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Thermal Analysis of Pavement for the East Bielsko-Biala Bypass

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ABSTRACT
Road surface temperature and road longitudinal temperature gradient value, may present a considerable challenge in the matter of traffic safety. The awareness of thermal conditions with due regard to location of significant temperature variability areas could be desirable information for road infrastructure operators. That knowledge would allow to select an appropriate location of traffic signs, variable message signs and road weather stations. In the wintertime it would enable road maintenance authorities to take more efficient actions. In the study authors present road surface temperature variability analysis based on measurements conducted on a 6.25-kilometer section of eastern bypass of Bielsko-Biala city. In analysis authors used the data from mobile road weather sensor. The sensor enables to measure road surface and dew point temperature, water film height and calculated friction.

KEYWORDS: mobile road sensor, road surface temperature, traffic safety

1. Introduction

Road surface temperature and longitudinal road temperature gradient value, may present a considerable challenge in the matter of traffic safety. While road surface temperature fluctuates around 0 ^{o}C the rapidity of thermal alteration seems be the key issue. Therefore the awareness of thermal conditions with regard to location of significant temperature variability areas could be a desirable information for road infrastructure operators. This knowledge would allow to select an appropriate location of traffic signs, variable message signs and road weather stations. Additionally, in the wintertime it would enable road maintenance authorities to take more efficient actions, paying a special attention to critical road sections [2].

The information about road surface temperature is usually obtained from sensors mounted in the pavement. This type of road sensors are standard equipment of weather stations used in intelligent transportation systems (ITS) solutions. Active sensing devices not only specify road surface and dew point temperature but also determine the presence of chemical agents and deicing substance. Additionally non-invasive sensors can be found more and more often. Non-intrusive measuring apparatus can be installed on gantries or other supporting structures. The examples of such solution may be Lufft NIRS31 sensor, Vaisala DSC111 and also the remote road surface temperature sensor DST111 LAB-EL. It is obvious that the information obtained from road weather information station concerns strict and precisely determined location. Based on stationary sensors measurements it is difficult to conclude on pavement conditions of adjacent road sections. Therefore, it is important that stationary weather stations should be located at selected, most representative points of the network. A highly helpful tool in the selection of such points are the thermal pavement characteristics [4].

The study presents road surface temperature variability analysis based on measurements conducted on a 6.25-kilometer section of eastern bypass of Bielsko-Biala city. The road section is a part of S1 expressway, situated in mountainous terrain. There are relatively many bridge structures and flyovers located on discussed route. As the effect of those specific factors a significant local road surface temperature variabilities may be expected. In analysis authors used the data from advanced mobile road weather sensor MARWIS. The sensor enables determining pavement conditions through road surface and dew point temperature measurement, water film height and calculated friction etc. As a part of analysis several test runs were performed. Measurements on a tested road section where carried out in both directions and in various weather conditions, including air temperature exceeding 25 °C, as well as around -10 °C. A majority of test runs were performed within -5 °C to 2 °C air temperature range, so in potentially most hazardous weather conditions in a matter of traffic safety. The results of presented analysis enables to identify places with high temperature variability.

2. MARWIS sensor

During the test MARWIS mobile road weather sensor was used. It is used to detect road condition by providing information about:

- road surface temperature,
- dew point temperature,
- relative humidity of the air above the road surface,
- water film height,
- ice percentage,
- friction – describing tyre to road adhesion within a range of 0.1 to 1.0,
- surface condition – the sensor distinguishes between 8 surface conditions (dry, damp, wet, snow-/ice-covered, chemical wet, black ice, critically wet),
- road surface temperature measurement is carried out in the range from -40 to 70 °C with a resolution of 0.1 °C, accuracy of ± 0.8 °C.

Sensor should be mounted on vehicle's roof or located on vertical surface such as back door of larger vehicles. During the measurement sensing device cooperates with a MARWIS App, that can be installed on smartphone, tablet or other mobile device. This solution enables to generate additional geolocation data using GPS system.

