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Original Research Paper

The effects of damage on sign visibility: An assist in traffic sign replacement

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ABSTRACT

Traffic signs often convey critical information to drivers. To ensure visibility in nighttime or low light conditions, traffic signs must be in compliance with the minimum retroreflectivity standards outlined by the manual on uniform traffic control devices (MUTCD). Among all of the assessment methods (visual nighttime inspection, retroreflectivity measurement) and management methods (expected life, blanket replacement, and control signs) outlined in the MUTCD, expected sign life has been the most selected by agencies for maintaining compliance. In current literature, little research exists with regard to schedule sign replacement, focusing rather on the current favorite predictor, sign age. However, after collecting data on 1683 in-service traffic signs across the state of Utah, this study primarily concluded that not only sign age, but other contributing factors affect sign retroreflective performance. Aiming to determine the effects of various damage forms on sign retroreflectivity, statistical methods, including regression models, chi-square test, *t*-test, and odds ratio were employed to analyze traffic sign data. At the conclusion, the strong association between damage and retroreflectivity compliance of traffic signs was evident. In addition, to identify more critical damage forms, the effects of various forms on traffic sign retroreflectivity were compared. These conclusions provide insight to inform transportation agencies in the development of sign management plans and schedule sign replacement.

1. Introduction

As the most frequent visual aids in roadways, traffic signs provide safer traffic environments through regulating, warning, or guiding the road users (Koyuncu and Amado, 2008; Rogoff et al., 2005). The goal of installing key traffic signs, such as stop signs, yield signs, and speed limits, is to increase traffic safety (Baratian-Ghorghi et al., 2015; Pour-Rouholamin et al., 2015; Prieto and Allen, 2009; Zhou et al., 2016). However, traffic signs are only effective when clearly visible. By incorporating sheeting made of retroreflective material, even signs that are

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not illuminated by external lights are still visible at night. Retroreflection works by redirecting light from the sign face back to the source (McGee, 2010). To ensure that drivers are able to comprehend traffic signs, the U.S. Congress introduced standards for minimum levels of sign retroreflectivity to the secretary of transportation in 1992 (United States Department of Transportation, 1992). To fulfill that mandate, in 2009, the manual on uniform traffic control devices (MUTCD) established minimum retroreflectivity standards for traffic signs, including an obligation for agencies to replace signs that were not in compliance with these levels. The coefficient of retroreflectivity, R_A, commonly referred to as retroreflectivity, is the ratio of a sign's luminance to its illuminance (FHWA, 2012).

The MUTCD outlined five methods that would guide agencies in achieving and maintaining minimum R_A levels. These methods included assessment methods (visual nighttime inspection and sign retroreflectivity measurement) and management methods (expected sign life, blanket replacement, and control signs). In general, assessment methods tend to evaluate each individual sign of the inventory on a periodical follow-up basis to assess sign retroreflectivity compliance. In contrast, sign attributes, such as sheeting type, color, age, and geographic conditions are utilized in management methods to categorize signs and predict their retroreflectivity without inspecting each in-service sign (Balali et al., 2015; Khalilikhah and Heaslip, 2016a). Over the course of the past few years, transportation agencies have aggressively developed methodologies to meet the MUTCD mandate. In 2011, the Utah Department of Transportation (UDOT) sponsored field investigations by a team to investigate the compliance of traffic signs with the guidelines set forth by the 2009 MUTCD. At the completion, the attributes of 1683 in-service traffic signs were measured in the field.

Of all the assessment and management methods, the expected sign life has been selected most often as a primary or secondary method (Re and Carlson, 2012). Using the expected sign life method, signs are replaced before their retroreflectivity degrades below the minimum levels. However, the expected life of a sign has been shown to exhibit discrepancies, depending on the manufacturer, sheeting type, color, and geographic location (Evans et al., 2012a). In this study, after reviewing recent studies and discussing our collected traffic sign data, the authors begin our analysis with assessing the association between in-service sign age and retroreflective performance. Then, the effects of damage on sign visibility are quantified. Next, various damage forms are compared in terms of their impact on traffic sign visibility. Finally, a sign replacement plan is suggested based on our findings.

2. Background

The minimum retroreflectivity levels established by the MUTCD require transportation agencies to implement an assessment or management method that is designed to maintain sign retroreflectivity at or above the established minimum levels. After adopting final revisions to the MUTCD in 2012, the three original target compliance dates for minimum retroreflectivity levels were changed (FHWA, 2012). However, federal and state funds can still be effectively allocated to fund efficient sign assessment and management methods. In the past, multiple studies were performed, focusing on assessment and management of traffic signs (Boggs et al., 2013; Carlson and Lupes, 2007; Harris et al., 2009; Khalilikhah et al., 2015; Khalilikhah and Heaslip, 2016b; Kipp and Fitch, 2009).

