify the accuracy of the T2GO measurement, to determine the rate of mutual compliance of its measurement with standard dynamic measuring devices and also to examine possible ways resulting in the real use of the T2GO in practice, in accordance with Czech technical standards.

1.1. State of the art

For the assessment of road surfaces, a large number of different measuring devices have been developed over time, especially those for the determination of the coefficient of friction by continuous measurement (CFME devices), which are often more suitable and considerably faster for practical use than the previously mentioned conventional stationary devices. At present, there is no uniform approach to the measurement of the coefficient of adhesion, nor to the specific specification of individual measuring devices. Therefore, a large number of countries or companies involved in surface quality assessment develop their own measuring devices, which often differ from each other, e.g. in design, measuring speed, type of measuring tyre used, load on the measuring wheel, thickness of the water film required, slip ratio, slip angle, etc [3–5].

Several foreign publications deal with the practical use of the T2GO device for various purposes. Some possible examples include the Chang'an University article that discusses the effect of particle pollutants on skid resistance of AC-13 asphalt pavement on wet and dry surface. Another research conducted by the Shanghai Normal University was focused on dynamic variation of the friction coefficient and its deterioration mechanism if the road surface is covered with snow or ice. However, both of these studies are focused only on the change of the coefficient of friction due to a polluted road surface [6, 7].

The experimental use of the T2GO device occurred within the testing of a special road surface, porous rubber pavement, at the University of Waterlooo. This special type of surface is not currently widely used in pavements. In Canada, its use is only limited to low volume traffic and low driving speed areas like parking lots and driveways. As a pavement material, its performance is still unexplored for the Canadian climate. This is precisely the focus of the cited research. In this research, the T2GO and British Pendulum Tester was used to measure the coefficient of friction of this surface and both devices showed similar values. However, it is a very specific surface with diametrically different characteristics than standard road surface types [8].

Interconversion of locked-wheel and continuous friction measurement equipment friction measurements was the subject of Virginia Polytechnic Institute and State University research. This research evaluates various methods to convert measurements from the traditional locked-wheel skid testers (LWSTs) to CFME, proposing a speed adjustment-based approach (FR60) as the most effective, with comparable accuracy to the full IFI F60 formula but without the need for static reference measurements. The study confirms appropriate repeatability of the three tested devices across different speeds and surfaces. However, these are not devices similar in characteristics to the T2GO device [9].

Based on the above, it can be concluded that there are scientific publications regarding the use of T2Go devices. However, this is only a simple use of the T2GO device for various research tasks, not a comparison with other dynamic devices and a search for correlations within different measuring speeds.

2. Methods for measuring friction

One of the many critical factors for road safety in all categories is friction, i.e. the contact between the vehicle tyre and the road surface, as mentioned earlier. The assessment of the skid resistance of road surfaces can be carried out in several ways. Indirectly, surface quality can be determined by analysing the texture of the unpolluted pavement surface, while direct methods of surface analysis are based on measuring the amount of friction between the surface and the measuring device. The most common and simplest method for assessing pavement texture is the so-called gauge (sand) method. The gauge method is used to determine the mean depth of surface texture (Mean Texture Depth – MTD), in other words, it determines the total volume of surface depressions. Of the group of methods for direct surface quality assessment by friction measurement, the British pendulum tester is probably the oldest and simplest.

A large number of different measuring devices have been developed over time for the assessment of road surfaces, especially those for the determination of the coefficient of friction by continuous measurement (CFME devices), which are often more suitable and considerably faster than the previously mentioned classical stationary devices for practical use. Currently, there is no uniform approach to the measurement of the friction coefficient, nor to the exact specification of the individual measuring devices. Therefore, a large number of countries or companies involved in surface quality assessment develop their own measuring devices, which often differ from each other, for example, in design, measuring speed, type of measuring tyre used, load on the measuring wheel, thickness of the water film required, slip ratio, slip angle and others [3–5].