Before conducting exact road test authors carried out a series of preliminary tests to verify sensor's measurement suitability for the planned measurements. In the first stage fluctuations of the MARWIS sensor readings were determined for the stationary measurement conditions, i.e. when the test car is not moving. In the next phase the test runs were performed using the delineated route enabling appropriate indications repeatability analysis and speed impact relevance. A summary of the obtained results is presented below, while more detailed information is given in [1] and [3].

2.1 Stationary tests

Tests were performed under daylight and after dark. Each time the measurement was carried out twice - once for the dry surface and once for the snow-covered road. Fig. 1 shows exemplary results obtained for day conditions. Additionally, Table 1 presents the standard deviation of the surface temperature measurements.

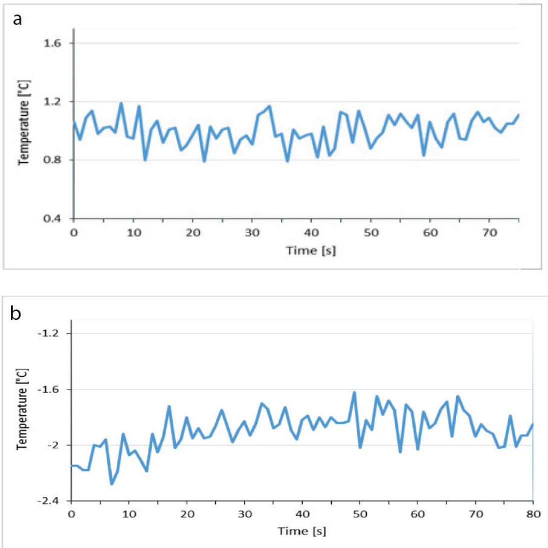

Fig. 1. Road surface temperature obtained in stationary test conducted during the day a) dry road b) snow-covered road [3]

Most relevant conclusions that can be drawn from the results of stationary test are as follows:

- stationary measurements of road surface temperature shows good stability, as evidenced by small values of standard deviation,
- the amplitude of the indication changes is less than 0.5 °C, and therefore does not exceed the accuracy of the measurement declared by the manufacturer.

Table 1. Standard deviation of road surface temperature measurement in stationary conditions [3]

Measurement condition	Standard deviation [oC]
day, dry road	0.098
day, snow-covered road	0.141
night, dry road	0.105
night, snow-covered road	0.117

2.2 Test drives - repeatability of indications

The test runs were carried out in mid-February 2018 in a typical winter weather conditions. The chosen route was relatively short and was about 2.5 km long. This allowed carrying out subsequent drives in small time intervals to minimize the impact of road state changes related to both the state of the atmosphere and the traffic. The drives were realised in two series, three drives per each one. One series was performed in the daylight, the other one after dark. In both cases precipitation did not occur. Road surface temperature on the test route for exemplary night pass is presented in Fig. 2. Road surface temperature for series of drives in daytime conditions as a function of the distance along the test route is presented in Fig. 3.

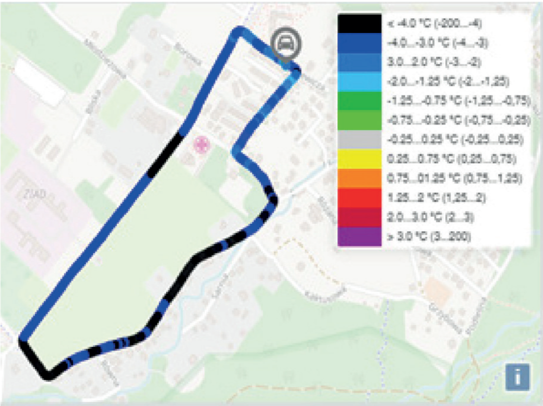

Fig. 2. Road surface temperature on the test route for exemplary night pass [3]

The results and analyses of the test runs indicate a high repeatability of the road surface temperature registered by the MARWIS sensor. The recorded differences in averaged indications for individual sections did not exceed 0.5 °C, what is the nominal measurement accuracy declared by the manufacturer.

