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TECHNICAL NOTE

CRIMINALISTICS

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Determining the Refractive Index Variation within Panes of Vehicle Windshield Glass

ABSTRACT: Refractive indices of seven double-paned vehicle windshields were measured to assess the variation across the pane of glass and to evaluate collection techniques for known glass standards by comparing false negative rates. Measurements were made using a Foster and Freeman GRIM3 instrument, and a minimum of 240 measurements were made per pane. The mean SD of the windshields was 0.00004. It was further determined that collecting a known sample from two different sections of a shattered windshield gave the lowest rate of false negatives when using $\pm$ 2 standard deviations to estimate the RI variation of the known glass. Additionally, refractive indices often were highest in the center of the windshield and decreased toward the left and right edges; in approximately half the sample set, the two panes of a single windshield were differentiated by one or more properties.

KEYWORDS: forensic science, glass, refractive index, windshield, GRIM, trace evidence

Glass is encountered as evidence in many different forensic cases, from property crimes such as burglary and vandalism to bar room assaults and hit-and-run fatalities. In the forensic comparison of known glass to fragments of glass from an unknown source, the measurement of the glass' refractive index (RI) is often one of the most discriminating techniques. In order for this comparison to be meaningful, one must accurately assess the RI variation that exists within the broken portion of the known glass, including the measured RI variation attributed to the measurement technique itself. However, if the known glass sample was collected from a small region of the broken object, the measured RI variation of the small area may underestimate the variation of the entire object, leading to false exclusions. While it is known that glass may exhibit distinct variations in RI across the thickness of glass sheets, and that original glass surfaces may differ greatly in RI from the bulk glass, studies of RI variation across individual panes are not comprehensive (1). The purpose of this study was to analyze seven laminated (double-paned) windshields to assess the overall RI range of each pane via a GRIM3 instrument, to investigate spatial trends in RI distribution within windshields, and to compare collection methods for known glass samples. In addition, the two panes of each windshield were intercompared.

Background

The different components used to make glass, as well as the variety of manufacturing methods, lead to physical and chemical properties that can be used to differentiate one item of glass evidence from another. Of the methods of glass analysis, RI measurement is perhaps the most common and can be highly discriminating in the quest to determine whether two pieces of glass may have originated from the same broken object.

RI is a measure of the speed at which light travels through a transparent medium, compared with the speed of light in a vacuum. Values for glasses are typically near 1.5. The RI of glass is dependent on its elemental composition and thermal history. The thermal history is the result of all the heating and cooling events the glass has undergone. If two glass objects have identical compositions but different thermal histories, they will typically have different refractive indices and *vice versa*. However, it is possible for two samples with measurably different compositions and thermal histories to have the same RI.

Few published studies have explored the variability of RI values within populations of windshield glass samples. In 1972, Ojena and De Forest (2) published research on the variation of RI in sealed beam headlights. In 1984, Locke and Hayes (3) reported that variations were found across the thickness of window, container, and windshield samples; they attributed these differences to varying manufacturing temperatures, especially for heat-strengthened and thick glass. Float glass in particular has been found to have variation in RI within a single sample in part due to the presence of the tin bath on one side of the glass during manufacture (1). However, these older studies used measurement techniques that did not allow the degree of precision possible with newer automated methods; therefore, imprecision in the method may have obscured detection of variability inherent in the glass. In 2001, Koons and Buscaglia (4) evaluated the overall variance in RI for all glass types examined in forensic laboratories and reported that RI variation has decreased in recent decades, likely due to the conversion of the manufacturing industry from roller-pulling methods to the float method. A recent study by Garvin and Koons (5) addresses the use of different "match criteria" and their false negative (incorrect exclusions) error rates with regard to float glass (including one

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windshield). This study analyzed a pane's variation by dividing it into quadrants and may have missed subtle RI gradients present in the windshield that could be detected if smaller areas of the windshield were assessed individually (5). Also, other than a single windshield measured at three locations in the Locke and Hayes (3) publication, none of these studies have specifically tested multiple windshields to evaluate the RI variation that could be due to the heating and reshaping of windshield panes during manufacture.