2.1. T2GO

The T2GO depicted in Figure 1 is a hand-pushed, portable device capable of continuous measurement of the longitudinal friction coefficient, with a recording step of at least 0.1 m and at a walking speed of approximately 2.5–4.0 km h^{-1}. Due to the low operating speed, no space is required to run the device up to the measuring speed and the measurement can be started almost immediately after the device is set in motion. Therefore, the T2GO is suitable for measurements, in locations with insufficient access or safety level, for standard dynamic devices measuring continuously at travel speeds. The T2GO measures the coefficient of longitudinal friction with a fixed slip ratio of 20 % when the measuring wheel is loaded with a force of 70 N and is capable of measuring on dry and wet surfaces and is equipped with a sprinkling system that applies a 0.5 mm water film in front of the measuring wheel on the surface to be measured [10].

$$\text{slip ratio} = \frac{\text{slip rate}}{\text{measuring speed}} \cdot 100\,[\%]. \qquad (1)$$

Figure 1. Skiddometer T2GO.

The T2GO skiddometer consists of two basic parts, the measuring device body and the operating terminal. The terminal is located on the handle of the device, which also serves to provide a water supply, by a hose from an 18 l portable tank (carried by the measuring technician on his back), to the nozzle in front of the measuring wheel. The body of the device consists of a load-bearing steel chassis which holds a pair of wheels (with smooth tyres in accordance with ASTM E1844) in series behind each other and fitted with different sized gears which are connected by a V-belt. In this way, the slip ratio between the front measuring wheel and the rear running wheel is defined. During the measurement, the V-belt between the wheels is tensioned, depending on the roughness of the surface, and the force with which the belt is tensioned is measured by a load cell located in the center of the device above the belt, between the wheels. At the same time, the device is equipped with a sensor for detecting the wheel speed, on the basis of which, in combination with the measured applied force from the belt or the measuring wheel, the longitudinal friction coefficient is determined. The T2GO skiddometer is also equipped with sensors for measuring temperature, humidity and a GPS module for recording the position of the measuring device at the start and end position of the measured line. The entire measuring device system is powered by a 12 V Li-ion battery with a capacity of 6 600 mAh.

The operating terminal on the handle of the skiddometer is used for basic operation, setting and calibration of the device, starting and stopping the measurement, or regulating the water supply to the device from a portable tank with an integrated pump. All data obtained during the measurement are transmitted on-line via Bluetooth port to a tablet, which is part of the T2GO skiddometer accessories and is equipped with a dedicated application for managing the measured data, such as storing it, displaying graphs of the measured longitudinal friction coefficient in real time, displaying the speed of the device movement and providing supervision of the appropriate measurement speed or the angle of inclination of the device handle via warning tones.

2.2. Comparison

The first available comparison (see Table 1) is a comparison made by SARSYS-ASFT itself, which establishes a comparison between the T2GO and the T-5S skiddometer (at 65 km h^{-1}), also of its own manufacture. This is a comparison of five measurements, over a 100 m length, made on both wet and dry surfaces, consisting of an unspecified mixture. The result of this comparison is a comparison between the two devices, which is 99.52 % for the measurements on the dry surface and 99.52 % on the wet surface [11].

Another comparison is the comparison of the measurements (made by the Swedish National Institute for Road and Transport Research – VTI) of the T2GO and the VTI PFT (Portable Friction Tester). In this case it is a comparison of measurements made on ten different samples of wet road markings of different age

Dry measurements		**Wet measurements**	
T2GO	**T-5S**	**T2GO**	**T-5S**
0.84	0.83	0.71	0.7
0.83	0.84	0.69	0.69
0.86	0.84	0.72	0.69
0.85	0.85	0.68	0.68
0.85	0.85	0.7	0.68
Average 0.846	**Average 0.842**	**Average 0.7**	**Average 0.688**

Table 1. Comparison of results with T-5S.

and quality. The results of this comparison, which can be seen in the Table 2, clearly show similar results for the two devices being compared.

3. Comparative measurement

For the purpose of comparing the measurement results of standard dynamic devices with the T2GO, two devices were selected, namely the BV 11 and the National Reference Device – Tatra Runway Tester (TRT). The recording step of both devices is 1.0 m. For this reason, the values obtained by T2GO (every 0.1 m) were averaged into a format that corresponds to the data format of the TRT and BV 11 device. The characteristics of the individual surfaces correspond to those that are standardly, most frequently, used in the Czech Republic and cover the entire range of the classification scale evaluating the coefficient of friction of road surfaces. These are mainly asphalt surfaces, cement concrete surfaces, various types of road markings and safety anti-slip surface.