A simulation of the sign inspection process to optimize sign management was conducted (Rasdorf et al., 2006). In addition, a risk-based approach for agencies to follow when checking for retroreflective sign compliance was developed (Liang et al., 2012). There have also been studies focused on long-term deterioration of traffic signs, with special attention given to color (Brimley and Carlson, 2013). One such study showed that sheeting age was one of the most significant variables affecting sign performance (Black et al., 1992). Other researchers have analyzed the retroreflective characteristics and deterioration of sheeting materials based on sign age (Kirk et al., 2001; Pike and Carlson, 2014; Re et al., 2010; Wolshon et al., 2002). A study discussed the uncertainty in sign retroreflectivity measured by handheld devices (Remias et al., 2011). Khalilikhah et al. (2016) and Khalilikhah and Heaslip (2016b) discussed traffic sign vandalism. However, little research exists in the current literature quantifying the effects of sign damage on visibility. This study is conducted to bridge this gap.

3. Data collection

In 2011, a sample set of traffic signs under UDOT's jurisdiction were collected. Throughout the course of the study, different regions were considered by the team, in order to provide an overall perspective of compliance with minimum retroreflectivity levels across the state (Evans et al., 2012b). Fig. 1 displays the locations of the measured signs. The overall effort was accomplished by a three-man team, with specific tasks assigned to each member. Throughout the data collection, a handheld retroreflectometer was used, as well as a GPS unit that included a customized data dictionary to record specific attributes of each traffic signs, including:

- Location (GPS coordinates)
- Roadway type (rural, urban, canyon, mountain)
- Background color (green, red, white, yellow)
- Sheeting type (Types I, III, III HIP, IX, and XI)
- Retroreflectivity measurements (cd/lx/m^2)
- MUTCD type and code (warning, regulatory, guide)
- Face direction (north, east, south, west)
- Mount height (ft)
- Offset from the edge of roadway (in)
- Installation date (month/day/year, if known)
- Form and severity of sign deterioration

The team also took a photo of each individual sign. At its completion, the sample data population consisted of 1683 traffic signs located across the state's major climatological regions in both rural and urban environments. Thus, of the more than 97,000 traffic signs maintained by UDOT, almost

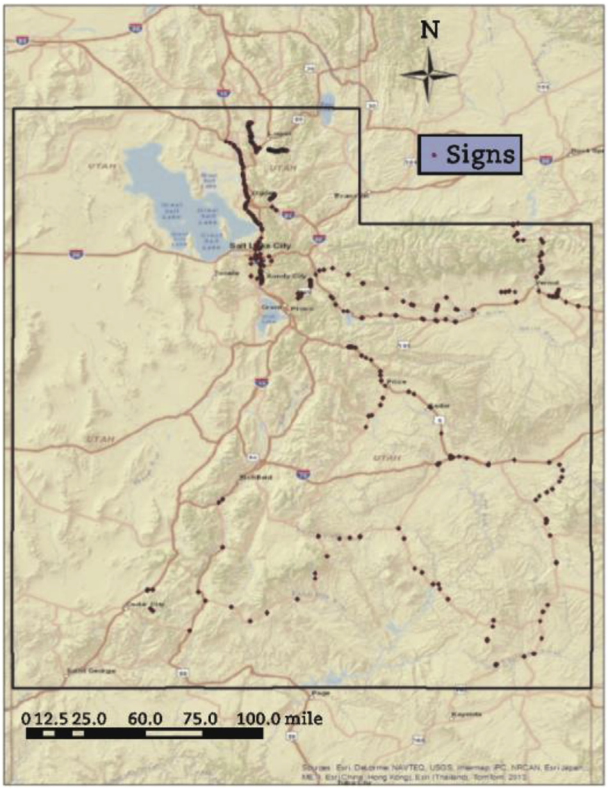

Fig. 1 – Locations of traffic signs.

1.5% was recorded by the research team that is an appropriate sample size by considering 95% confidence level. Fig. 2 illustrates a summary of the captured signs based on the sheeting type and color. As shown in Fig. 2, recorded retroreflectivity sheeting included Types I, III, III HIP, IX, and XI (Federal Highway Administration , 2011). Traffic sign background sheeting type was identified by using the Federal Highway Administrations (FHWA) identification guide. In terms of the resistance against rough handling,

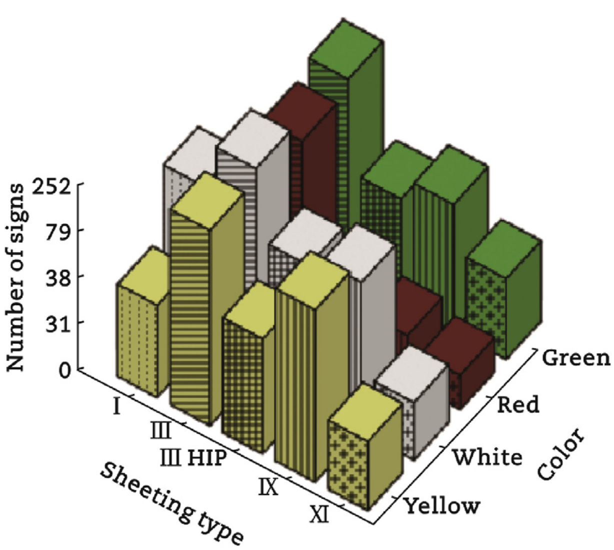

Fig. 2 – Summary of surveyed signs by type and color.