During windshield manufacture (6), two pieces of appropriately sized windshield glass are cut out of cooled sheet glass. The two sheets may or may not have the same chemical and physical properties. One sheet is placed on top of the other, and they are moved onto the bending iron which is the shape of the desired windshield. The bending iron and glass are then moved into the bending lehr, a large oven where the glass is heated until it deforms into the shape of the iron. After deformation, the glass is allowed to slowly cool and toughen (a process known as annealing) before the pieces are pulled apart and a vinyl layer is placed in between. The glass and vinyl sandwich is then pushed between rubber rollers to remove air bubbles before being placed in an autoclave where pressure and heat remove any remaining air bubbles, rendering the vinyl layer completely transparent. After being removed from the autoclave and cooled, a frame is then added to the windshield and it is ready to be mounted in a vehicle.

The annealed windshield glass is cooled slowly, allowing stress within the glass to dissipate. This increases the glass' temperature- and mechanical-durability, making windshields more resistant to breakage due to temperature fluctuations and mechanical shock (7). If broken, the laminate layer holds the glass fragments together and reduces the amount of injury from flying glass; the laminate also acts to resist penetration of the glass by projectiles (8). The annealing process may also create slightly different thermal histories for different regions of a given windshield. A slower or faster cooling process could result in detectable differences in RI across the windshield, which could result in a larger overall variability in RI of a windshield when compared with a piece of flat glass of similar size (9).

Typically, a forensic glass examiner does not receive the entire broken object into the laboratory, but instead receives a small sample of fragments meant to represent this object. These fragments may have been collected by trained forensic personnel, but often they are collected by investigating officers who may have minimal forensic training. It is unknown whether these small samples adequately represent the whole when a large object such as a windshield is broken; it is possible that they could underestimate the variation in RI across the breadth and height of the pane. Regardless, estimates of the total RI range of the broken portion of an object must be made to conduct forensic comparisons. Several estimation methods are currently in use in the forensic community; these include fixed value ranges (e.g., mean of known glass +/− 0.0002 units), ranges based on variance (e.g., the mean of known glass $\pm$ 2 standard deviations), and known/questioned glass range overlap (10). All of these methods are inherently compromised if the submitted sample is not representative of all the broken portions of the object.

Materials and Methods

The glass samples were analyzed with the GRIM3 instrument (Foster and Freeman, Evesham, U.K.) attached to a Leica DMLB phase contrast microscope with a 10× objective and Mettler hot stage. Measurements were recorded using the sodium D wavelength (589 nm). In the GRIM3 software, a minimum edge count of 80 (11) was required for both the cooling and heating runs in order for a measurement to be accepted. Instrument calibration was performed using eleven standard glass samples of known RI (Locke Scientific Ltd., Basingstoke, U.K.). Each day before beginning sample analysis, the RI of the Locke Scientific glass standard B4 was measured to ensure that the instrument was operating properly. This B4 standard had not previously been included in the calibration curve. The manufacturer of this instrument ensures that the system is capable of a RI standard deviation of < 0.00003 over a 5-day period (12). In-lab performance of this GRIM3 instrument, calibrated annually, has shown that expected value to be valid over a period of thirty months (April 2010–October 2012), as checked with Locke glass B4.

Seven vehicle windshields were recovered from various windshield replacement companies and laboratory staff members near Portland, Oregon, USA. Information on the vehicle make, model, and year for the respective windshields is presented in Table 1.

Each windshield was divided into sections of one square foot (roughly 930 square cm). This allowed for eight to fifteen sections, depending on the original size of the windshield, as shown in Fig. 1. A roughly two-inch-by-two-inch square (26 square cm) was colored in the center of each section and the windshield was flattened. The colored squares were excised using a screwdriver and mallet and labeled to show their original placement in the windshield and to indicate interior and exterior panes. Ten glass fragments were taken from each sample from both interior and exterior panes and placed in appropriately labeled vials based on windshield number, section letter, and interior or exterior pane designation.