3.1. Individual results

The input measured data for the following evaluation are of the following structure. For TRT and BV 11, one data set corresponding to one measurement was used for each speed. This approach is possible due to the long-term guaranteed repeatability of the measurements of these devices. On the other hand, in the case of the T2GO device, the average of the results obtained in three repeatable measurements is used for each comparison section. Primarily, this was done to eliminate any unexpected deviation in the measurement.

3.1.1. Asphalt surface

The surface is characterised by its significant macrotexture, which is mainly determined by the coarseness of the aggregate used in the asphalt mix of the surface cover, which ranges from approximately 4–15 m. The aggregate used also has a relatively pronounced microtexture and protrudes considerably from the surface of the asphalt binder mixture. As can be seen in Figure 2, the values of the coefficient of friction measured on this surface are relatively close to each other, across

Surface No.	Measurement 1	2	Verifictaion Device	Deviation	Precision
1	0.74	0.73	0.76	0.02	0.01
2	0.52	0.5	0.66	0.14	0.01
3	0.59	0.6	0.65	0.06	0.01
4	0.66	0.62	0.69	0.03	0.04
5	0.63	0.64	0.65	0.02	0.01
6	0.67	0.72	0.67	0	0.05
7	0.73	0.71	0.67	0.06	0.02
8	0.48	0.5	0.39	0.09	0.02
9	0.67	0.73	0.69	0.02	0.06
10	0.7	0.63	0.66	0.04	0.07
Average	**0.64**	**0.64**	**0.65**	**0.05**	**0.03**

TABLE 2. Comparison of results with VTI PFT (Portable Friction Tester).

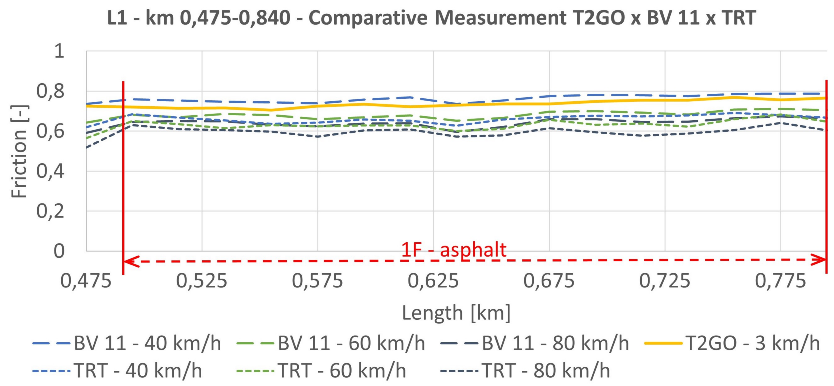

FIGURE 2. Comparison of T2GO × BV 11 × TRT measurements on asphalt surface.

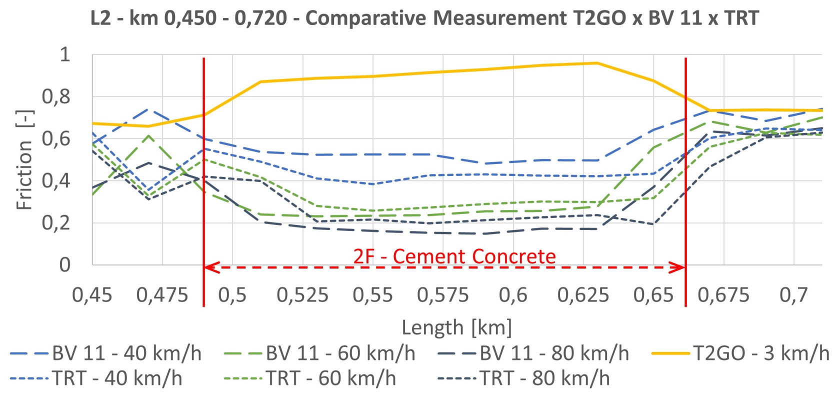

FIGURE 3. Comparison of T2GO × BV 11 × TRT measurements on a cement concrete surface.

all three devices, and approximately match the nature of the surface.

