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Determining the influence of factors on retroreflective properties of traffic signs

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Abstract. One of the distinguishing features of future autonomous cars is the ability to take into account and communicate with traffic infrastructure. Thereby detection and recognition of vertical traffic signing is an obvious requirement. Automatic recognition of traffic signs allows to check driver's reaction time, if it is necessary to react, and in that way to contribute to and increase the road safety. It is especially important in the darkness when the retroreflective sheeting materials on the traffic signs help to increase visibility. Unfortunately, environmental conditions around the traffic signs exert considerable influence on the sign's surface and alter their retroreflective properties. Many scientists explored different impacts on retroreflective properties of signs. Some impacts attracted more attention (such as detection distances and deterioration with age), some impacts were studied by several scientists only (such as dew and frost) and some factors were even omitted at all (e.g. the temperature during measurements of in-service signs). The paper is focused on the impact analysis of insufficiently explored factors influencing retroreflective properties of traffic sings. The findings of this research can support the development of further experimental research and could become a basis of reliable traffic signs usage on modern and smart roads.

Key words: autonomous cars, traffic safety, meteorological conditions, quality of signing.

List of abbreviations:

AC	artificially cleaned	ANOVA	analysis of variance
ADAS	advanced driver assistance systems	R_A	coefficient of retroreflection
AHR	after heavy rain	TSDR	traffic sign detection and recognition
AMR	after moderate rain	WR	without rain

INTRODUCTION

Every year, about 1.35 million people die as a result of traffic accidents that ranks to the eighth leading cause of death worldwide (Global status report on road safety, 2018). According to statistics, the main reason for the traffic accidents is a human factor (Rumar & Elsenaar, 2004). In order to eliminate the risk of traffic accidents due to drivers' negligence, ADAS was developed (Hechri et al., 2015). One of the main components of this system is TSDR that offers vital information to drivers about road restrictions in real time. However, the complexity of the surrounding environment and the scenes around the traffic signs cause difficulties in road signs recognition (Toth, 2012).

Motorists of the Federal Republic of Germany conducted the experiment focused on the usage of TSDR technology in various car brands. Experimental results display that the maximal rate of successful recognition of road signs is 92% (Autoweb, 2011). The study showed that the TSDR system loses its sensitivity in the darkness, although it is especially required to enhance the road safety. The results were explained by declining brightness of the traffic signs.

The brightness of the traffic sign, according to its visibility in the darkness (Allen & Straub, 1956; Molino et al., 2013), is provided by a retroreflective sheeting of the sign, which reflects the light directly back to its source (Sivak & Olson, 1983; Federal Highway Administration, 2009; Kutz, 2011). The R_A is the conventional measure for this special kind of reflection in the case of retroreflective traffic signs (RS 101 Reflection, 2004). Since the first retroreflective sheetings were discovered and applied to the traffic signs, many types of research have been carried out with these materials.

Before the establishment of minimal retroreflective levels for retroreflective signs (Federal Highway Administration, 2007), a major part of the research studies were conducted to determine it (Black et al., 1992; Goodspeed & Mercier, 1993; Bildstein, 2001; Hawkins & Carlson, 2001; Carlson & Hawkins, 2003; Austin & Schultz, 2009). Later on, the mandated standards for 'adequate visibility' of the traffic signs (Austin & Schultz, 2009) were determined and most of the studies were focused on evaluating compliance of in-service traffic signs with mandated standards (Ellison, 2008; Ré et al., 2011a; Evans, 2012; Hummer et al., 2013). As a part of these researches, a greater number of variable factors were recorded during measurements in different combinations. These variables or some of their combinations are e.g.: characteristics of the sheeting type, headlight-beam pattern, vehicle types, sign position, roadway geometry, characteristics of drivers face direction/orientation, mount height, roadway type, form and severity of the sign's deterioration, geographic location, environmental factors (Kirk et al., 2001; Schoettle et al., 2001; Hildebrand, 2003; Carlson & Lupes, 2007; Austin & Schultz, 2009; Carlson et al., 2011; Khalilikhah & Heaslip, 2016).