Before RI testing, thickness measurements were recorded for five of the ten fragments from each section, interior and exterior panes, using digital calipers (Mitutoyo Digimatic Caliper). Each of the ten fragments was further broken using a metal spatula to

TABLE 1—*Vehicle make, model, and year.*

Windshield	Make	Model	Year
1	Dodge	Sprinter Van	2008
2	Volvo	XC70	2007
3	Chevy	Silverado	2009
4	Dodge	1500 Pickup	1994
5	Honda	Accord	2001
6	Honda	CRV	2007
7	Toyota	Unknown	x

x, unknown.

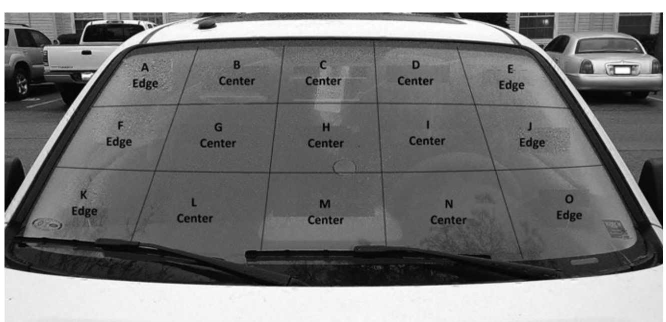

FIG. 1—*Example windshield with fifteen sections labeled.*

produce fragments small enough to prepare slides for analysis. Float glass is known to have a range of RI values across the thickness of the glass with very different values near each surface when compared with the remaining bulk of the glass. For this reason, original surfaces were avoided, as they are in casework, to avoid increasing the measured RI variation due to this known variable. The glass fragments were mounted on a glass slide using Locke B silicone oil (Locke Scientific Ltd.) and crushed to create smaller, sharp-edged fragments appropriate for analysis. A glass cover slip was then placed over the glass and oil. Both the slide and cover slip were cleaned using methanol and a tissue wipe before use. The glass slides and cover slips (McCrone and Associates, Chicago, IL) used for the analysis each had refractive indices well outside the normal range for windshield glass.

On each of the ten slides, three edges were chosen from individual glass particles. Thus, a total of 30 measurements per windshield square-foot section were collected. Fourteen panes (seven interior and seven exterior) resulted in a total of 1800 glass fragments and 5400 RI measurements. The smallest windshield (#5) had eight square-foot sections, resulting in 240 data points, while each of the largest with fifteen sections (#1, 3, and 4) provided 450 data points. For each section, using the 30 data points, the range (minimum to maximum) was determined, and the mean RI and SD were calculated. See Table 2 for an example using the interior pane of windshield 1. The mean RI and SD were also calculated for the entire pane using all measurements.

To evaluate methods of collecting known windshield samples in forensic casework, the rate of false negatives (incorrect exclusions) was calculated for different scenarios. To determine the rate of false negatives when using only one section as a known sample, one square foot section from each pane of glass was chosen to represent the entire windshield. This simulates a common situation in which the entire pane is broken but the known glass sample is collected from only one region of that pane. The RI range ("match criterion range") for that section was then determined using the formula: $\bar{x} \pm 2\text{SD}$, where $\bar{x}$ is the section's mean and SD is the standard deviation of the data set. This match criterion range generation formula is the one used by the Oregon State Police Forensic Services Division in typical glass casework and has been identified as one of several match criteria currently used by the forensic community. Refractive indices of the rest of the windshield's sample fragments (from the remaining square-foot sections) were compared as individual questioned particles (the average of the three measurements of each particle was used for the comparison). They were counted as false negatives if they fell outside the known sample's inclusive match criterion range. This was repeated by treating each section of the windshield in turn as the known sample and recording the number of false negatives as well as the original location of the known sample section. Due to the greater curvature of the windshield in the side-to-side plane, sections taken from the extreme left and right were considered edges and all other sections were considered center (Fig. 1). The total false negative count for each windshield was then converted to a false negative rate by dividing the total number of false negatives by the total comparisons possible for a given windshield.