Type I signs are the most durable signs with basic reflective sheeting. Type III sheeting signs are made of two layers with a cost about twice that of Types I signs. In UDOT's sign inventory, Types IX and XI are the most recently adopted sheeting types. Types IX and XI use the newest sheeting, and they are about six times brighter than Type I signs. However, with this micro-prismatic sheeting, their cost is about five times that of Type I (FHWA, 2011). Approximately 60% of the surveyed signs were either white or yellow, while sheeting Type III was used by the majority of the dataset (58% of the signs).

Using a Delta RetroSign Model 4500 retroreflectometer, the retroreflectivity values were also measured. The Model 4500 illuminates the sign at a -4° entrance angle, with the angle of observation being 0.2°. Holding the retroreflectometer vertical and stable against the sheeting was a detail that the team took into consideration during the collection process (Evans et al., 2012b). The sign retroreflectivity was recorded in units of candelas per lux per square meter ($cd/lx/m^2$). Following American Society for Testing and Materials standards, four measurements were taken for each individual sign (ASTM, 2009). For all of the surveyed signs, the measurements were taken at the same four areas regardless of sign damage. Then, the four measurements were averaged in order to determine the overall retroreflectivity of each individual sign. Table 1 shows the required standards levels (FHWA, 2012). If the captured retroreflectivity was below the minimum level, the sign was recorded as failing in the database. At the conclusion of the study, the rate of failure for the entire sample population was nearly 8% (128 out of 1683 surveyed signs).

4. In-service sign age

Since 2008, UDOT has required agencies to have an installation sticker on both the front and back of all signs placed in the field. Typically, the sticker on the front of the sign has a transparent background with a black legend for the year it was installed, whereas the back contains the month and year of installation, as well as the company that constructed the sign. However, this policy was not consistently fulfilled by the stations and contractors installing signs for UDOT (Evans et al., 2012b). As a result, at the completion of the data collection, only 17% of the surveyed signs were placed with an installation date. Retroreflectivity measurements of these signs, based on the sign background sheeting type and color, are shown in Fig. 3. In this figure, the age of signs is shown in days. We obtained sign ages by subtracting sign installation date from sign survey date. The plots are also enhanced with a linear regression model. Surprisingly, no surveyed Type I sheeting had known age. Approximately 64% of signs with known installation date were green guide signs. A few number of red signs had known age. With the exception of Type IX signs, classifying signs by their color, sheeting type, and age also led to low numbers of yellow and white signs in each group. Based on the data, it was not possible to draw strong conclusions for any one category. Therefore, this section focuses on green signs including destination (D1), distance (D2), milepost (D10), interchange (E1), and exit (E5)

Table 1 – Minimum retroreflectivity levels (MUTCD).

Sign color	Sheeting type (ASTM D4956-04)				Additional criteria
	Beaded sheeting			Prismatic sheeting	
	I	II	III	III, IV, VI, VII, IX, X	
White on green	W G ≥ 7	W G ≥ 15	W G ≥ 25	W ≥ 250; G ≥ 15	Overhead
	W G ≥ 7	W ≥ 120; G ≥ 15			Ground-mounted
Black on yellow or black on orange	Y; O	Y ≥ 50; O ≥ 50			Text and fine symbol signs measuring at least 1200 mm
	Y; O	Y ≥ 75; O ≥ 75			Text and fine symbol signs measuring less than 1200 mm
White on red	W ≥ 35; R ≥ 7				Sign constant ratio ≥3:1
Black on white	W ≥ 50				–