According to the accomplished detailed literature review, it is possible to conclude that the common feature of all studies is a lack of the input data description that does not directly relate to the factors under the study. For example, the majority of the studies do not provide data about temperature and air relative humidity (except (Ré et al., 2011b)) during the experiment. However, according to the standards (EN 12899-1 Fixed, vertical road traffic signs, 2007; ASTM D4956 Standard Specification for Retroreflective Sheeting for Traffic Control, 2017), these tests should be carried out at the specified temperature and relative humidity to determine the R_A value. Precisely the determination of the degree of influence of air temperature and relative humidity on the retroreflection is one of the objectives of this work. This is especially important for the TSDR system that operates in real time and 'reads' the signs with the instantaneous value of R_A.

Weather conditions such as rain, drizzle, fog, dew, hoarfrost impair the 'instantaneous' visibility of the traffic signs by changing the refraction and scattering of the light beams and rendering less bright signs (Woltman, 1965). Despite the fact that these factors often lead to a significant number of accidents (Shahabi et al., n.d.; Abdel-Aty et al., 2010; Unified transport vector map, 2017), there are only four works devoted to the study of the influence of these factors on traffic signs retroflexion. The results of the three of them were based on the subjective assessment of the participants. Munehiro et al. (2005) have made a conclusion that fog during the night does not have as great negative effect as that in the daytime. However, 'the subjective visibility values of targets under the night-time cloudy condition were worse than those under the daytime dense fog condition'. According to De Waard et al. (2005), for 9% of the participants, fog or dew was a reason of worse legibility of the signs. Hutchinson & Pullen (1978) have rated relative effects of dew and frost on target values of different types of retroreflective materials for sign's legend and background. And only E. Hildebrand (Hildebrand, 2003; Hildebrand & Bergin, 2004) has made conclusions in his works based on the measurement of R_A value. According to Hildebrand (2003), frost reduces the retroreflective level of the in-service traffic signs on average by 79%, dew – on average by 60%. The type of retroreflective material and its colour has a significant influence on the degree of degradation of the retroreflective values under dew and frost conditions.

Another degrading factor of the traffic sign optical properties is the dirtiness on its surface (Department for Transport, 2013). However, this factor to some extent loses its degree of importance, as the material's quality improvement provides new properties to it that eliminates the influence of the dirt. For example, Woltman (1982) has shown that the existence of the dirt on the surface of traffic signs reduces its reflective ability by 50%. Twenty years later, Wolshon et al. (2002) found that the average increase in retroreflectivity was about 33% after the signs had been washed. Ten years later, Jackson et al. (2013) determined that dirt reduces retroreflectivity of the signs by about 10%.

The purpose of this work is to study the 'instantaneous' factors affecting retroreflection of the signs and to determine the degree of their influence for improving detection and recognition systems of traffic signs.

MATERIALS AND METHODS

This research is divided into two parts: the first part of the study contains determination of the influence degree of dew, frost, drizzle and dirt; the second part describes identification of the correlation between retroreflectivity of a traffic sign and measurement conditions (air temperature and relative humidity). The first part includes data collection of in-service signs, during the second part measurements were carried out in the laboratory.

Study locations and test samples

The number of all tested samples of retroreflective films is represented in Table 1, that were divided according to their technology, class and study location. The classification depends on the mandated minimum R_A values which increases with the class number (EN 12899-1 Fixed, vertical road traffic signs, 2007).

In-service. The study encompassed 82 in-service traffic signs, located in Prague 6 or Horoměřice in the Czech Republic. Since 96% of all types of road signs in this country contain white and/or red elements on them (TP 65 Principles for traffic signs on communications, 2013), all selected signs also contain elements of these colours. Date of manufacture of road signs ranged from 2005 till 2017. All measurements were conducted during 2018.

Laboratory. Ten types of retroreflecting samples were chosen for studying the properties of sign's retroreflection in the laboratory. According to (EN 12899-1 Fixed, vertical road traffic signs, 2007; EAD 120001-00-0106 Microprismatic retro-reflective sheetings, 2016), for each type of microprismatic film 3 samples were created, for films with glass bead technology – 2. Microprismatic test samples were 20cm by 20 cm, glass bead – 10 cm by 10 cm. In addition, the measurement included a sample for calibration of the reflectometer, that had already been mounted by the device manufacturer on the front plate of the adapter.

Table 1. Summary of surveyed retroreflective sheeting according to its type and study location

Technology*	Class*	Number of samples	
		in-service	laboratoy
Microprismatic	RA1	4	6
	RA2	7	3
	RA3	8	12
Glass Bead	RA1	54	6
	RA2	9	

* – according to EN 12899-1 (EN 12899-1 Fixed, vertical road traffic signs, 2007).

