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Retroreflection of traffic signs for the safe operation of agricultural machinery

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Abstract: Recent studies have discussed the increasing number of accidents caused by agricultural machinery and tractors, specifically on higher-class roads. High-quality traffic signage with the required retroreflection can prevent these serious accidents, especially under reduced visibility conditions. The retroreflective materials are divided into three classes: R_{A1}, R_{A2} and R_{A3} according to their optical performance. This distribution apparently turned out to be insufficient, as significantly different optical materials may be assigned to the same class. This research focused on the detailed optical resolution of retroreflecting sheeting with the aim to support enhancement of the current standards. The coefficient of retroreflection (CR) was measured under standard requirements. It was concluded that the combination of 3M 3930 sheeting (CR = 7.81) and 3M 4090 (CR = 9.03) sheeting is not recommended, as the difference between these values and the other monitored samples is significantly higher than CR = 2. Especially with the introduction of autonomous mobility, the recognition of signs will also have fundamental effects on agricultural technologies, where elements of independent mobility will be gradually introduced.

Keywords: coefficient of retroreflection; retroreflective sheeting; safety; tractors; traffic accident

One-third of agricultural machinery accidents occur in built-up areas, while almost two-thirds occur outside the city. Eighty-five percent of accidents happen during the day, 11% occur at night and the rest are at dusk. However, outside the cities, an accident is twice as likely in the dark as in the city (Kühn and Bende 2011).

In the case of injuries, it is necessary to distinguish between people using the agricultural tractor, i.e. the policyholder, and the injured party: While 90% of people in a tractor survive an traffic accident without any injury but at the other participants of the accident it is only 22%. Three percent of the victims die, 21% are seriously injured, and another 54% are lightly injured (Kühn and Bende 2011).

In Austria, 24 people died in tractor accidents in 2019. Among the people who died in tractor accidents, there were two people under 18 years of age, 13 people between the ages of 18 and 60, and 9 people over 60 years of age (Luger 2020).

In traffic accidents in 2019, 17 people died in connection with driving a tractor, of which 3 were on the roads, 9 on forest and field roads and 5 on sloping meadows or a sloping terrain (Luger 2020).

The key aspects in the perception of traffic signs are considered to be: physical and mental condi-

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tion of the driver (age, physical fatigue, vision, etc.), location of the retroreflective surface, optical performance, condition and construction of the retroreflective surface, type and quality of the vehicle headlights (light source) (Hawkins et al. 2005) and the vehicle type.

In recent years, there has been a significant increase in the number of road accidents at local (unclassified) road junctions (Casado-Sanz et al. 2019) and the ageing population has been identified as a potential risk factor. According to Eurostat data from 20 July 2017, people over 65 years of age will constitute 23.9% and 27% of the population in 2030 and in 2040, respectively (Eurostat 2017).

Demographic research by Eurostat shows that the Europe population is ageing, as the relative proportion of people over 65 years of age has risen from 10.5% in 1970 to 15.9% in 2005. According to the average variants of the United Nations projection, it can be expected that the share of European seniors will increase to a total of 19% by 2020 (United Nations Secretariat 2008).

Drivers 70–74 years of age are twice as likely to die in an accident as drivers 30–59 years of age (drivers aged 80 and older are five times more likely) (Chao 2013). Drivers 80 years of age and older need 40% more time and 8 times more lighting to respond adequately to an object or traffic signs than younger drivers (Federal Highway Administration 2012).

Various eye defects of drivers should be taken into account as well. According to the Institute of Health Information and Statistics of the Czech Republic (2014) based on the European Health Interview Survey, 19.7% of the respondents reported vision problems (even if they use glasses or other visual aids), the impaired ability of older drivers to quickly accommodate the eye for changes in the incident light level, bad weather conditions, the dazzle from oncoming vehicle headlights, driver fatigue and the possible soiling of the road sign and windshield. Thanks to this, we better understand why night driving is critical and care must be taken to maintain traffic signs that are clearly visible during this period (Prášil 2006).

The basic property requirements that traffic signs should meet are: their visibility, clarity and legibility (Borowsky et al. 2008). The clarity and legibility of a traffic sign are affected by several elements, in particular the shape, colour and brightness. The increased brightness of traffic signs significantly shortens their reading time (Schnell et al. 2009).