To determine the rate of false negatives when using two sections as known samples, a similar method was employed. However, instead of just using one section's mean RI and SD, the mean and SD of the two combined sections were calculated, using a total of 60 measurements. This simulates collection of the known glass sample from two areas of the broken pane. The mean and SD of the two combined sections were then used (same method as above) to determine the RI match criterion range of the known standard, and false negatives were calculated using every combination of two sections for each windshield. Both the total and location-specific false negative rates were then determined. Comparisons were categorized into three groups, according to the locations of the sections: edge & edge, center & center, or edge & center.

For both the one-section and two-section false negative analyses, the calculations were repeated twice: once using the actual SD of the section or sections and again using the study's average of fourteen windshield pane SD values (0.00004).

Calculations were completed using averages and standard deviations without rounding. The only values rounded were the match criterion range limits used to determine false negatives. These were rounded to the fifth decimal place, which is the GRIM3 limit of precision. All statistical calculations were performed using Microsoft Excel.

TABLE 2—*Windshield 1, interior pane.*

Section	Measured RI Min–Max	RI Average	RI Standard Deviation
A	1.52254–1.52271	1.52264	0.000042
B	1.52256–1.52275	1.52266	0.000042
C	1.52255–1.52278	1.52266	0.000049
D	1.52259–1.52274	1.52266	0.000036
E	1.52255–1.52273	1.52264	0.000043
F	1.52251–1.52277	1.52262	0.000050
G	1.52256–1.52276	1.52265	0.000048
H	1.52256–1.52275	1.52265	0.000055
I	1.52258–1.52271	1.52266	0.000037
J	1.52256–1.52277	1.52262	0.000042
K	1.52257–1.52269	1.52263	0.000031
L	1.52258–1.52279	1.52264	0.000039
M	1.52258–1.52269	1.52262	0.000024
N	1.52260–1.52269	1.52264	0.000026
O	1.52255–1.52269	1.52261	0.000028

Results and Discussion

Refractive Index Variability for Windshield Panes

The mean RI and SD for each pane of glass are given in Table 3. The range of the mean RI values of all 14 panes was 1.51864 to 1.52264. These results are consistent with previous results seen in this laboratory for windshield glass. Individual section standard deviations ranged from 0.00002 to 0.00007. The individual pane standard deviations ranged from 0.00003 to 0.00005; averaging the standard deviations of the fourteen panes resulted in an average SD for this study of 0.00004. This average value for windshield standard deviation may be useful in casework when it is suspected that the known glass provided does not adequately represent the entire broken portion of the windshield. These values are consistent with those previously described in referenced studies.

Data collection periods per single pane ranged from 24 to 190 h. RI data were assessed to note any time-related trends or instrument drift in the measurements. No trend in SD values was noted in measurements collected in shorter versus longer time periods. No trend in RI data could be associated with the order of the collection, either in a single pane or in the study overall. Therefore, in this study, differences in RI values are deemed independent from the order of their measurement and the time period over which they were measured.

TABLE 3—*Summary of all windshield panes.*

Windshield	Side	Color	Thickness (mm)	Mean RI	RI Standard Deviation	Number of Sections
1	Interior	Pale green	2.10	1.52264	0.00004	15
	Exterior	Pale green	2.04	1.52264	0.00004	
2	Interior	Very slight green	2.12	1.52257	0.00003	13
	Exterior	Pale green	2.54	1.51978	0.00005	
3	Interior	Pale green	2.26	1.52246	0.00004	15
	Exterior	Pale green	2.26	1.52245	0.00005	
4	Interior	Pale green	2.27	1.52039	0.00005	15
	Exterior	Pale green	2.26	1.52036	0.00005	
5	Interior	Pale green	2.02	1.52024	0.00004	8
	Exterior	Colorless	2.02	1.51864	0.00004	
6	Interior	Pale green	1.94	1.51955	0.00004	14
	Exterior	Green	2.15	1.52189	0.00005	
7	Interior	Very slight green	2.04	1.52040	0.00003	10
	Exterior	Very slight green	2.07	1.52053	0.00005	