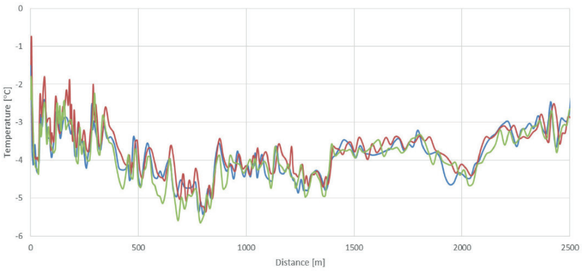

Fig. 3. Road surface temperature along the test route for daytime passes [3]

2.3 Various speed test drives

In order to determine speed impact relevance three test runs were performed. Test drives were realised in daylight conditions at speeds respectively: 30, 45 and 60 km/h. During the measurements the air temperature fluctuated around 2 °C, no precipitation was observed. Fig. 4 presents road surface temperature registered during the variable speed test drives. The introduced results are slightly effected by increasing air temperature registered during the tests. As a consequence, the average surface temperatures for the first, second and third drive were as follows: 2.33 °C, 3,52 °C and 3.68 °C. As the first test run has been realised with a speed of 45 km/h, second with a speed of 60 km/h and the third 30 km/h, it stands to a reason that the average temperature growth was caused by raising air temperature, not by the vehicle speed.

The test vehicle speed change in a range of 30 ÷ 60 km/h did not resulted in a significant impact on the road surface temperature measurement. Obtained temperature discrepancies has not been greater than variability during the stationary tests. As mentioned in [3] authors point out that MARWIS may be used as basic measuring device for local meteorological shield system development on the bypass.

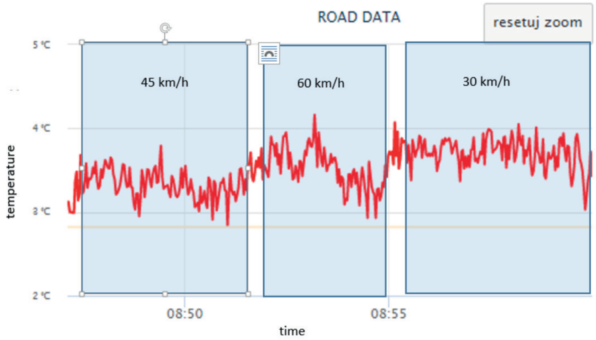

Fig. 4. Road Surface temperature fluctuations at various speed [own study]

3. Test route on the bypass

The road test analysed in this article had been carried out on dual carriageway road section which is a part of eastern bypass of Bielsko-Biala city. Due to the fact that the bypass is situated in mountainous terrain and there are bridge structures and flyovers, the significant local pavement temperature variabilities may be expected. As the result in the autumn and winter time black ice may occur locally, which dramatically decreases the safety of road users. The selected route was about 6.25 km long - see Fig. 5 with marked starting and ending point.

Fig. 5. The test route on a bypass, cartography based on Google Maps [own study]

Bridge structures located on the test route are presented in Table 2. The location is given with regard to starting point. Moreover, along the vast majority of the route there are noise barriers.

Table 2. Bridge structures located on the test route [own study]

no.	structure	location		
		latitude [°]	longitude [°]	route [km]
1.	Viaduct crossing over Gorska St. and Straconka stream	49.801853	19.080906	1.44
2.	Viaduct crossing over Złoty Potok valley	49.811333	19.08203	2.6
3.	Viaduct crossing over Polna St.	49.819201	19.086592	3.45
4.	Viaduct crossing over Niwka stream	49.820792	19.087078	3.64
5.	Overpass crossing over railway tracks and Krzywa stream	49.829579	19.084344	4.65

4. Test drives and result analysis

For the purposes of this study 14 different runs have been performed. The drives took place at different time of day and various weather conditions - Table 3. During the research no precipitation was observed and the road surface was dry. The odd-number test runs were realised from starting to ending point (Fig. 5) and even-number drives in the opposite direction. Thereby measurements were registered for both lane of the road. During the test runs the speed was kept steady in the range of 65 ÷ 70 km/h.