Instrumentation

The retroreflectometer Zehntner ZRS 6060 was used for all measurements; this equipment allows to determine R_A in accordance with the European standard EN 12899–1 (EN 12899-1 Fixed, vertical road traffic signs, 2007), for illumination angle 5° and tree observation angles – 0.2°, 0.33°, 1°. Also, each measurement contains information about the colour of the sample, ambient temperature, relative humidity, GPS coordinates.

Methodology of measurement

The measuring principle with the retroreflectometer to get R_A value was the same for all measurements (except measurement of calibration standard). The first step is the calibration of the device using a calibration standard that is mounted on 'calibration side'. Than front plate is mounted on the 'measuring side'. The second stage is direct measurement when the instrument is planted on the surface of the traffic sign and the trigger is pulled. The measurement values are shown beside each observation on the display. Using the handheld retroreflectometer, three readings of each sign colour were collected.

Also, all for the first-time used samples for the research in the laboratory were measured. These R_A values for the first time used in-service signs were obtained from the manufacturer of the specified traffic signs. All inputs data were set according to EN 12899-1 (EN 12899-1 Fixed, vertical road traffic signs, 2007).

The difference in data collection consisted in a variety of data collection time for each specific factor affecting the retroreflection.

Dirtiness. The term 'dirty traffic sign' does not include the definition of the degree of contamination of the sign. Since there is no maintenance program for cleaning traffic signs, the only way of removing contamination is the influence of the atmospheric phenomenon, such as rain. Rain supposedly should sufficiently clear the sign. In order to verify the veracity of this statement, R_A values were measured for different types of retroreflective sheeting under the conditions WR, AMR and AHR.

The measurements of in-service traffic signs were carried out in March, the signs were not washed. Last precipitation (light rain) was fixed 16 days before measurements.

Next measurements were conducted in June and 3 days after a heavy rain (the intensity of rainfall was higher than 10 mm per hour) when the examples were dried. Then measurements were carried out two months later, after 3 days of moderate rain (the intensity of rainfall was between 2.5–10 mm per hour). For comparison all signs were washed by water (AC) and R_A values were measured after.

Dew, frost, drizzle. The measurement of retroreflection was conducted in the presence of dew, hoarfrost on the surface of the sign and during light drizzle from October till December. The traffic signs with a cover of frost were measured in December.

Temperature and relative humidity. In the laboratory, the test samples were measured in the range of ambient temperature −3–25 °C, and the range of relative humidity of air 25%–100%. The measurement of the calibration standard was carried out when the front plate of the retroreflectometer was mounted on the 'calibration side'. Total **1,400 measurements were conducted** in the same range of temperature and relative humidity as laboratory test samples.

Data analysis

The data analysis software 'MappingTools' was used to export measured data and generate measuring reports. For statistical analysis, the 'STATISTICA' software was used, which allows to carry out a statistical analysis for comparison measured R_A values in different conditions.

Dirtiness, dew, frost, drizzle. A one-way repeated measures *ANOVA* was used to determine whether there is no difference between traffic signs with the impact of different types of precipitation or different level of dirtiness on the signs surface, at the significance level of 0.05. This test was used because three or more impacts were studied for the same test's samples. The *t-test* for dependent samples was used only if there were not sufficient number of measurements for each type of impact. For both tests, the null and alternative hypotheses were defined as follows:

H_0: no difference in means of R_A values between few data sets.

H_1: the average value of the R_A between few data sets is significantly different.

The null hypothesis for the performed tests can be rejected if the obtained *P*-value is lower than 0.05. In order to control the family-wise error rate for this case and to figure out which impact has considerable influence on the R_A, the *Tukey's* honestly significant difference post hoc test was carried out at the significance level of 0.05. The homogeneity of groups is controlled by the same test.

The average of R_A values was also obtained from *Tukey's* post hoc test but only meaningful difference between them will be discussed in this paper. The difference between groups is presented in percentage for the illustrating results in better way of perception.

Temperature and relative humidity. The one sample *t-test* was conducted in order to identify if the R_A values significantly changes with the changes in air temperature and relative humidity. As a constant for comparison were used R_A values that were measured by a manufacturer of sheeting in compliance with the standard according to the procedure described in the standard (EN 12899-1 Fixed, vertical road traffic signs, 2007) and they are assumed as true mean. The test was carried out at the significance level of 0.05 with the following null and alternative hypotheses:

H_0: the difference between the true mean and the average measured value is equal to zero.