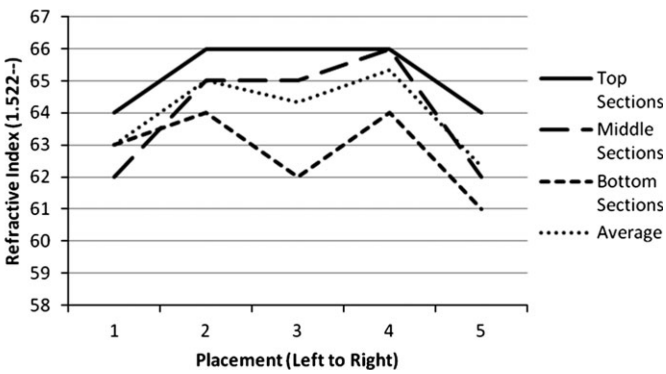

FIG. 2—*Refractive index layout for windshield 1 interior.*

Spatial Trends in RI Distribution

Average pane thicknesses are given in Table 3. Two windshield panes serve as examples of the relationship between thickness and refractive index. Windshield 2 exterior's refractive index increases as the glass becomes thicker within the pane whereas windshield 3 exterior's refractive index decreases as the glass thickens within the pane. The other windshield panes are split between slightly positive and slightly negative correlations between the refractive index and glass thickness. Thus, there does not appear to be a definite relationship between thickness and refractive index for windshield glass.

Spatial trends in RI distribution were assessed by charting each section's mean RI in relation to its position on the windshield. An overall pattern for each pane was determined by averaging the RI values in each vertical row in that pane to compare RI values from left to right. Figure 2 shows this for the interior pane of windshield 1. The windshield panes fell into one of three groups. The first group, ten of the fourteen panes, included all panes in which the center refractive indices were greater than or equal to the edge refractive indices (arcing up pattern). Group 2, three panes, had center RI of less than or equal value to the edges (arcing down pattern). A single windshield pane did not demonstrate an arcing pattern of either type. These numbers indicate that there may be a relationship between RI and the glass's location in the windshield: glass sometimes has a slightly higher RI near the center area of the windshield compared with the far left and right edges. This may have an effect on forensic comparisons if the known and unknown glass fragments are from different locations of the pane. The four windshield panes in groups 2 and 3 came from windshields 2 and 6. These were the only two windshields that did not have the same number of sections in each horizontal row of sections. Windshield 2 had four sections in two rows and five in the other one, whereas windshield 6 had four sections in one row and five in the other two. This less symmetrical sampling of the windshield, due to its size and shape, may explain the anomaly in RI patterns.

Statistical Analysis of Section-by-Section RI Comparisons

The set of 30 RI data points for each windshield section was compared, one at a time, to the data set for every other section in that windshield using a T-test (two-tailed, unpaired, unequal variance, $\alpha = 0.05$) in Microsoft Excel 2010. Significant differences ($p <= 0.05$) between the two data sets occurred in all of the windshields. Windshield 7 (exterior) was found to have the fewest instances of significant difference between two sections (18% of the comparisons showing significant differences) while 84% of the comparisons in windshield 4 (interior) showed significant differences in the compared data sets.

However, many of these differences, although determined to be significantly different by the T-test, show a measured difference of section mean RI within the instrument's expected variability of 0.00003 units over a 5-day period. Variation within this amount could be due to factors related to the measurement techniques. Removing these instances from the totals resulted in a low variation of 0% significant differences for windshield 7 (interior) and a high variation of 70% for windshield 3 (exterior). The authors considered these values to be a better measure of the inherent variation within each windshield and therefore of note to glass examiners.

Evaluation of each pane's complete data set by analysis of variance (ANOVA) indicated that there are significant differences within each windshield. Additionally, intrapane pairwise comparisons resulted in an average occurrence of statistically significant different data sets (as determined by a T-test) of 27%. That is, roughly one-quarter of the time, two sections of a given windshield produced data sets that appeared to be discrete from one another. These results indicate that there are real differences in RI values in a majority of the windshields. See Table 4 for individual pane results. Looking more closely at these comparisons, it was found that comparisons that paired a center section with an edge section accounted for an average of 53% of all comparisons (ranging from 51 to 57% depending on the size and shape of the pane). However, a study average of 70% of the