Table 3. Weather conditions characteristic for individual test runs [own study]

Test drive	Condition characteristic	Date	Time at starting point
I	temp. -10 ÷ -11 °C , sunny, foggy	26.02.2018	09:58
II			10:40
III			11:46
IV			11:09
V	temp. 1 ÷ -1 °C, cloudiness with occasional sunbeams	21.03.2018	11:33
VI			12:08
VII	temp. -1 ÷ 0 °C, sunset		17:21
VIII	temp. 1 ÷ -1 °C, shortly after sunset		17:58
IX	temp. -5 ÷ -3 °C, dusk		20:12
X	temp. -4 ÷ -5 °C, dusk		20:46
XI	temp. -4 ÷ 0 °C, sunny, partial shading caused by noise barriers along the road	22.03.2018	08:23
XII	temp. 2 ÷ 0 °C, sunny		08:59
XIII	temp. 25 ÷ 27 °C, sunny, partially cloudy	09.04.2018	14:15
XIV			14:48

Table 4 present basic statistical data regarding road surface temperature during particular test runs. Besides mean and median, the standard deviation, minimum and maximum values were calculated.

Table 4. Basic statistics for the road surface temperature [own study]

Drive no.	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Mean	-6.2	-4.8	-4.2	-3.8	4.3	3.2	0.8	-0.8	-4.0	-4.5	-1.8	3.1	32.6	33.0
Median	-6.6	-5.1	-3.9	-3.7	4.5	3.2	0.7	-0.9	-3.9	-4.5	-2.2	2.9	32.1	32.9
Standard deviation	1.7	1.4	1.5	1.3	0.8	0.6	0.5	0.4	0.4	0.5	1.7	1.1	2.5	1.5
Minimum	-9.5	-8.2	-7.6	-7.6	0.1	0.9	-0.3	-1.6	-5	-5.5	-4.1	-0.5	23	23.5
Maximum	-2.5	-1.3	-1.1	-1.6	5.9	4.6	2.0	0.4	-2.3	-1.9	2.9	5.6	36.3	36.7

4.1 Similar weather conditions test drives analysis

Due to mentioned MARWIS sensor variability, indicators presented in the study have been created using averaged data with 3-observation moving mean. Besides temperature individual spot measurement, both one previous and one subsequent observation have been included. This procedure allowed to eliminate minor instrument reading variability and avoid temperature distortion. It is also necessary to be aware that at the same time it reduced the local temperature amplitude fluctuations which have been registered during the measurements.

The authors, having one sensor at their disposal, did not have the possibility to perform two or more test runs simultaneously. As mentioned before, the drives were carried out on the different traffic lanes with as short as possible time gap (necessary for i.a. changing the movement direction). The measurement results for selected test runs are presented in the figures. The drives were performed in the same day and in similar weather conditions. The results summary are presented as follows: test runs I-IV (Fig. 6), IX and X (Fig. 7), XI and XII (Fig. 8). Fig. 6a), 7a) and 8a) illustrate road surface temperature variability, while Fig. 6b), 7b) and 8b) concerns temperature gradient variation. To ensure facilitate readability of Fig. 6b), authors decided to illustrate only data regarding I and IV test runs. Those are test runs for which time gap was the longest and exceeded one hour. The horizontal lines in the figures indicate the location of bridge structures (given in Table 3).

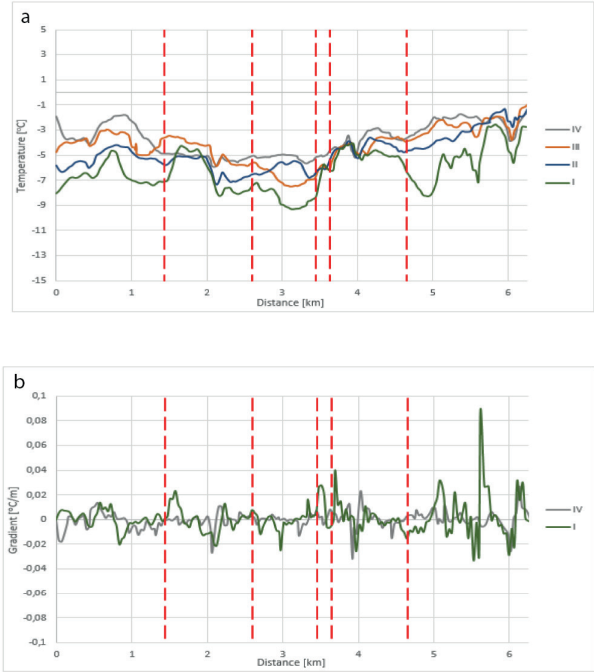

Fig. 6. Drives I-IV measurement results [own study]