Similarly, an increase in the size of the sign, respectively lowering of the readability index, also shortens the reading time of the sign. Research suggests that larger and clearer traffic signs are more effective (Carlson and Hawkins 2002).

Therefore, in order to perceive a road sign at night in the same way (Howe 2006) as in the daylight, a retroreflection effect is used and, thus, traffic signs serve as retroreflective surfaces with a glass beaded or microprismatic design (Hummer et al. 2013). During the day, the retroreflection of traffic signs is not necessary, as visibility is ensured by diffuse reflection (Prášil 2006).

The basic angles in the field of retroreflection are the viewing and illumination angles. The viewing angle (α) is the angle formed by the lines between the headlights of the vehicle, the traffic signs and the driver's eyes. The angle of illumination (β) is the angle formed by the lines between the vehicle headlights – the traffic sign and the line of the reflected light perpendicular to the area of the sign (Obeidat et al. 2015).

In the case of vertical traffic signs, the light coming from a vehicle's headlights is redirected from the front of the sign back to the vehicle (to the light source), which makes the sign visible to the driver. We distinguish three types of light reflection: mirror, scattered and retroreflective (Lee et al. 2015).

The first retroreflective sheeting was formed by glass beads, which were not protected in any way, which caused condensation on the surface of the retroreflective sheeting. These droplets deflected light rays in undesired directions and the signs became non-reflective for drivers (Paniati 1989).

A special glass surface on the rear side of the glass bead turned out to be even more effective. Nowadays, development is focused on much more effective microprismatic retroreflective sheeting (Schnell et al. 2009). In some microprismatic retroreflective sheeting, rotational symmetry is determined, i.e. the extent to which the retroreflection is affected by the rotation of the retroreflective sheeting. The development in the field of retroreflective sheeting, including the composition of the most important parts, is shown in Figure 1.

The use of retroreflective sheeting in the field of traffic closures on motorways is regulated in detail by special technical regulations, which state that the retroreflective sheeting must be at least in the R_{A2} class. Only the yellow-green traffic sign "Work" must, in terms of traffic importance, comply with

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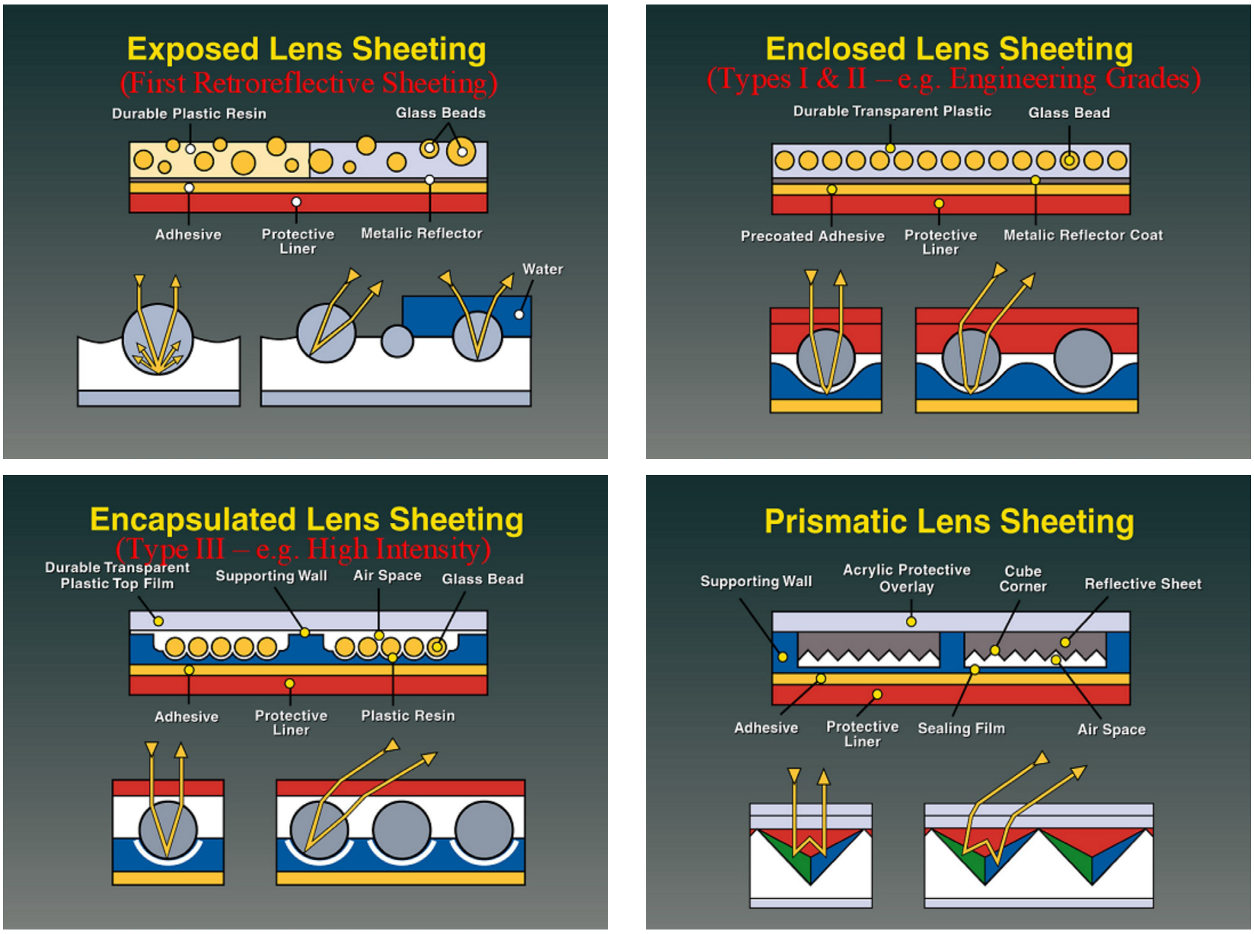