TABLE 4—*Intrapane mean RI comparison using a* T-*test.*

Windshield	A	B (%)	C	D	E (%)	F (%)
1 Ext	40	38	18	16	89	51
1 Int	40	38	15	12	80	51
2 Ext	43	55	27	16	59	54
2 Int	31	40	7	4	57	54
3 Ext	84	80	73	44	60	51
3 Int	80	76	42	35	83	51
4 Ext	79	75	50	22	44	51
4 Int	88	84	60	23	46	51
5 Ext	18	64	12	12	100	57
5 Int	12	43	2	2	100	57
6 Ext	28	31	12	7	58	53
6 Int	36	40	14	8	57	53
7 Ext	8	18	4	3	75	53
7 Int	13	29	0	0	0	53

A = Number of comparisons with significantly different means.
B = Percent of total pane comparisons with significantly different means.
C = Number of comparisons with statistically significant differences (mean differences >0.00003).
D = Number of comparisons with statistically significant differences, center versus edge.
E = Percent of D/C.
F = Center versus edge comparisons as a percent of total pane comparison.

TABLE 5—*False negative rates using one section for known sample.*

	Section SD	Avg. SD (0.00004)
Edge	9.95%	5.03%
Center	10.32%	5.59%
Total	10.15%	5.36%

TABLE 6—*False negative rates when using two sections for known sample.*

	Section SD	Avg. SD (0.00004)
Edge	6.96%	4.44%
Center	5.85%	3.96%
Combo	3.56%	2.91%
Total	4.80%	3.48%

pairwise comparisons showing significant RI differences was a center-edge pairing, a greater rate than would be expected for randomly distributed RI variability. Forensic comparisons of glass fragments from an edge of a windshield with glass from the center are especially prone to appearing to be from distinct data sets and could result in false exclusions if match criteria are based on a statistical test such as the *T*-test.

False Negative Rate Comparison by Sampling Method

When using a "match criterion range" based on ± 2 SD, a 5% false negative rate is expected for data that is normally distributed (5,10). The authors consider this a reasonable false negative (incorrect exclusion) rate for forensic RI comparison. Attempts to decrease the false negative rate to zero would likely have the undesirable consequence of increasing the false positive rate. Therefore, our laboratory's goal for RI comparisons is to devise methods that do not exceed the 5% false negative rate and are also simple to implement.

Tables 5 and 6 illustrate the rates of false negatives when one and two sections were used as the known samples, respectively. Using two sections instead of one lowers the rate of false negatives, regardless of which two sections are chosen, due to the more accurate estimation of the standard deviation. Assessing this data, the authors conclude that this phenomenon is not due to the doubled number of data points, but rather that using two sections captures more of the variation within the windshield than using a single section. Specifically, choosing one section from the edge and one from the center of the windshield yields the lowest rates of false negatives. Also shown are the false negative rates when using the study's average SD (0.00004) to determine the ± 2 SD match criterion range versus the individual section's SD. Using the study's SD for all calculations decreases the rate of false negatives for comparisons using both the one and two section known sample techniques. This decrease in false negatives was linked to certain sections that were highly homogeneous and thus had smaller standard deviations than other sections or the windshield as a whole. These small standard deviations led to artificially small match criterion ranges, thus creating a greater proportion of false negatives when glass fragments from other areas of the pane were compared with these homogenous sections. By using the study average SD for all calculations, these small match criterion ranges were eliminated. In those sections with standard deviations larger than the study average, the proportion of false negatives created by decreasing their match criterion range sizes was less than the false negatives that were eliminated by the average SD as described above.

Two windshields (3 and 4, each with fifteen sections) had unusually high rates of false negatives when compared with the other windshields. These had total false negative rates above 15% and 8% for the one- and two-section rates when using the individual section's SD values, respectively. This is compared with false negative rates that were generally below 7% and 4% for one- and two-section comparisons. Although these windshields had individual sections with smaller standard deviations than the other windshields, when the SD for the entire windshield was calculated, it was similar to the other windshields. Other windshields of comparable size did not show similar results. The main difference seen between these two windshields and the other five would be that they are from trucks whereas the other windshields are from vans, cars, and SUVs. Thus, some of the difference might be attributable to the different types of vehicles for which the windshields were manufactured. Too many variables are in play within this study's small sample set to draw any general conclusions; a larger sample set would be needed to explore this question.