The most significant conclusions that can be formulated based on presented results (Fig. 6 – Fig. 8) are as follows:

- results of measurement from test drives performed in comparable weather conditions are similar, especially with regard to road temperature gradient, which is very important for traffic safety,
- the road surface temperature discrepancies regarding drives I-IV are highly determined by condition changes caused by significant time gap between the drives performed partly in mid-morning hours and changeable sun exposure,
- also comparing test runs XI and XII, the significant influence of rapid air temperature rise and sunlight exposure is clearly noticeable,
- in most cases the road sections with the highest road surface temperature variation do not cover with the location of bridge structures.

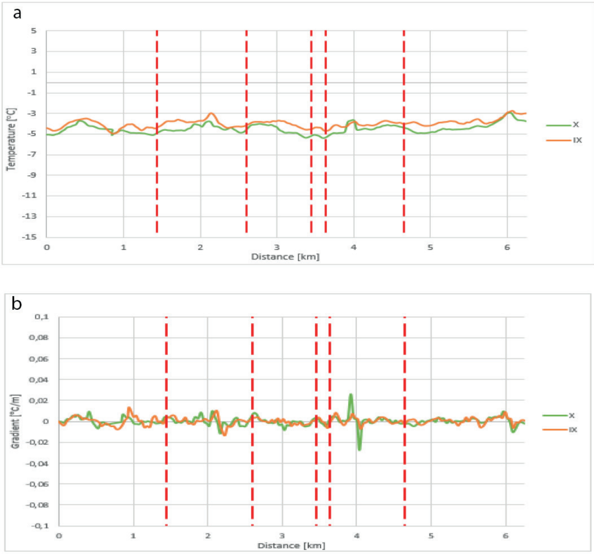

Fig. 7. Drives IX-X measurement results [own study]

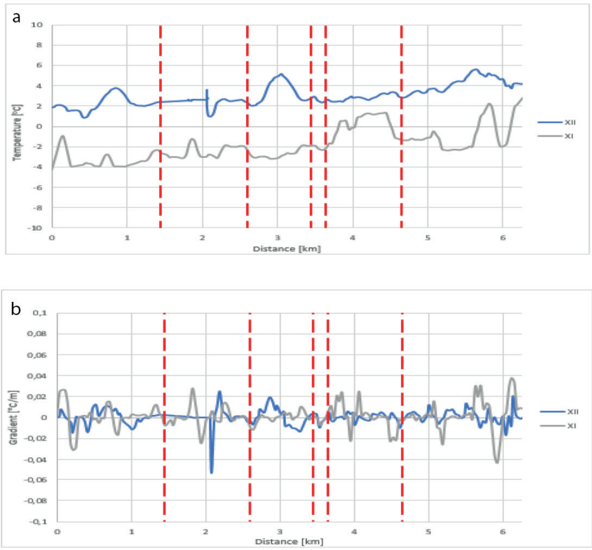

Fig. 8. Drives XI-XII measurement results [own study]

4.2 Various weather condition test drives analysis

To analyse the location of highest road surface temperature variation, firstly authors listed resulted of selected daytime test runs which has been performed in variable ambient air temperature conditions. Fig. 9 illustrates road surface temperature variation for drives II, V, XII and XIV. Fig. 10 presents road surface temperature gradients observed for test runs II and XIV which has been performed in greatest conditions diversity.