Figure 1. Development and basic composition of glass beaded and microprismatic retro-reflective sheeting (3M 2008)

the R_{A3} class of retroreflective sheeting (Ministry of Transportation of the Czech Republic 2015).

However, the constant development in the field of retroreflective materials shows that the existing formal distribution into 3 classes (R_{A1}, R_{A2} and R_{A3}), according to ČSN EN 12899-1 (ČSN EN 12899-1 2008), is insufficient.

In addition to the above-mentioned information, it should be noted that the retroreflection value is affected by many other factors. The manufacturing process, as proper screen printing, can negatively affect the retroreflection by up to 22% and the brightness levels by up to 10% (Pigner 1997). The cleanliness of the sign surface is also important, and it is affected by the height of the sign above the road and the altitude at which the road sign is fixed. The importance of altitude stems from the fact that a higher frequency of snowfall occurs in areas with higher altitudes (Boggs et al. 2013). Traffic signs placed at a low level above the road surface are often made dirty by dust, snow and pollen particles (Amparano and Morena 2006). The retroreflection of signs placed at a height of up to 2 m was 1.55 to 1.72 times higher than that of traffic signs placed at a height of more than 2 meters (Khalilikhah and Heaslip 2016).

Figure 2, in the top row, shows pictures of a "Work" traffic sign that were photographed in the daylight. It is the first traffic sign placed when approaching a traffic closure. In the lower row, the traffic signs are shown in a way that they can be seen by a driver at night. On the left, there are traffic signs where the R_{A1} and R_{A3} retroreflective sheeting are combined (bad solution). In the middle, retroreflective sheeting of the R_{A2} and R_{A3} class is shown (bad solution). On the right, there is a sign that fully complies with the R_{A3} class (the correct solution).

Sulfur dioxide compounds also influence the contamination of the sign. Traffic signs installed in areas with higher concentrations of air pollutants (industrial areas or areas with high traffic density) are likely to be dirtier (Khalilikhah and Heaslip 2016). The average annual precipitation affects the degree

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Figure 2. Combination of retroreflective sheeting on the "Work" traffic sign on a fluorescent substrate

of pollution affecting traffic signs as well. Although regular precipitation has the potential to clean traffic signs, this is not the case for snow, which, in turn, is a contributing factor to sign pollution (Khalilikhah and Heaslip 2016).

Among other various influences affecting the retroreflection of traffic signs, vandalism is a leading cause. Vandalism of road signs is a serious problem because it can lead to an increase in dangerous driving situations (Nowotny et al. 2012). In addition, it leads to an increase in the cost of road maintenance since it is necessary to replace, repair or maintain traffic signs to keep them in a satisfactory condition (Woltman 1984).

Many studies that deal with the retroreflection of traffic signs have been published. Some scientific articles have dealt with durability issues (Sørensen 2011) or factors influencing the durability or use of retroreflective surfaces (Hummer et al. 2013).