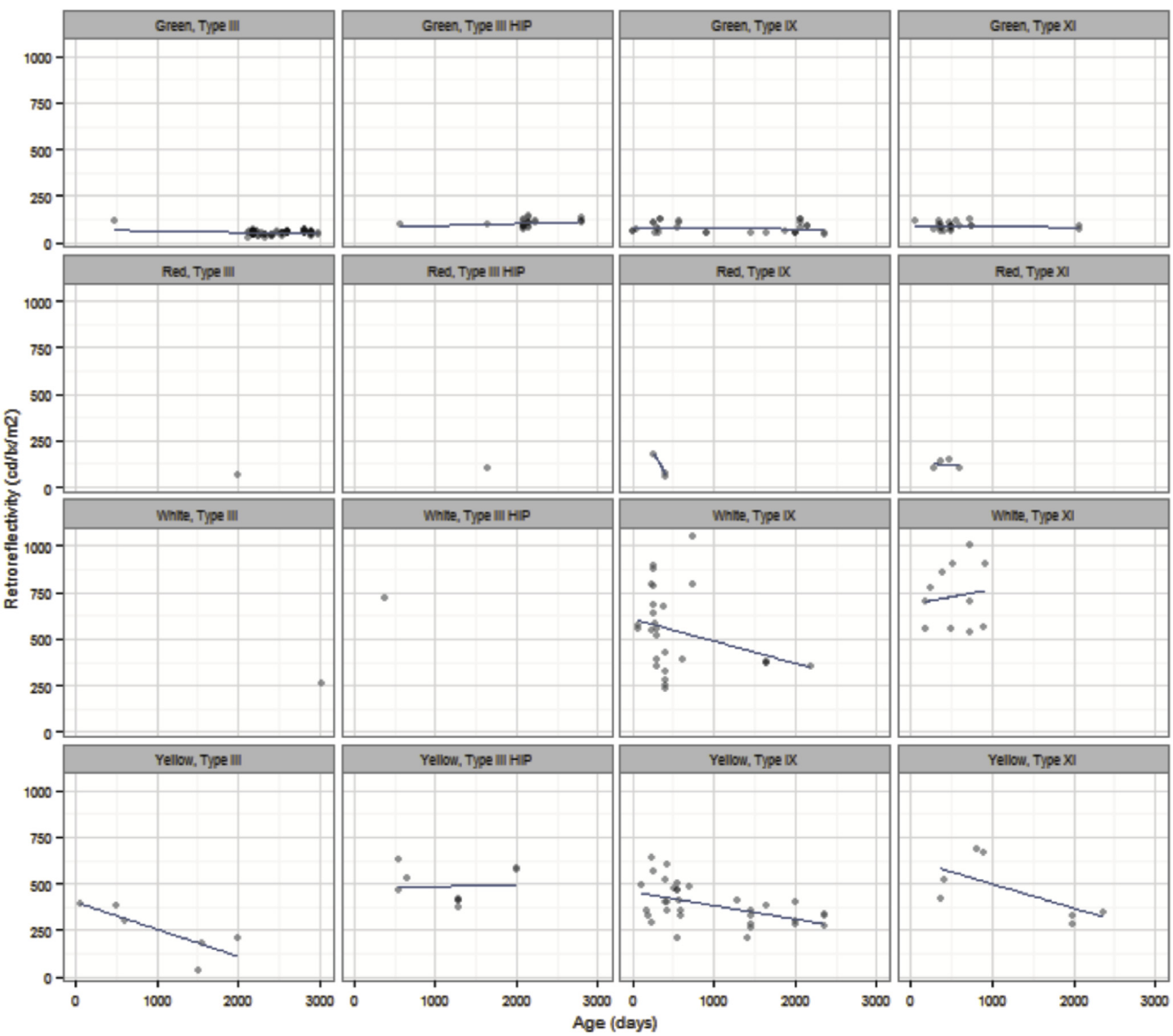

Fig. 3 – Sign retroreflectivity measurements by sign age.

MUTCD type signs and discusses the relationship between sign age and retroreflective performance.

The range of installation dates of the surveyed green signs was from 2003 to 2011. Of the 186 green signs, only 5% were measurable damaged. The majority of signs were also Type III sheeting. It is interesting to note that all of the in-service green signs with known installation dates maintained the minimum retroreflectivity levels. However, these measured retroreflective values were variable. Table 2 presents a summary of descriptive statistics, including the highest and lowest values of the measured retroreflectivity for each group of sign ages, as well as the mean and standard deviation of each group. To make better sense of the association between sign age and retroreflective performance, the sign age data was classified into categorical groups in 2-year intervals. Generally, with the increase in sign age comes a steady decrease in the average values of sign retroreflectivity, with few exceptions though. In Type III HIP green signs, the average retroreflective value of signs 4–6 years old is fairly lower than that of signs 6–8 years old. The same result should be obtained for Type IX signs, the average retroreflectivity of signs 2–4 years old is lower than that of signs 4–6 years old. The majority of Type XI signs are 2 years old or younger. However, surprisingly a larger standard deviation is observed in R_A values proving the existence of other contributing factors.

To provide more comprehensive conclusions, the authors also developed regression models. Since the relationship between age and retroreflective measurements is unknown, a linear regression model was developed, as well as quadratic and cubic polynomial models for each sheeting type, to examine the association. When the relationship between response and predictor variables is unknown, polynomial regression may be used (Weisberg, 2005). In other words, polynomial regression approximates the association between variables, while a function is smooth but not straight. However, after fitting the models, linear and cubic polynomial regressions were both ill-fitted to the task. Thus, their results are not shown in this section. The coefficient of age and quadratic age variables was statistically significant at level of 0.05 only for the Type III models. The fitted models for Type III green signs with known age showed poor R^2 values too, respectively 0.06 and 0.36.