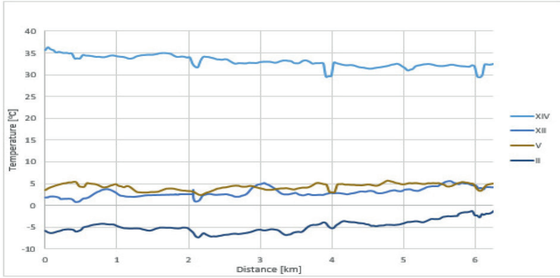

Fig. 9. Road surface temperature variation for day-time drives II, V, XII and XIV [own study]

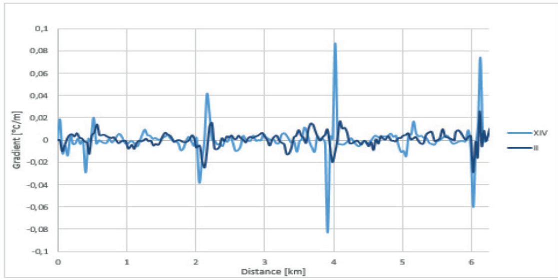

Fig. 10. Road surface temperature gradients for day-time test runs II and XIV [own study]

The next diagram (Fig. 11) illustrates a road surface temperature variation for daytime test run no. II and two night drives, no. IX and X respectively. Fig. 12 presents road surface temperature gradient observed during run II and IX.

Based on the recorded data presented in Fig. 9 and Fig. 10 it is possible to observe that there are a significant road sections where considerable local road surface temperature variation can be pointed out. What is particularly important, the variation appears regardless of weather conditions. Analysis of the data shown in Fig. 11 and Fig. 12 allows to formulate a thesis that the high road surface temperature gradient values may be expected also under night-time conditions.

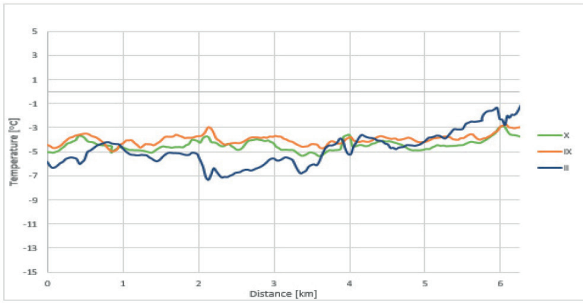

Fig. 11. Road surface temperature variation for compilation of daytime test run II and night drives IX and X [own study]

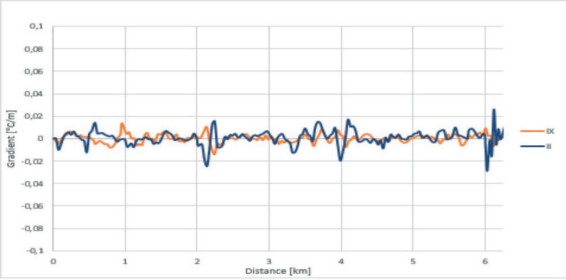

Fig. 12. Road surface temperature gradients observed during test run II and IX [own study]

On the basis of geolocation data in Fig. 13 the areas showing high thermal variability has been indicated. In marked points significant fluctuations of the road surface temperature has been registered during most of the test runs (see Fig. 10 and Fig. 11). In all cases, the bypass runs beneath the viaduct structures of other local roads.

Fig. 13. Areas showing high thermal volatilities based on different test runs, cartography based on Google Maps [own study]

Within the context of the analyses, authors compared the results obtained for test runs X and XI. Mentioned drives are the ones that are characterised by minimum (drive no. X) and maximum (drive no. XI) standard deviation of the road surface temperature. Fig. 14 presents comparison of surface thermal variation observed in both test runs. Fig. 15 illustrated comparison of temperature gradients. In should be noted that during XI drive the surface was more overshadowed. This phenomenon was observed due to noise barriers mounted along the eastern side of the route.

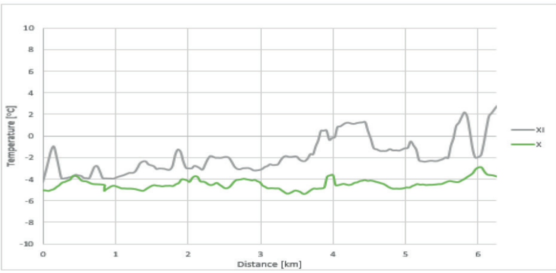

Fig. 14. Road surface temperature variation observed in test runs X and XI [own study]