However, none of these specialised articles dealt with the possible combination of retroreflective materials in one cross-section up to now. Although this is a daily problem in practice, the correct combination has a major impact on the visibility and, consequently, on road safety.

The retroreflection coefficient (CR) is used for the practical assessment of the amount of retroreflection regardless of the formal classification into the classes R_{A1}, R_{A2} and R_{A3}. The measured values of the previously most widespread 3M 3200 white retroreflective sheeting, which reaches an average value of 85.1 $cd \cdot lx^{-1} \cdot m^{-2}$ (CR = 1), were taken as a basis.

For other retroreflective sheeting, the constant represents the ratio of the measured value to this base. From the point of view of practice and through expert estimation, it can be said that retroreflective sheeting with a CR difference greater than 1 with a different type of retroreflective sheeting construction (glass beaded and microprismatic) must not be used on new-state traffic signs. If changes in the design are necessary during their service life, the CR should be around a value of 2 and retroreflective sheeting with different types of construction (glass beaded and microprismatic) must not be used also.

The aim of the research on white retroreflective sheeting, at a basic viewing angle of $\alpha = 0.33$ and an illumination angle of $\beta = 5°$ will be to prove, in class R_{A1}, the possibility of combining all the glass beaded retroreflective sheeting.

MATERIAL AND METHODS

To evaluate the optical properties of the retroreflective sheeting, the retroreflection values of 30 samples in total (white, red, and blue retroreflective sheeting with a size 210 × 297 mm, produced by three different manufacturers) were monitored. The samples were produced by the companies 3M, Avery Dennison (AD) and Oralite (OR), which are, currently, the most often retroreflective sheeting used under ordinary road traffic conditions.

As part of the measurements performed, the samples were repeatedly tested and displayed on the roof of a building (south side) of the Technical Faculty of the Czech University of Life Sciences in Prague (Figure 3) at an angle of 45° according to Article 4.1.1.5.2 of ČSN EN 12899-1 (ČSN EN 12899-1 2008).

The formal point of view shows that the performance the R_{A1} class, according to ČSN EN 12899-1 (ČSN EN 12899-1 2008), is represented by samples of the glass beaded 3M 3200, AD 1500, OR 5710 and the microprismatic retroreflective sheeting type 3M EGP.

In the performance of the R_{A2} class, the 3M 3930, AD 6500 and OR 5910 microprismatic retroreflective sheeting were measured. In the performance of the R_{A3} class, 3M 4090, AD 7500 and OR 6910 retroreflective sheeting samples were selected. The functional service life (at least for the period requirements according to the standard) of the R_{A1} retroreflective sheeting is 7 years.

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Figure 3. Retroreflective sheeting displayed at the CULS building roof

The functional service life of the retroreflective sheeting classes R_{A2} and R_{A3} is 10 years. Glass beaded retroreflective sheeting (GB) and microprismatic retroreflective materials (M) are tested according to ČSN EN 12 899-1 (ČSN EN 12899-1 2008) and European technical approval (EOTA 2016), respectively.

The R_{A1} and R_{A2} retroreflective sheeting class are measured according to these technical regulations: $\alpha = 0.2°$, 0.33° and 2° in the viewing angle and β_1 + 5°, + 30°, + 40° in the illumination angle. The R_{A3} retroreflective sheeting class is measured according to these technical regulations: 0.33°, 1°, 1.5° in viewing angle and + 5°, + 20°, + 30°, + 40° in the illumination angle.

To obtain uniform measurement conditions, an illumination angle of $\beta_1 = 5°$ and an observation angle of $\alpha = 0.33°$ were chosen to compare the retroreflective sheeting samples. The individual retroreflective sheeting samples have been clearly described and exhibited since the beginning of August 2017.

The individual retroreflective sheeting samples were further optically divided into 6 individual fields with dimensions of approximately 0.1 × 0.1 meters. Before the actual measurements, individual retroreflective sheeting samples were removed from the roof and thoroughly cleaned with a cotton cloth to remove any possible dust and pollen particles that could distort the performed retroreflection measurement.

Subsequently, a Zenther 6060 measuring device was used to calculate and then display the detected values on its display (Figure 4) so that it can measure three viewing angles of $\alpha = 0.2°$, 0.33° and 2° and one illumination angle of $\beta_1 = 5°$, while $\beta_2 = 0$ was used with the retroreflective sheeting according to the requirements of SN EN 12 899-1 (ČSN EN 12899-1 2008).