Linear model: $\text{Retroreflectivity} = 71.39–2.74 \cdot \text{Age}$

Polynomial model:
$\text{Retroreflectivity} = 150.28–29.85 \cdot \text{Age} + 2.30 \cdot \text{Age}^2$

Generally, the developed models for in-service green signs were not statistically significant enough to predict the expected service life of the signs. In addition, poor values of R^2 reflected the point that there are numerous other contributing factors affecting sign performance. Other studies focused on developing models for retroreflectivity with respect to sign age have found the same results, in that the fitted models were not significant (some of them with a lack of degradation) and yielded a poor value of R^2 (Bischoff and Bullock, 2002; Black et al., 1992; Pike and Carlson, 2014; Re et al., 2010). In other words, the claim of predicting sign retroreflectivity with respect to sign age is seriously questioned. To address this issue, we aimed to assess the effects of damage on the sign's retroreflectivity.

5. Sign damage vs. retroreflectivity measurement

During the data collection effort, the team observed various damage forms on the signs' face (Evans et al., 2012b). In addition, photos were taken of every surveyed sign in order to further classify each form. Ultimately, the damaged signs

Table 2 – Retroreflectivity specifications for green signs by sheeting type and age.

Sheeting type	Age (year)	Number of signs	Retroreflectivity (cd/lx/m^2)			
			High	Mean	Low	S.D.
III	0–2	1	–	115.00	–	–
	2–4	–	–	–	–	–
	4–6	3	64.00	48.20	28.80	17.87
	6–8	104	73.00	53.13	28.00	7.87
	8–10	2	49.50	48.50	47.50	1.41
III HIP	0–2	1	–	99.8	–	–
	2–4	–	–	–	–	–
	4–6	16	141.30	101.68	71.30	20.22
	6–8	6	132.00	115.82	105.80	9.63
	8–10	–	–	–	–	–
IX	0–2	14	124.30	86.69	50.50	27.91
	2–4	3	55.50	53.77	51.00	2.42
	4–6	11	126.80	79.99	48.30	29.94
	6–8	2	54.30	48.55	42.80	8.13
	8–10	–	–	–	–	–
XI	0–2	19	127.30	89.59	60.00	19.85
	2–4	2	92.30	90.40	88.50	2.69
	4–6	2	88.50	80.75	73.00	10.96
	6–8	–	–	–	–	–
	8–10	–	–	–	–	–

were categorized into six groups, including bending/cutting, cracking, fading, peeling, vandalism, and other forms, as shown in Fig. 4. Bending damage described signs with significant portions of the sheeting bent, included signs bent by wind, snow, or vehicles. Signs with multiple cuts on the sheeting, deliberate damage as a result of transportation and installation of the sign, were categorized into cutting group. Cracking damage consisted of the retroreflective background cracking over time, while signs with faded background colors were classified as fading damage form. Peeling damage occurred on the legend of a sign, made the legend peeling off the sheeting. The most diverse category of sign damage, vandalism, included any deliberate damage to the sign face caused by humans, such as paintball damage, ballistic damage from firearms, glass bottle impacts, eggs, stickers, dents, graffiti, and over painting. Other forms included signs damaged by contact with trees or tree sap.

To enable more in-depth analysis, box plots of retroreflectivity measurements by background color, sheeting type, and the existence of damage for the surveyed signs are displayed in Fig. 5. The rotated squares in the plots display the mean values of the measured retroreflectivity for each group. For all of the surveyed colors, white and yellow signs showed the greatest range of retroreflectivity measurement. As seen in Fig. 5, for the majority of groups, it can be stated that the range of retroreflectivity measurements for damaged signs was narrower than signs with no damage. Focusing on the surveyed Type I signs, all of average values were below the minimum MUTCD levels regardless of the existence of damage. It is necessary to mention that regardless of what obtained from this study, UDOT is replacing Type I signs, due to such poor performance. By comparing the current data, with no Type I red sheeting signs, to the data collected in 1999, in which there were a remarkable number of Type I red sheeting signs, UDOT's process of replacement of Type I signs is evident (Evans et al., 2012b). As seen in the table, the average retroreflectivity of damaged signs was lower than non-damaged for Type I signs.

With the exception of white signs, for all colors of Type III signs, the average retroreflectivity of damaged signs was lower than signs with no damage. The average retroreflectivity values measured for white Type III damaged and non-damaged signs were very close though, respectively 278.56 and 274.88. Types III HIP (high intensity prismatic), IX, and XI signs showed a very high performance level, all of the average values were above the minimum MUTCD levels regardless of being damaged or not. In addition, with the exception of 22 Type IX yellow damaged signs, the number of damaged signs observed in the Types III HIP, IX, and XI samples was not significant. In total, only 13 out of 190 (almost 7%) Type III HIP, 39 out of 259 (almost 15%) Type IX, and 12 out of 117 (almost 10%) Type XI signs were recorded with a form of damage. Thus, no strong conclusion might be drawn with respect to the difference in average retroreflectivity measurements for damaged and non-damaged signs. Since the number of damaged and non-damaged signs for each color of Type III signs were remarkable, a statistical test was conducted to determine whether or not there was a statistically significant difference between the retroreflective performance of Type III signs. Table 3 compares the retroreflective performance of the surveyed Type III traffic signs grouped by their background color and the existence of damage. A statistical two tailed *t*-test was also conducted to determine whether or not the difference was statistically significant at the level of 0.05. The null and alternative hypotheses were defined as follow.