H_1: the difference between the true mean and the average measured value is not equal to zero.

The null hypothesis for the tests is rejected if the obtained *P*-value is lower than 0.05.

In order to determine the influence of two independent variables such as air temperature and relative humidity on the dependent variable as the R_A, the multiple linear regression analysis at the significance level of 0.05 was carried out.

RESULTS AND DISCUSSION

Making traffic signs retroreflective is one of the ways to increase their brightness and reduce the number of traffic accidents in the darkness. Compliance with the necessary minimum of the retroreflective level is especially important in the context of detecting and recognizing traffic signs by autonomous cars. However, in the existing procedure for determining the level of retroreflection, there are several shortcomings that make an objective assessment difficult especially for in-service signs under field conditions. These disadvantages are such measurement conditions when the sign should be dried and cleaned, the measurements are conducted only at certain ranges of ambient temperature and relative humidity.

Dirtiness

The number of measurements was sufficient to perform static analysis using a one-way repeated measures *ANOVA*. The results of the tests were *P*-values that are shown in the Table 2. The *P*-values of red microprismatic RA1 and RA3 sheeting are higher than 0.05. That means that dirtiness does not have significant influence on the retroreflection. But this statement cannot be considered as a final conclusion since this analysis does not take into account an elevation of traffic signs and traffic intensity that have influence on the level of dirtiness of the sign (Khalilikhah & Heaslip, 2016).

Table 2. The results of a one-way repeated measures *ANOVA* and *Tukey's* post hoc test that are presented as *P*-values under pairs of conditions WR, AMR, AHR, AC

Technology	Class	Colour	***ANOVA***	***Tukey's***					
				WR vs AMR	WR vs AHR	WR vs AC	AMR vs AHR	AMR vs AC	AHR vs AC
Microprismatic	RA1	red	0.099						
		white	**0.026**	0.188	0.076	**0.021**	0.869	0.322	0.684
	RA2	white	**0.048**	0.830	0.453	**0.039**	0.781	0.118	0.283
	RA3	red	0.078						
		white	**0.010**	0.052	0.058	**0.007**	0.989	0.557	0.518
Glass Bead	RA1	red	**0.00***	**0.00***	**0.00***	**0.00***	0.260	**0.007**	0.411
		white	**0.00***	**0.001**	**0.00***	**0.00***	**0.009**	**0.002**	0.955
	RA2	red	**0.00***	**0.001**	**0.001**	**0.00***	0.989	0.700	0.675
		white	**0.00***	**0.00***	**0.00***	**0.00***	0.060	**0.001**	0.350

* – values lesser than three decimal places after decimal point were neglected.

As shown in the Table 2, the presence of dirt has influence on all types of glass bead sheeting and white microprismatic RA1 and RA3 sheeting. For those sheeting's data sets the *Tukey's* post hoc test was carried out in order to find the pairs of groups where the mean difference is statistically significant. The results of this significant difference between pairs are also presented in the Table 2. According to the obtained *P*-values, there are significant differences between unwashed and artificially washed traffic signs (pair 'WR vs AC'). For all types of glass bead sheeting the rainfall intensity is a decisive factor since there is a significant difference between pairs 'WR-AMR', 'WR-AHR' (Table 2). For microprismatic sheeting the presence of precipitation is not so important because even after a heavy rain the R_A values do not significantly increase.

The largest difference in average values (between WR and AC) is observed for red microprismatic RA3 – 64%, the smallest for red glass bead RA2 – 8%. The difference in mean between AHR and AMR varies within 9%, except red microprismatic RA3 for which the difference is 14%.

It is worth noting, that almost all types of sheeting, even under the condition WR, met the standards (EN 12899-1 Fixed, vertical road traffic signs, 2007), their retroreflection coefficient significantly exceeded the minimum level. But 71% of the signs with the glass bead RA2 sheeting were under the minimum retroreflective level and increased above it only AHR or cleaning.

Precipitation on the surface of the sign

Dew and frost, which directly form water droplets (or even hoarfrost) on the traffic surface of the sign and minute water droplets that occurred during drizzle, were attributed to precipitation on the surface of the sign. It should be noted these types of precipitation differ not only in the phase of water but also in the size of the droplets that arise. For example, during the dew, larger drops were observed on the surface than during the drizzle. Fig. 1 shows the dew and hoarfrost on the surface of the sign that were observed during measurements.