3.1.2. Cement concrete surface

This surface is formed, in addition to the binder, by aggregate with dimensions of 1–10 mm, while its upper layer is roughened and its projections thus fall primarily into the category of microtexture, with almost minimal macrotexture irregularities. While the friction coefficient values of the BV 11 and the TRT are relatively regularly scaled depending on the speed, the friction coefficient values measured by the T2GO are in a completely different range of values. The results are shown in Figure 3. Such significantly different measurement curves between the standard dynamic measuring devices and the T2GO are due to the surface characteristics already mentioned and, above all, to the effect of the different measuring speeds of the measuring devices involved. The cement concrete surface has a minimal macrotexture due to the surface

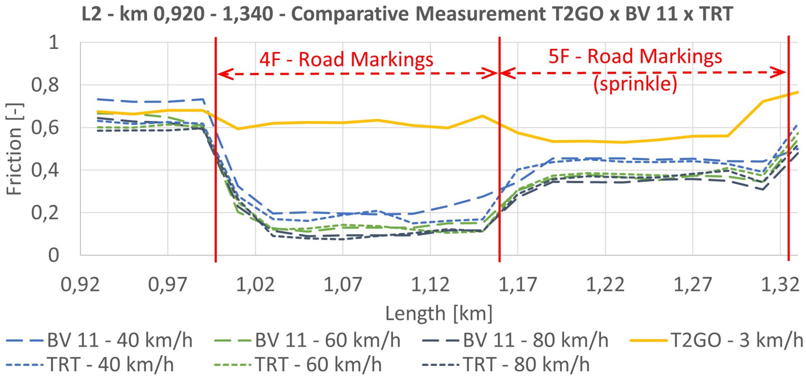

FIGURE 4. Comparison of T2GO × BV 11 × TRT measurements on road markings.

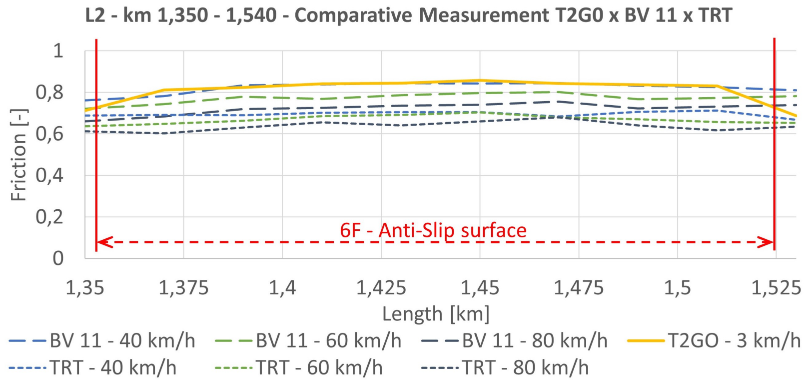

FIGURE 5. Comparison of T2GO × BV 11 × TRT measurements on anti-slip surface.

modification and is thus evaluated as very slippery when measured with standard dynamic measuring devices, i.e. it has a low resulting coefficient of friction, due to the fact that the microtexture of this surface itself is not able to transfer the necessary amount of frictional forces from the measuring wheel at speeds of $20\,\mathrm{km\,h^{-1}}$ or more. However, the measuring speed of the T2GO, $4\,\mathrm{km\,h^{-1}}$, is located in the interval where the microtexture has the largest effect on the friction coefficient, which is also reflected in the friction coefficient measured on this surface.

3.1.3. Road markings

The third and fourth surfaces are road markings without and with ballotine sprinkles, respectively. From Figure 4, it is evident that the T2GO skid tester measured significantly higher values for the road markings without ballotine sprinkles compared to other dynamic devices, despite the smoother microtexture of the surface, which subjectively feels slippery, aligning with the values obtained by standard dynamic measuring devices. The fourth measured sample is a road marking with ballotine sprinkles, where the surface is covered with abrasive balls up to 1 mm in size to improve the friction coefficient during driving. During T2GO skid tester measurements, an opposite trend emerged, and the average friction coefficient for the horizontal marking with ballotine sprinkles was slightly lower compared to the marking without ballotine sprinkles, even though the ballotine sprinkles treatment created macrotexture on the horizontal traffic marking. This reduction in the average friction coefficient is due to the atypical surface of the ballotine sprinkles, which are smooth and lack microtexture compared to the marking without ballotine sprinkles, which has some minimal microtexture. On the other hand, when measuring with standard dynamic devices, the microtexture of the surface is not as crucial due to the higher measuring speed, and the added macrotexture created by ballotine sprinkles enhances its adhesive properties.