H_0: no difference in average retroreflectivity measurements for damaged and non-damaged Type III signs.
H_1: average retroreflectivity measurements for non-damaged signs was higher than damaged Type III signs.

The null hypothesis for the performed *t*-test can be rejected for yellow Type III signs since the obtained *p*-value was strongly significant at the level of 0.05. In other words, according to the obtained *p*-values, there is statistically

Fig. 4 – Traffic sign damage categories.

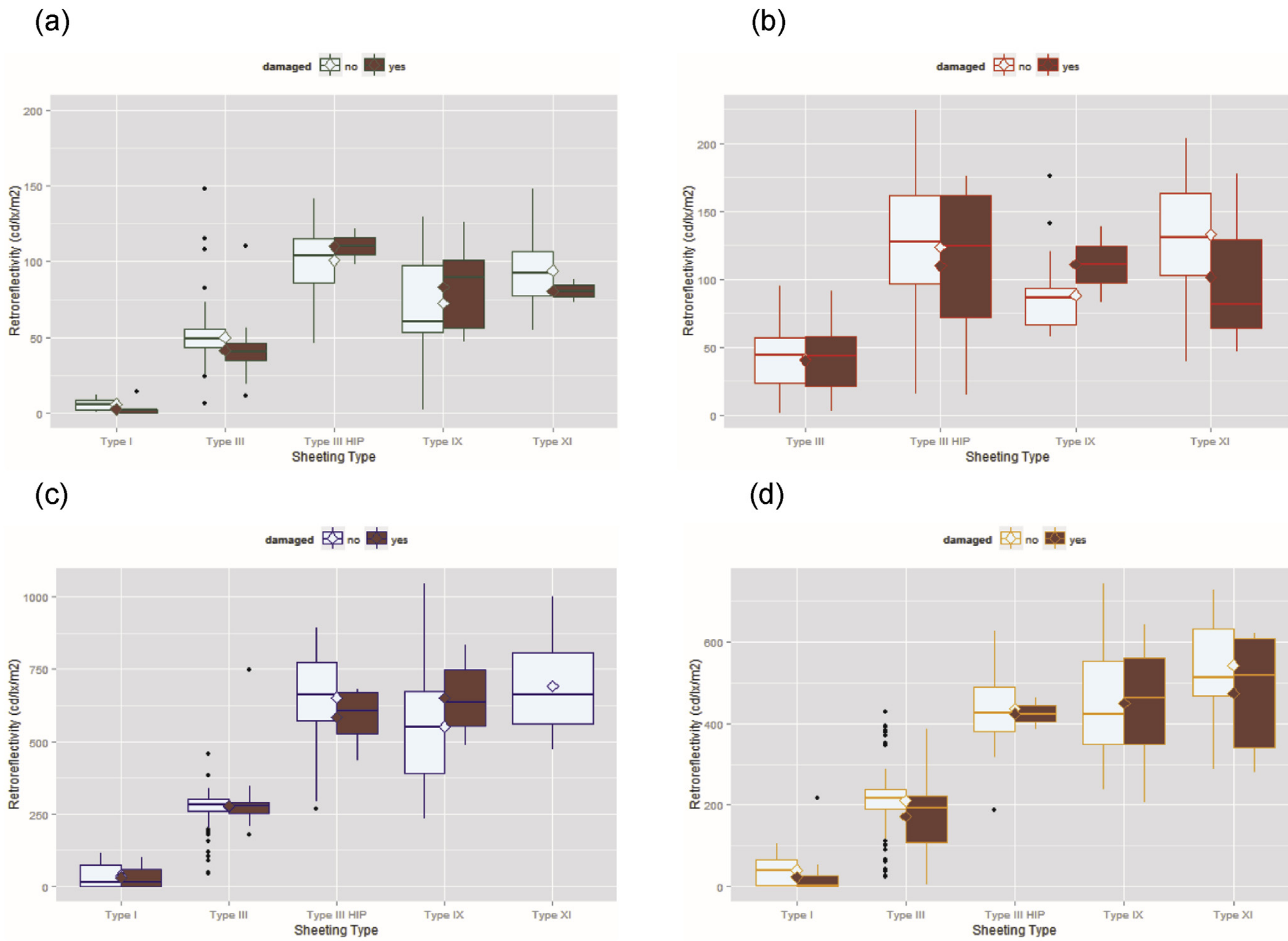

Fig. 5 – Box plots for the retroreflectivity of surveyed signs. (a) Green signs. (b) Red signs. (c) White signs. (d) Yellow signs.

Table 3 – Retroreflective performance of sheeting type III signs by color and damage.