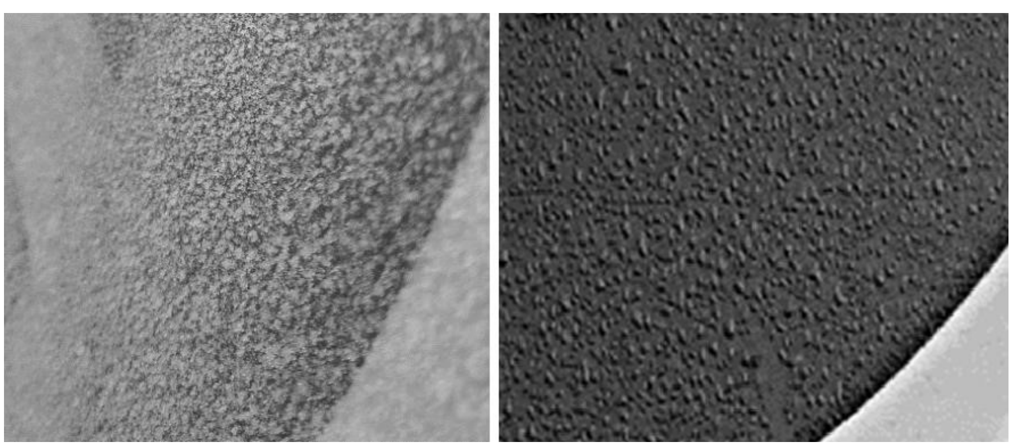

Figure 1. The presence of hoarfrost (left) and dew (right) on the surface of traffic sign.

In contrast to the previous series of measurements, during the study of these factors, the necessary number of measurements was not collected for all types of materials. For microprismatic RA2 and glass bead RA2, the effect of frost was only studied.

The measured data was analysed by one-way repeated measures *ANOVA*. The retroreflectivity of the signs with a different kind of precipitation on its surface were alternately compared with each other. The test results were *P*-values and they are presented in the Table 3. Almost all *P*-values did not exceed 0.05 (except red glass bead RA1 sheeting), which indicates significant differences between data sets. For red glass bead RA1 the presence of water droplets does not significantly impair the level of retroreflection as for microprismatic sheeting. The negligible difference for the red glass bead RA1 sheeting can be explained by the low required minimum R_A values, that means that even high difference in the R_A values is not statistically significant.

Table 3. The results of a one-way repeated measures *ANOVA* and *Tukey's* post hoc test that are presented as *P*-values under pairs of different type of precipitation on the sign's surface

Technology	Class	Colour	*ANOVA*	*Tukey's*					
				AC vs dew	AC vs fog	AC vs frost	dew vs fog	dew vs frost	Fog vs frost
Microprismatic	RA1	red	**0.001**	**0.004**	**0.036**	**0.002**	**0.036**	0.886	**0.013**
		white	**0.010**	**0.037**	0.659	**0.015**	0.247	0.951	0.109
	RA3	red	**0.047**	0.670	0.524	**0.031**	0.965	0.186	0.249
		white	**0.011**	0.194	0.296	**0.006**	0.994	0.208	0.145
Glass Bead	RA1	white	**0.00***	0.078	0.069	**0.00***	0.988	0.114	0.124
		red	0.088						

* – values lesser than three decimal places after decimal point were neglected.

As seen in the Table 3, both for microprismatic and glass bead sheeting the difference between clean signs and signs with the hoarfrost on the surface of the signs is significant, the influence of other type of precipitation is not observed except microprismatic RA1 sheeting. For this type of material dew, fog and frost decrease the retroreflection properties.

The *t-test* for dependent samples was used to compare the difference in R_A values between two groups, AC and in the presence of hoarfrost, for microprismatic RA2 (white) and glass bead RA2 (white and red). The results of three tests show the significant difference between these two groups because all *P*-values were less than 0.05.

From the average R_A values, it was found that hoarfrost on the surface of the signs decreases the retroreflective properties more than 76%. Moreover 93% of traffic signs in the condition of frost do not meet the standards because R_A values are significantly below the minimum retroreflective levels. Very interesting discoveries were made, particularly that the dew has a worse effect on the retroreflectivity of the signs, especially for microprismatic sheeting material. The presence of dew on microprismatic RA1 reduces the retroreflectivity by about 61%, under the minimum level.