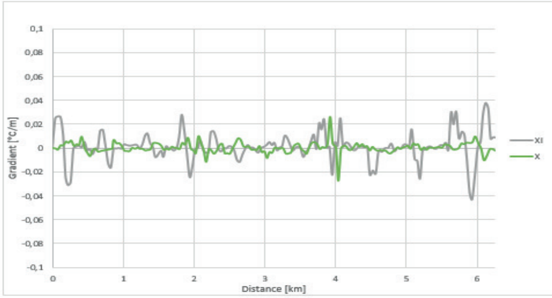

Fig. 15. Road surface temperature gradients observed during test run X and XI [own study]

The result of measurements shown in Fig. 14 and Fig. 15 clearly identifies that in case of test run no. X, in which there were fragments of road shaded by noise barriers the road surface temperature variability is particularly high.

5. Conclusion

Conducted research has proved the suitability of MARWIS sensor for temperature measurement and analysis. The measurement is convenient, not troublesome and results are characterised by good quality and reliability.

Due to educational activities and media campaigns most of the drives are aware that appropriate care should be taken near the bridge constructions, viaducts and watercourses, particularly while air temperature fluctuate around 0°C. The obtained results indicate that dangerous road conditions may occur also in other locations which could surprise the driver. Undertaken analyses identify two potentially hazardous cases.

The first one are the bridge structures and overpasses leading over the road. Conducted research points out that in this locations the drivers may expect significant road surface temperature variability during the sunny weather. Moreover, the high variability can be also observed under the night conditions. Since the high road surface temperature gradients on road sections are naturally related to the viaduct width, they are usually not very long. However, when the ambient air temperature drops around 0°C and the unaware drivers travel with a high speed, dangerous vehicle sliding may occur. The risk of sideward skid increases on curvilinear road sections.

The second one concerns influences due to noise barriers and other structures (e.g. long buildings near the road). They may generate greater impact on the road surface temperature gradients than the presence of viaducts, overpasses and other bridge structures along the road (see Fig. 15). As with viaducts running over the road, hardly any of the drivers expects significant thermal variations in those areas as well as friction changes in case of air temperature fluctuates around 0°C. The phenomenon is even more dangerous when it appears under certain conditions (sunny weather) and solely in particular time of day. It may be observed until noon or in the afternoon depending on noise barriers positioned relative to the road and current position of the sun. Therefore, for the vast majority of the year, road conditions in particular points are stable and predictable, while in certain and usually quite short periods of time they may be very dangerous. Described 'localness' of noise barriers impact on the road surface temperature variability is confirmed by standard deviation comparison for drives no. XI and no. XII. These drives were performed one after another on two different traffic lanes with minor time offset. The large parts of the road surface was shaded by noise barriers located along the route during drive XI. The shaded areas occurred only sporadically while drive XII was performed. Due to this fact the value of standard deviation for drive XI in relation to driver XII is more than double.

The usage of road mobile sensor enabled to effectively obtain thermal characteristics map of the test route. It allows to indicate critical, due to significant gradients of road surface temperature, road network points. What is more, crucial areas could be easily identified. The study indicates that hazardous conditions may be observed not only when air temperature oscillate around 0°C. High gradients of the road surface temperature occur regardless of the weather. Additionally, a special attention should be paid to qualifying the hazard of road shading caused by infrastructure facilities such as noise barriers. Also in this matter more important issue than the ambient temperature, seems to be the sun exposition of the road. It is necessary to determine mutual position of roadway and noise barriers (depending on time of day when roadway shading may occur) and time of the year (due to variable shadow length).

The critical areas indicated during the test drives should be appropriately signposted and the meteorological shield device should be implemented in those sections. Due to growing popularity of road sensors usage, in potentially dangerous locations (e.g. under and over the bridge structures, viaducts, overpasses, near noise barriers etc.), it seems appropriate to provide continuous measurement of road surface temperature using two road sensor in order to calculate the gradient. In case of an emergency, the information could be displayed in VMS, which should be located before the critical area. In the near future the warnings could be provided to the driver using I2C (infrastructure to car) communication. The I2C solutions are increasingly considered and applied in practice. The information delivered to the driver using this technology can be personalised and therefore will be undoubtedly more absorbable.

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