Color	Damaged	Number of signs	Retroreflectivity (cd/lx/m^2)			
			Mean	Difference	t-statistic	*p*-value
Green	No	193	50.17	3.73	0.70343	0.242200
	Yes	59	46.44			
Red	No	105	41.52	1.37	0.35069	0.363400
	Yes	43	40.15			
White	No	264	274.88	−3.68	−0.41353	0.659800
	Yes	63	278.56			
Yellow	No	172	211.06	38.91	3.55680	0.000272
	Yes	80	172.15			

strong evidence that the average value of retroreflectivity for non-damaged signs was higher than damaged Type III signs regardless of surveyed signs age, climate, and localized conditions. For green, red, and white Type III signs the null hypothesis cannot be rejected though since the *p*-values were not statistically significant at the level of 0.05. The next section discusses the association between the existence of damage and sign retroreflectivity compliance. To do so, every damage form is discussed separately.

6. Comparison between the effects of various damage forms on failure rate

Table 4 summarizes the retroreflective performance of surveyed signs with regard to the existence of damage on sign face. As seen in the table, 68 out of 375 traffic signs that exhibited a form of damage, almost 18% were not in compliance with the minimum MUTCD levels. The rate of

Table 4 – Summary of sign retroreflective performance by damage.

Damaged	Retroreflective performance		Total
	Fail	Pass	
Yes	68	307	375
No	60	1248	1308
Total	128	1555	1683

Chi-square test statistic = 74.19.
p-value < 0.0001.

retroreflective failure for signs without any damage was only 4% (60 out of 1308). In other words, in the context of data, traffic signs with a form a damage on the face were less likely to maintain the standard levels. After employing a chi-square test, the strong association between sign damage and retroreflective performance was evident, whereas the chi-square value was statistically significant at the level of 0.05 based on the obtained p-value.

Contingency tables according to sign damage form (bending/cutting, cracking, fading, peeling, and vandalism, and other forms) and retroreflective performance (fail, pass), were also created for this study to compare sign failure rates. Since all 24 traffic signs with other forms of damage than above types were in compliance with the minimum levels, the authors excluded them from Table 5. Certain potential measures were taken into account, including difference of proportion, relative risk, and the odds ratio (Agresti, 2007). Of these three possible measurements, the authors used the odds ratio for this study. Odds ratio is the most widely used measurement in practice by far since it is invariant regarding whether a study is prospective or retrospective and it is best-suited when the outcome is relatively rare (Corcoran, 2013). Table 5 shows the odds ratios calculated to compare damaged signs with non-damaged signs in terms of their retroreflective performance. If P_{0i} is the probability that signs without damage form i fail to comply with the minimum MUTCD standards and P_{1i} is the probability that signs with damage form i on the face fail to maintain the minimum levels, formally speaking, the authors were interested in a test of follow Eq. (1).

$$\begin{cases} H_0 : P_{0i} = P_{1i} \quad \text{or} \quad H_0 : \log\left[\dfrac{\text{Odds}(P_{1i})}{\text{Odds}(P_{0i})}\right] = 0 \\ H_1 : P_{0i} \neq P_{1i} \quad \text{or} \quad H_0 : \log\left[\dfrac{\text{Odds}(P_{1i})}{\text{Odds}(P_{0i})}\right] \neq 0 \end{cases} \tag{1}$$

In addition, a 95% confidence interval for the odds ratios are shown in Table 5, given by $\alpha = 0.05$, thus $z_{1-\frac{\alpha}{2}} = z_{0.975}$.

$$\exp\left\{\log\left[\frac{\text{Odds}(P_{1i})}{\text{Odds}(P_{0i})}\right] \pm Z_{0.975} \cdot \text{S.E.} \log\left[\frac{\text{Odds}(P_{1i})}{\text{Odds}(P_{0i})}\right]\right\} \tag{2}$$

At the conclusion, it was found that the odds of sign failure for signs with fading damage were 15.77 times higher than other signs, with a confidence interval equaling (6.84, 36.96). In addition, it was 95% confident that the odds of sign failure for cracked signs were between 5.82 and 15.68 times those for signs with other forms of damage or non-damaged signs. The odds of retroreflective failure for peeling and vandalism forms were respectively 2.31 and 1.61 times of the others. These results did not provide a significant difference between retroreflective performance of traffic signs with bending/cutting damage forms and other surveyed signs.

7. Discussion

Since the existence of damage affects retroreflective performance of traffic signs which leads to safety issues for drivers, transportation agencies should plan on the replacement of key damaged signs. To do this, agencies can schedule more frequent sign inspections to identify damage signs, or people can report problems with traffic signs to agencies. For example, individuals in New York City can report traffic sign problems (damaged, blocked, or missed signs) to the Department of Transportation on phone or online (NYC, 2015). After collecting sign data, agencies may prioritize the replacement of damaged signs to provide safer environment for the users. Fig. 6 represents the rate of retroreflective failure in signs surveyed with a form of damage, or no damage. Fading damage has, by far, the highest rate of failure, with 13 out of 24 (54%) signs exhibiting this form of damage were non-compliance with MUTCD retroreflectivity requirements. The

Table 5 – Odds ratios for failure rates by damage form.