3.1.4. Anti-slip Surface

It is a special mixture of binder and crushed bauxite, applied to an existing asphalt surface, with a very distinctive macrotexture and microtexture of individual bauxite grains. The surface texture corresponds to the measured averages of the BV 11 and the TRT, which are at very high levels for all three measuring speeds. The average value of the coefficient of friction obtained by the T2GO is also very high. The graph clearly shows that all devices show very similar values on this surface. Therefore, a successful mutual compliance can be observed on this surface as demonstrated by Figure 5.

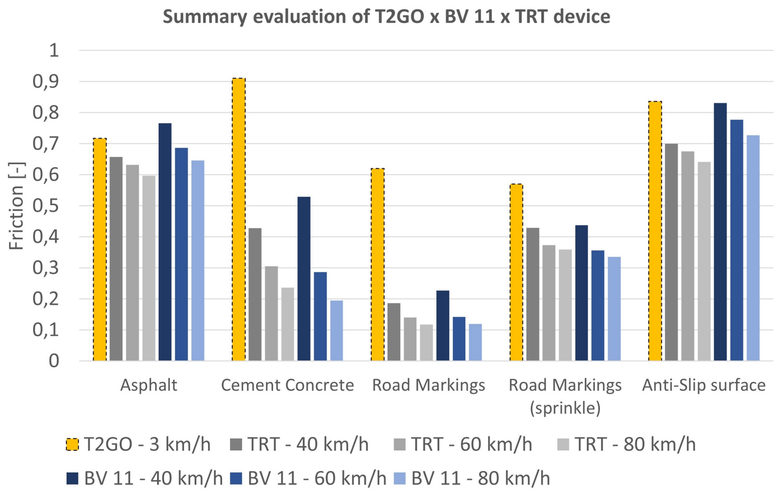

Figure 6. Summary evaluation of T2GO × BV 11 × TRT device.

	Asphalt [∅ **Fp**]	**Cement concrete** [∅ **Fp**]	**Road markings** [∅ **Fp**]	**Road markings (sprinkle)** [∅ **Fp**]	**Anti-Slip surface** [∅ **Fp**]
T2GO $3\,\mathrm{km\,h^{-1}}$	0.72	0.91	0.62	0.57	0.84

Table 3. Average results of T2GO.

	National Reference TRT measuring device									
	[∅ **Fp**]	[%]	[∅ **Fp**]	[%]	[∅ **Fp**]	[%]	[∅ **Fp**]	[%]	[∅ **Fp**]	[%]
TRT $40\,\mathrm{km\,h^{-1}}$	0.66	91.60	0.43	47.02	0.19	30.00	0.43	75.21	0.70	83.63
TRT $60\,\mathrm{km\,h^{-1}}$	0.63	88.14	0.30	33.48	0.14	22.49	0.37	65.43	0.67	80.68
TRT $80\,\mathrm{km\,h^{-1}}$	0.60	83.18	0.24	25.93	0.12	18.92	0.36	62.90	0.64	76.61

Table 4. Percentage agreement of devices T2GO and TRT.

	Skiddometr BV 11									
	[∅ **Fp**]	[%]	[∅ **Fp**]	[%]	[∅ **Fp**]	[%]	[∅ **Fp**]	[%]	[∅ **Fp**]	[%]
BV 11 $40\,\mathrm{km\,h^{-1}}$	0.77	93.15	0.53	58.09	0.23	36.61	0.44	76.63	0.83	99.30
BV 11 $60\,\mathrm{km\,h^{-1}}$	0.69	95.77	0.29	31.42	0.14	22.87	0.36	62.47	0.78	92.86
BV 11 $80\,\mathrm{km\,h^{-1}}$	0.65	90.13	0.19	21.35	0.12	19.17	0.33	58.70	0.73	86.90

Table 5. Percentage agreement of devices T2GO and BV11.