The retroreflection meter consists of an LED lighting system and a 3.5" high-resolution colour touch screen with an adjustable tilt display for excellent visibility in all light conditions and in bright sunlight. The device can be used for all types of retroreflective materials and colours with automatic colour indication. Each measurement is saved, and the average value is continuously updated.

Measurements can be evaluated using the included software for mapping and data analysis. Innovative options for adapting the reflector to personal requirements include an integrated camera with a resolution of 5 megapixels, a GPS unit, a case, handles (Figure 4). The retroreflective sheeting samples were measured before exposure on the roof of the building, both horizontally and vertically, to eliminate the effect of rotational symmetry, which can significantly affect the measured values of some types of retroreflective sheeting.

The resulting CR values are based on the measurement of white samples in a new state (before exposure), which is the most effective use in practice. Determining the exact CR values for printed inks is not practical, as it depends on many variable parameters, such as the retroreflective sheeting production process (screen printing, digital printing, machine adjustment, etc.). These processes affect the resulting retroreflection and CR values. It can be stated that, for the retroreflective sheeting dyed by screen printing or digital printing, the retroreflection coefficient must not be lower than 56% of the relevant values specified in ČSN EN 12899–1 Article 4.1.1.4. Table 1 (ČSN EN 12899-1 2008) shows the retroreflection values detected for the white samples in a new state, that is, before exposure (01.08.2017) and at the end of the set date for measurement (01.12.2019).

Figure 4. Zenther measuring device

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Table 1. Values of white retroreflective sheeting samples

Sample	Class	Date 01.08.2017		01.12.2018		01.12.2019	
		R*	CR	R*	CR	R*	CR
3M 3200	R_{A1}	85.1	1	78.5	0.92	76.4	0.89
AD 1500	R_{A1}	79	0.93	74.1	0.87	69.8	0.82
OR 5710	R_{A1}	105.9	1.24	96.5	1.13	81.3	0.96
3M EGP	R_{A1}	127	1.49	118	1.38	104.9	1.23
3M 3930	R_{A2}	665	7.81	649	7.62	618.7	7.27
AD 6500	R_{A2}	405	4.76	359	4.22	320.2	3.76
OR 5910	R_{A2}	591.5	6.95	550	6.46	484.5	5.69
3M 4090	R_{A3}	768.1	9.03	763.1	8.97	688.7	8.09
AD 7500	R_{A3}	419.9	4.93	369	4.34	359.7	4.23
OR 6910	R_{A3}	431	5.06	425.5	5	374.2	4.40

*R – value of retroreflection (cd·lx^{-1}·m^{-2}); CR – retroreflection coefficient

RESULTS AND DISCUSSION

The values of the samples tested are in accordance with the standard. The data (see Table 1) prove that within the R_{A1} class, all types of retroreflective sheeting can be combined with each other except for 3M EGP, as it is a microprismatic retroreflective sheeting. In the R_{A2} class, the samples OR 5910 and AD 6500 can be combined with each other. Similarly, with the R_{A3} class, it is possible to use the AD 7500 and OR 6910 retroreflective sheeting in one cross-section. The measurement results show that, results of the optical performance are considerably different in the same class. For clarity, the retroreflection values for the red and blue retroreflective sheeting are shown in the Figure 5.

The formal classification, according to the valid ČSN EN 12899-1 (ČSN EN 12899-1 2008) standard, it divides the retroreflective materials into three classes, although the optical performance, especially in the R_{A2} and R_{A3} classes, is quite different. For example, within the R_{A3} class, retroreflective sheeting with an optical performance of approximately 400 cd·lx^{-1}·m^{-2} is formally included, as well as retroreflective sheeting with an optical performance of approximately 700 cd·lx^{-1}·m^{-2}. Until ČSN EN 12899-1 (ČSN EN 12899-1 2008) is changed and the related introduction of more formal classes is carried out, it is necessary to use the CR value that serves as an aid for a more detailed classification of retroreflective sheeting.