Damage form		Retroreflective performance		Odds ratio	95% CI	
		Fail	Pass		Lower	Upper
Bending/cutting	Yes	1	61	0.22	0.01	1.00
	No	127	1494			
Cracking	Yes	31	50	9.60	5.82	15.68
	No	97	1505			
Fading	Yes	13	11	15.77	6.84	36.96
	No	115	1544			
Peeling	Yes	9	50	2.31	1.03	4.60
	No	119	1505			
Vandalism	Yes	14	111	1.61	0.86	2.82
	No	114	1444			

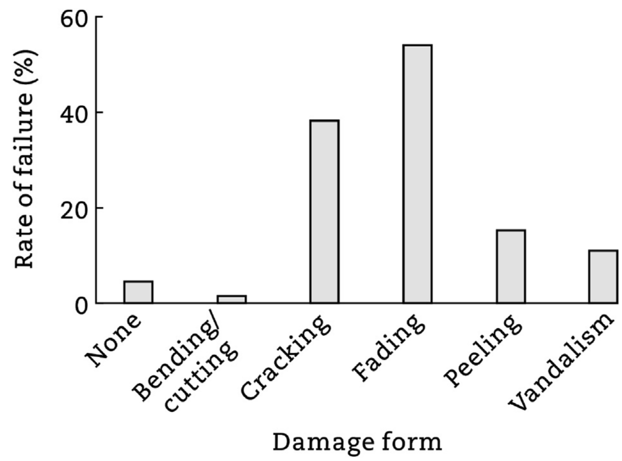

Fig. 6 – Sign retroreflective failure rate by damage form.

rate of failure for cracking damage was also significant, 38%. Almost 15% of traffic signs with peeled legend off did not maintain the minimum levels. Our suggestion for agencies is prior to the replacement of peeled signs, which measure signs' retroreflectivity. If sign maintains the levels, agencies can just repair the legend, instead of replace sign. 14 out of 125 vandalized sign were not in compliance with MUTCD minimums. In total, the retroreflective performance of vandalized signs was highly dependent on the size of sheeting impacted by damage. If the damage on the sign face was not sizeable, such as paintball or ballistic damage, and sign had enough legibility, agencies could plan on just sign repair. For larger size of vandalism damage, such as stickers, graffiti, or over painting, they can remove them from the face as long as sign retroreflectivity does not fall down below the minimum levels. The failure rate for bending/cutting damage forms was unremarkable. It is may be a reflection of using handheld retroreflectometer devices. Measurements from twisted and leaning signs can result in retroreflectivity above the minimum levels, while the actual luminance of the sign under nighttime conditions may be lower than the requirements (Carlson, 2011). Thus, agencies should ensure that bent signs maintain the MUTCD standards through nighttime inspections. For signs without any form of deterioration on their face, only 60 out of 1308 (4.6%) signs did not maintain compliance.

8. Conclusions

Sign replacement is a low-cost safety treatment helping drivers navigate roads in a safer and more efficient manner. Regardless of the method used, traffic agencies are required to replace traffic signs that are not in compliance with the minimum MUTCD retroreflectivity levels. Expected sign life has been the most selected method though to guide sign replacement in recent years. However, this study's initial analysis indicated that except sign age, there are other contributing factors potentially affecting traffic sign retroreflectivity performance not yet accounted in current literature. This research examined the effects of damage on the retroreflective performance of traffic signs. To accomplish this goal, the data collected in the state of Utah were used. For the majority of surveyed colors and sheeting types, the average value of retroreflectivity measurements for damaged signs was lower than signs with no damage. After applying *t*-tests to Type III signs, the *p*-value was statistically significant at the level of 0.05 for yellow signs.

Categorizing damage forms into six groups, including bending/cutting, cracking, fading, peeling, vandalism, and other forms, the more critical damage forms for sign visibility were identified using chi-square test and odds ratio. At the completion, it was confirmed that there was a statistically significant difference between signs retroreflective performance based on sign damage form. Based on this study's findings, the suggestion for transportation agencies regarding traffic sign replacement plan is as follows.

- Since faded and cracked signs had the highest rate of retroreflective failure, the replacement of these damaged signs may be warranted. This failure is more critical for regulatory and warning signs.
- Traffic signs surveyed with legend peeling off were also likely to fail to convey their message to the road users. However, if sign maintains the minimum levels, agencies can just plan on legend repair instead of sign replace.
- Vandalized signs should be inspected in the field to ensure that they are not repairable. The effects of sign vandalism on retroreflectivity greatly depend on the size of damage. Another consideration should be taken by agencies is that cleaning vandalized signs is labor intensive and sometimes cause sign visibility to degraded.
- Although bent traffic signs showed a well retroreflective performance, since the actual luminance of the sign under nighttime conditions may be lower than the requirements, they should be examined in nighttime to ensure sign visibility.

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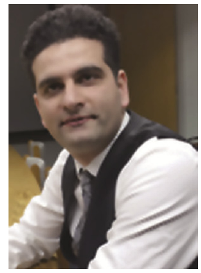

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