In addition to assessment of the intrapane variability, this study also included comparisons of the two panes that comprised a given windshield. For six of the seven windshields, it was obvious from the RI data whether the interior and exterior panes were similar or were discriminated by RI (see Table 3). Three of the seven windshields (windshields 1, 3, and 4) had similar refractive indices and thickness for the interior and exterior panes. Thus, the interior and exterior panes may have come from glass that was manufactured on a single glass line within a short time frame. For another three of the seven windshields (windshields 2, 5, and 6), the panes' mean RI values or thicknesses (or both) were substantially different. It was also noted that these interior and exterior panes had visibly different coloration; therefore, it would be expected that they would have different refractive indices due to the differences in chemical composition. In addition, they would have been manufactured separately, which could have resulted in different thermal histories and different thicknesses.

For the remaining windshield, windshield 7, the RI values initially appeared to be fairly close, with some overlap of individual data values. The RI data of the interior and exterior panes of

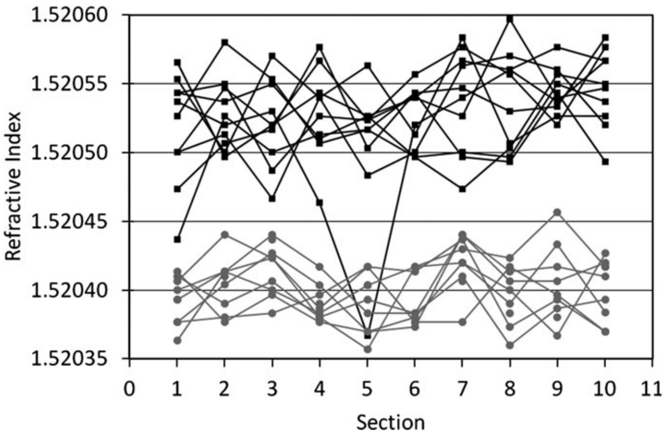

FIG. 3—*Windshield 7 refractive index values of interior (circles) and exterior (squares) panes.*

windshield 7 were compared using a two-sample unpaired Student's t-test. The null hypothesis that the two means were equal $(H_o : \bar{x}_{int} = \bar{x}_{ext})$ was tested against the one-sided alternative hypothesis that the interior average is less than the exterior $(H_A : \bar{x}_{int} < \bar{x}_{ext})$ with a significance level of $\alpha = 0.05$. Using the windshield 7 data, a *t*-test yielded a *p*-value much < 0.05, the stated level of significance. Thus, the null hypothesis was rejected and the data support the idea that the interior and exterior panes' average RI values are significantly different. Figure 3 provides a graphic representation of the difference in refractive indices seen in windshield 7, supporting the statistical findings of the Student's *t*-test.

Conclusions

The RI average SD of the fourteen windshield panes in this study is 0.00004, with individual pane standard deviations for RI varying from 0.00003 to 0.00005. The standard deviation expected from the measurement technique is also 0.00003. Although this study encompasses a small sample set, knowing the typical SD of refractive indices across a windshield pane may assist analysts in determining whether they have a sufficient known sample to represent an entire broken pane. If only one small section of a large broken windshield was collected for a comparison standard, the resulting RI match criterion range may be artificially small. Under those conditions, the analyst could instead use this study's average SD of 0.00004 to avoid falsely excluding unknown samples based on an inadequate known sample. In cases where the known samples yield a larger SD, it would not be advisable to use the smaller average SD, because the windshield could have a greater amount of variability than this study indicates. Thus, it is recommended that the analyst uses a SD of 0.00004 or the measured SD, whichever is greater.