3.2. Overall results

Based on the above analysis of the measured data on these surface types, it is clear that the mutual compliance between the T2GO and standard dynamic measuring devices only occurs on specific surface types that indicate a sufficient representation of macrotexture, but also a certain quality of microtexture within the surface structure. A summary of the results of the comparative measurements with TRT and BV11 is presented in the following Figure 6.

This trend can also be observed from the percentage agreement of measurements with T2GO, shown in Table 3, Table 4, and Table 5 compared to standard dynamic measuring devices, where the highest level of agreement was found on asphalt surfaces with safety anti-skid treatments, which have the most pronounced macrotexture. Some agreement of measured data was also observed on horizontal traffic markings with abrasives, although it was likely negatively influenced by the nature of the microtexture, to which T2GO measurements are highly sensitive due to its low measuring speed.

Figures 7 and 8 below show the resulting comparison of the T2GO results compared to the TRT and BV 11 devices on each surface. This graphical illustration indicates again a significant dispersion between the

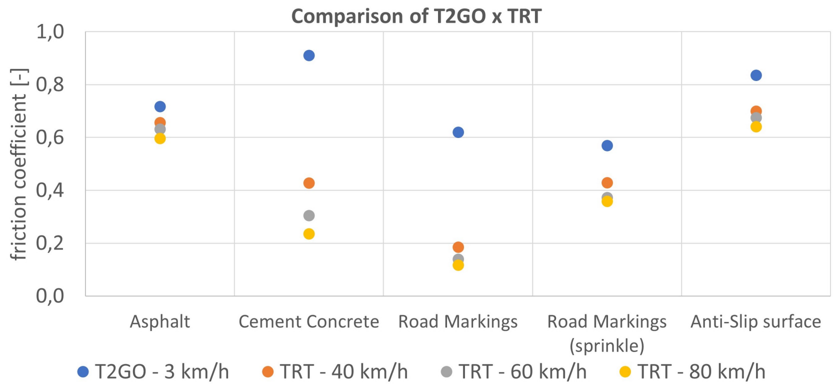

Figure 7. Comparison of T2GO and TRT.

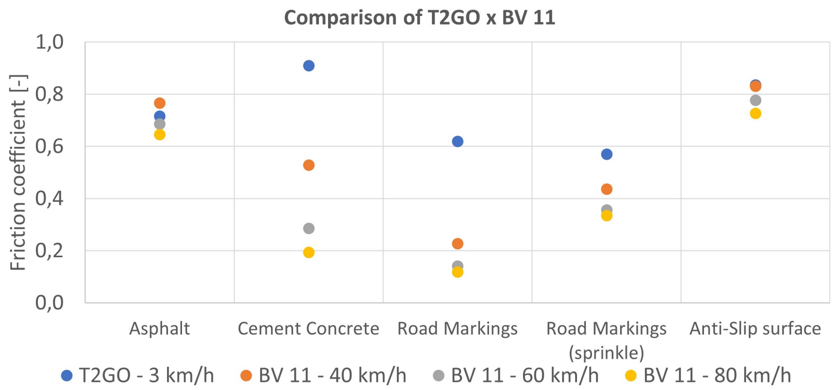

Figure 8. Comparison of T2GO and BV 11.

measured results on the cement concrete surfaces and the two types of road markings.

3.3. The issue of different measuring speeds

Based on the conducted research, knowledge of technical specifications of the compared devices, and the results of comparative measurements, it is evident that the results of measurements by dynamic devices at higher speeds (TRT and BV 11) are significantly influenced by the quality of macrotexture. Conversely, the microtexture of the surface does not have an impact on the results due to the high measurement speeds, as the texture of individual parts of the surface layer cannot be taken into account from a physical perspective at these speeds. However, at very low measuring speeds, as used by T2GO, the results are almost exclusively affected by the microtexture of the surface. At such low speeds, the T2GO skiddometer is capable of considering the micro-textural properties of the surface, but for the same reason, it is unable to assess the qualities of macrotexture.

However, it is not entirely necessary to achieve identical values with the T2GO skiddometer as with dynamic devices, but it is at least essential to identify a similar trend within the measured data. In this case, it is possible to determine a conversion coefficient between the compared devices. However, this can only be done for two out of the five tested surfaces.