Temperature and relative humidity

During the measurement of R_A values of the same type of sheeting it was found that the values vary if the temperature or relative humidity changes. The assumption was made that retroreflection is influenced, among other factors, by temperature and humidity during measurements with a handled retroreflectometer. To test the assumptions, a series of measurements with different temperatures and humidity were carried out. The measurements were analyzed using one sample *t*-test and as a result, *P*-values were obtained that are shown in Table 4. As shown in Table 4, the *P*-values are higher than 0.05, that the retroreflectivity of samples 3–5 and 7 does not change with temperature and relative humidity. For other samples, the difference is significant, especially for sample number 10.

Table 4. The results of the one sample *t-test* for measured signs by sheeting type and colour that was compared with values measured by manufactures

Technology	Manufacturer	Class	Colour	Sample sheeting number	*P*-value
Microprismatic	3M	RA1	white	1	0.022
			red	2	0.017
		RA2	white	3	**0.063**
		RA3	fluorescent	4	**0.086**
			red	5	**0.131**
			white	6	0.027
			red	7	**0.052**
Glass Bead	Avery	RA1	white	8	0.024
	Oralite		white	9	0.025
			red	10	0.001

In order to assess the accuracy of the measurements, excluding all factors except the ambient temperature of the relative humidity, 1,400 measurements of the calibration standard were carried out. The multiple linear regression analysis was used to find the level of influence of each factor. As a result of the analysis, the coefficients for linear equation was obtained (Eq. 1) with the coefficient of determination equal to 0.917.

$$R_A = 228.793 + 0.792 \cdot T + 0.141 \cdot \varphi \qquad (1)$$

where R_A – the coefficient of retroreflection; T – temperature; φ – relative humidity.

The correctness of the model was tested by substituting the temperature and humidity specified by the standard (EN 12899-1 Fixed, vertical road traffic signs, 2007; 23 ± 3°,50 ± 5%). The results corresponded to the retroreflection coefficient specified in the manufacturer's calibration standard.

CONCLUSIONS

The goal of this paper was to assess factors as dirtiness, precipitation, drizzle and dew occurring on the surfaces of traffic signs and if they can cause a significant deterioration in the retroreflection level, and, accordingly, impair visibility of the traffic signs. Based on the series of measurements and subsequent statistical analysis, it was found that the presence of any type of precipitation on the surfaces of signs significantly impairs its retroreflective properties. This is particularly relevant in the presence of hoarfrost when the retroreflective level for all types of sheeting material decreases by more than 76% and in most cases falls under the minimum level. The effect of dew and drizzle is also significant, though to a lesser extent. It is possible to conclude that the level of deterioration of retroreflection is largely related to the size of the water droplets formed on the surface of the sign. The large size of the droplets leads to a large distortion of the light reflection angles and the level of retroreflection falls.

The negative effect of dirt on the sign's surface was also confirmed during the statistical analysis. It was observed that red microprismatic RA3 sheeting material is more sensitive to purification, AHR, the retroreflection level may increase up to 64%. Despite the fact that in the Czech Republic there is no maintenance program for cleaning signs, the susceptibility of signs to 'natural' cleaning should be taken into account, since the distribution of the number of precipitations during the year is uneven and the direction of the raindrops could affect cleaning effect. In winter, when the amount of precipitation is the smallest (snow cannot be taken into account), it is still worth cleaning the sign manually, because according to the measurements, the retroreflection coefficient of glass bead RA2 sheeting is below the established minimum level. After a heavy rain, the level of retroreflection is set up above the minimum.

According to the results of the survey carried out and statistical analysis, the influence of ambient temperature and relative humidity on the traffic sign's retroreflective properties has been identified. Moreover, the dependence on ambient temperature during measurement is more apparent and that was demonstrated in the equations created on the basis of 1,400 measurements of the calibration standard. For example, a change in temperature of 25 °C leads to a 10% change in the retroreflective level. However, it was found that retroreflection does not always depend on the changes in temperature and humidity e.g. for sheeting with a high level of retroreflection, such as microprismatic R2/R3, significant changes in the measured values have not been observed. It proves necessity of the next future research to obtain true and verified information about sheeting properties.

The revealed dependence could not only explain the difference in the results of the previous studies but also, along with other established dependencies, may help to improve the recognition of traffic signs by adjusting the computational processes for different pairs of temperatures and humidity, with or without precipitation on the sign. And it could also serve as an impetus for cleaning signs not only in the Czech Republic but in every country where these procedures are not usual during the winter season.

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