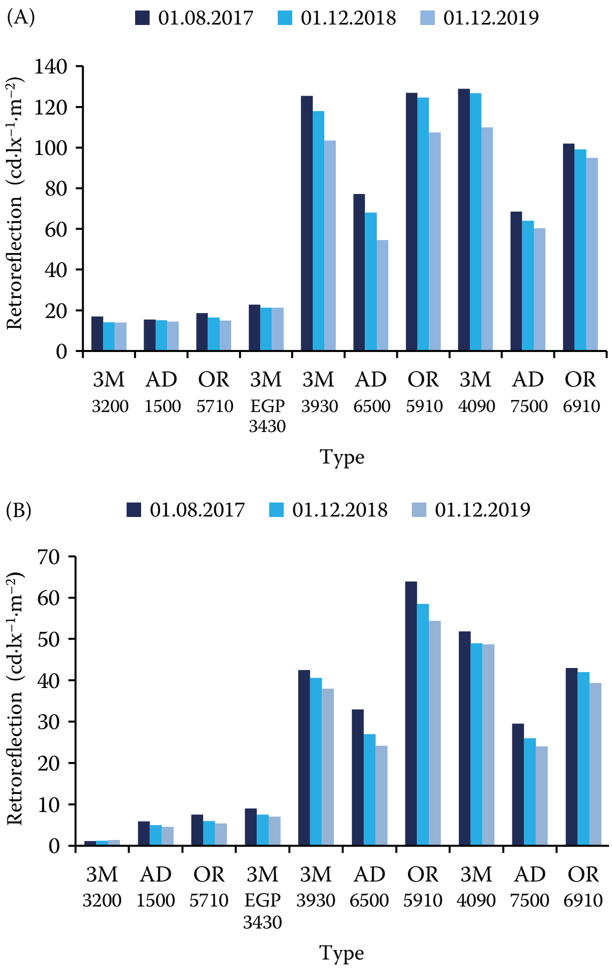

Figure 5. Retroreflection values for red (A) and blue (B)

3M – 3M company; AD – Avery Dennison company; OR – Oralite company

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However, even with the use of the CR value, it is not possible to guarantee that the correct combination of retroreflective materials will be used, as it depends on several of the variable parameters mentioned above. The variable parameter is, e.g. the age of the retroreflective sheeting, because the retroreflective material degrades over time (climatic conditions, exposure to salts in winter, UV radiation, etc.), and so there will certainly be a difference between the optical performance between the new retroreflective sheeting and one at the end of its service life.

Another factor is the method of producing retroreflective sheeting that has affected the printed inks. Different retroreflection values can be expected, both for retroreflective sheeting directly obtained from the manufacturer and for retroreflective sheeting whose final colouring is performed by the sign manufacturer.

The colouring can be printed by screen printing or on a digital printer. For screen printing, it is highly dependent on the settings of the machine and the skill of the operator. All these aspects have an impact on determining the CR value; to simplify the calculations, we, in practice, took the values of the white retroreflective sheeting in a new state (before exposure) which were taken as the base.

CONCLUSION

In the case where it is not possible to use a single retroreflective sheeting on the traffic sign, it is necessary to take the retroreflection coefficient into account, at least until the European standards for traffic signs change and become effective, as it can ensure similar visibility at night.

The combination of different retroreflective sheeting from the point of view of their optical performance on one portable traffic sign is possible only on the basis of determining the retroreflective coefficient that serves to easier determine the suitable combination of retroreflective materials. From an optical performance point of view, retroreflective sheeting with a difference in the retroreflection (CR) value of more than 2 should not be used for portable signs in a single cross-section.

The measurements of white retroreflective sheeting show that, at a basic measured viewing angle of $\alpha = 0.33°$ and an illumination angle of $\beta = 5°$ for the R_{A1} class, a combination of all glass beaded retroreflective sheeting is possible, as the maximum value of their optical performance is in the range of CR 0.82 to 1.24. The tested microprismatic retroreflective R_{A2} sheeting has CR values of 4.76 to 7.81. From the point of view of the R_{A3} retroreflective sheeting, the CR values are 4.93 to 9.03.

Therefore, it is not recommended to combine 3M 3930 and 3M 4090 retroreflective sheeting, as the difference in the CR values compared to the other monitored samples is higher than 2. Retroreflective sheeting measurements will continue and the development of retroreflection values will be monitored in the coming years.

The retroreflection and colour of traffic signs ensure the correct visibility and, therefore, the effectiveness of the signs. These are the key parameters for the future development and subsequent use of autonomous agricultural vehicles.

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