From the above-mentioned partial measurement results on individual surfaces, it is evident that there is a discrepancy in the outcomes, which is caused by different measuring speeds in relation to distinct qualitative states of microtexture and macrotexture. On surfaces that show significant or at least sufficient quality in both microtexture and macrotexture, satisfactory results were attained (asphalt and anti-slip surface). The compared data demonstrate very similar values or reflect a similar trend, indicating a successful possibility of using the T2GO skiddometer in practice. At the same time, based on the findings, it cannot be definitively stated that the friction coefficient values determined by the T2GO skiddometer, especially on surfaces with unsuccessful mutual compliance, are unequivocally unsatisfactory. They may be considered as values that are suitable for other speed levels, given the characteristic measurement capability of the T2GO skidometer, which measures at speeds of 2.5–4 $\mathrm{km\,h^{-1}}$. As mentioned earlier, due to this measurement speed, the microtexture of the surface is predominantly considered, which is why the friction coefficient values on surfaces with dominant microtexture and less favorable macrotexture are considerably higher compared to measurements conducted by standard dynamic measuring devices. Based on this reasoning, we can say that the T2GO skiddometer is potentially applicable for assessing anti-skid properties of surfaces in areas where the traffic speed does not exceed $20\,\mathrm{km\,h^{-1}}$, a speed at which the influence of microtexture on anti-skid properties is most significant. Such areas may include pedestrian and cyclist infrastructure, pedestrian crossings, or certain road sections in close proximity to pedestrian crossings, where vehicles decelerate and move at low speeds.

4. Discussion

All comparative measurements performed with the T2GO allow significant clarification of the correlations and deviations in the measurements reported by the manufacturer, which incompletely assess the measurement capabilities of the T2GO only on selected types of surfaces. The mutual compliance of the T2GO with TRT and BV 11 measuring devices on five reference surfaces was assessed. The results of these comparative measurements indicate that the overall mutual compliance of the T2GO with standard dynamic measuring devices is too low to consider a successful correlation. When considering the mutual compliance of the T2GO with other measuring devices on individual surfaces individually, the results are much more acceptable. In fact, a mutual compliance was found between the TRT National Reference Device and the BV 11 on asphalt surfaces. A sufficient level of mutual compliance has been identified for these two standard dynamic measuring devices even on the anti- slip surface. For these surfaces and surfaces with similar characteristics, with a dominant macro-texture (and also some micro-texture), the realistic use of the T2GO for the assessment of the surface properties of conventional road surfaces can be considered. An insufficient mutual compliance was found in the case of the cement concrete surface and the road markings without balotine sprinkling. Thus, the use of the T2GO for assessing the slip resistance properties of these 303–304 surfaces and, in general, of surfaces with predominantly microtextured road surfaces in practice cannot be recommended.

5. Conclusions

At present, it is not technically possible to implement the T2GO skiddometer in the Czech standards in the usual way, as the standards and technical specifications concerned do not recognise the concept of dynamic measuring devices operating at walking speed. Assuming that the European Technical Specification CEN/TS 15901, following the example of ASTM E3304-22, for the T2GO skiddometer is obtained, it is necessary to modify the measuring speed, suitable for dynamic measuring devices operating at walking speed, in the Technical Specification TP 207, which establishes the conditions of participation and the course of the Equipment Accuracy Experiment. Another necessary modification to this Technical Specification is the addition of an alternative method of verifying the accuracy and correlation of dynamic measuring devices operating at walking speed with the National Reference Measurement Device. A possible solution is to establish a comparison procedure for these devices with the British pendulum tester, which is more suitable for these purposes than standard dynamic measuring devices, even though the British pendulum tester device is only able to measure pavement surface characteristics point by point. Another possible solution seems to be the establishment of a separate standard for the assessment of the characteristics of surfaces with low speed of traffic, including pedestrian and cycling infrastructure. This standard would address the assessment of these surfaces by dynamic measuring devices operating at walking speed, with an upper limit of approximately $20\,\mathrm{km\,h^{-1}}$ for the operating speed of the surfaces assessed under this standard. Therefore, the T2GO is currently only applicable in the context of forensic expertise for the purpose of indicative determination of the coefficient of friction on asphalt surfaces and generally on surfaces with a dominant surface macrotexture.

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