To accurately represent the RI variation seen in an entire broken windshield, at least two areas of the known glass should be collected and analyzed. Ideally, these samples will come from separate areas on the windshield, one near the center and the other from an edge area. It is also crucial to remember that in cases in which only a portion of the windshield is broken, the known glass sample is best taken from within that region, rather than sampling from the entire pane or from a separate unbroken location, to minimize false positive results that could come from assigning a greater variability to the broken area of glass than may be present. Ideally, the known glass submission would be collected from the entire pane in cases in which cracks or fractures are widely distributed across the pane. Depending on the condition of the windshield and vehicle, the technique of collection can be either that of prying individual fragments of each pane from the laminate or that of cutting out a portion of the windshield comprised of both glass layers and the laminate material. Both sampling techniques were compared in a small-scale experiment and resulted in very similar mean RI values. With either technique, it is important to obtain full-thickness fragments, rather than merely surface flakes. These recommendations should be shared with those tasked with collecting known glass samples from vehicle windshields. Collecting the known samples in this way decreases the rate of false negatives associated with glass comparisons.

In this study, in four of the seven windshields, the two panes of glass were differentiated by RI (as well as other properties such as thickness and color which may not be observable in forensic samples). The remaining three windshields were made up of two panes that were indistinguishable from one another. This reinforces that when windshield comparison standards are collected, both panes must be sampled in order for the final conclusions to be accurate. In some cases, unknown fragments may be associated with one pane but not the other, while in other situations, both panes must be considered as a possible source.

While this is the most complete study of windshield refractive indices to date, only seven windshields were analyzed. This study has clarified certain issues related to the collection of known samples and the RI variation within vehicle windshields, but other questions have come to light. Areas for further investigation include the apparent pattern of RI values in relation to their windshield location and whether RI variability is correlated to vehicle class, windshield size, vehicle manufacturer, location of manufacture, or other factors. Despite the need for further research, the information learned in this study will be helpful to examiners currently conducting forensic glass comparisons and can be implemented immediately to improve windshield known sample collection methods.

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References

1. Underhill M. Multiple refractive index in float glass. J Forensic Sci Society 1980;20:169–76.
2. Ojena SM, De Forest PR. A study of the refractive index variation within and between sealed beam headlights using a precise method. J Forensic Sci 1972;17:409–25.
3. Locke J, Hayes CA. Refractive index variations across glass objects and the influence of annealing. Forensic Sci Int 1984;28:147–254.
4. Koons RD, Buscaglia J. Distribution of refractive index values in sheet glasses. Forensic Sci Communications 2001;3(1):http://www.fbi.gov/about-us/lab/forensic-science-communications/fsc/jan2001/index.htm/koons.htm (accessed January 22, 2014).
5. Garvin E, Koons R. Evaluation of match criteria used for the comparison of refractive index of glass fragments. J Forensic Sci 2011;56:491–500.

6. Windshields/English Saddles/Butter/Post Clocks [video recording]. How it's made. The Science Channel, 2006; http://www.tv.com/shows/how-its-made/windshields-english-saddles-butter-post-clocks-841456/ (accessed January 15, 2013).
7. ASTM International. ASTM C162-05 standard terminology of glass and glass products. West Conshohocken, PA: ASTM International, 2010; http://www.astm.org/Standards/C162.htm (accessed January 15, 2013).
8. Almirall J, Buckleton J, Curran J, Hicks T. Examination of glass. In: Curran J, editor. Forensic interpretation of glass evidence. Boca Raton, FL: CRC Press, 2000;1–26.
9. Bennett RL, Kim ND, Curran JM, Coulson SA, Newton AWN. Spatial variation of refractive index in a pane of float glass. Sci Justice 2003;43:71–6.
10. Curran JM, Hicks TN, Buckleton JS. Forensic interpretation of glass evidence. Boca Raton, FL: CRC Press, 2000.
11. Ruddell DE. Does edge count matter? Examining the effect of the edge count on GRIM3 measurements. In: Proceedings of the 59th Annual Meeting of the American Academy of Forensic Sciences; 2007 Feb 19-24; San Antonio, TX. Colorado Springs, CO: American Academic of Forensic Sciences, 2007;63–4.
12. Foster + Freeman. Foster + Freeman GRIM3 (Glass Refractive Index Measurement System) user manual technical note. Worcestershire, U.K.: Foster + Freeman, 2009; 44–1.

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