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Study of Transfer and Persistence of Glass in a Mock Kidnapping Case

ABSTRACT

Information about the transfer and persistence of glass, as well as the frequency of occurrence of background glass in the general population, is key for the forensic interpretation of glass evidence. In this study, a mock case was designed to evaluate how glass shards are transferred during the breaking of a vehicle side (tempered) window, to what extent they persist through numerous activities, and to what extent they are prone to secondary transfer. Prior to the breaking, background glass was collected from those participating to provide a baseline control. A kidnapping scenario was devised and consisted of the breaking of a driver's side car window with the victim in the driver's seat and two suspects positioned around the breaking window. Following the smashing of the window, the victim was bound and thrown into the trunk of the suspects' vehicle and then the suspects drove away. After the scenario concluded, evidence was collected from the victim, the suspects, the exterior of the victim's car, and the interior of both the suspect and the victim's vehicles. The number of fragments, their size, and the distribution per location offered useful insight about the transfer events. The results show that persistence of glass in individuals not involved with broken glass was low, while the number of glass fragments deposited by primary and secondary transfer ranged from a few fragments to thousands of fragments, depending on the proximity and relative location to the breaking glass, as well as post-breaking activities. Glass recovery inside the vehicle offered information about fragment distribution patterns and potential transfer to passengers during similar breaking events. Fragments larger than 1mm were lost very easily during common post-breaking activities, while fragments smaller than 1mm were more persistent after primary or secondary transfer. Finally, secondary transfer of glass was observed between objects and individuals during the suspect-victim interaction, the driving activities, and the recovery of glass from personnel involved in the crime scene.

Keywords: Glass Evidence, Glass Persistence, Glass Transfer, Trace Evidence, Vehicle Glass.

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INTRODUCTION

In cases where glass is prevalent, such as hit and runs, motor-vehicle accidents, vehicular burglaries, and robberies, the recovery of broken glass could become relevant for the investigation. Glass is often examined to determine if known and questioned fragments can be differentiated based upon their physical, optical, or chemical properties. If the glass fragments are not dissimilar in any of the measured properties, the possibility that they originated from the same source of glass cannot be eliminated [1-3]. The question then arises about what can be inferred from those observations. Regardless of whether or not formal probabilistic approaches are used for the interpretation of the evidence, the significance of such evidence is ultimately assessed by the court under specific case context and inferences that can be drawn as to the guilt or innocence of the suspect. The quantity, size, location of, and type of glass are examples of key pieces of information which contribute to the assessment of glass evidence and its significance. Therefore, scientifically acquired knowledge about the transfer and persistence of glass fragments becomes essential in assisting the court in their deliberations.

When glass is initially broken, the fragments are projected from their original location onto nearby materials, whether that be a person, surrounding objects, or the scene itself. This initial distribution is commonly referred to as primary transfer. Fragments may remain on the object/person or at the location they were initially transferred to, which is known as the persistence of evidence. However, following the original transfer, fragments seldom stay where they are deposited as they can be lost via various activities. On the other hand, when glass shards are subsequently displaced to another object or individual, secondary transfer may have occurred.

The transfer of the glass and its subsequent persistence depends upon a number of factors, such as post transfer activity, the fabric or type of material it is projected onto, the transfer location/substrate (hair, skin, clothes, shoes, etc.), and extraneous environmental factors [4].

A vast majority of transfer and persistence studies have focused on the study of architectural windows. One of the first studies involving the breaking of windowpanes dates back to 1967 and highlighted the relevance of assessing the significant likelihood of glass transfer to the suspect [5]. Quite a few years later, a study conducted by Luce *et al.* focused on the study of backward fragmentation of window glass [6]. Glass fragments not only travel in the direction of the breaking force but are also backscattered in the reverse direction. The authors utilized a pendulum, a weight, and a hammer to break windows of flat glass and to evaluate fragment transfer to nearby individuals and to the surrounding area. This study established an important precedent on the relationship between the fragment size and the interpretation of glass evidence. The study also discovered quantities of recovered fragments correlated to the force and/or orientation of the breaking force. With regards to the transfer onto the individuals, the majority of the fragments were recovered from the top or jacket worn due to the parallel nature of the pane to the persons' torsos.

In the 1990s, a series of studies revealed that the transfer of glass is influenced by the relative location of the individual to the breaking glass, the composition of fabrics, the dry and wet conditions of garments, the type of glass, the thickness of the glass, the number of times a window is struck, as well as post-breaking activities and time elapsed between the moment the glass was broken and the recovery of the evidence. Likewise, the studies demonstrated that the majority of transferred fragments were within 5mm - 1mm, and brought secondary transfer mechanisms to the attention of the forensic community [7-15].

Another study by Allen *et al.* was focused on the shattering and cracking of toughened windscreens [16]. Their experiments showed that shattered windows resulted in a higher amount of fragments being dispersed than crazed panes, with the concentration of fragments distributed being inversely proportional to the distance from the breaking point. The study's testing of toughened versus laminated glass discovered little difference between the respective fragment amounts. If the windscreen was simply crazed, the fragments within the vehicle originated solely from the inner surface while shattering resulted in fragments from the inner and outer surfaces being distributed to both the interior and exterior of the car.

These pioneer studies contributed to what is known today about how flat glass breaks, transfers, and persists. Since then, relatively few studies have further investigated the mechanisms and variables that affect the transfer and persistence of glass. In 2005, Hicks *et al.* proposed a model for predicting the amount of glass transferred to the ground and to the garments of individuals nearby during the breaking of float, laminated, and toughened glass with firearms and hammers [17]. The study determined that variables such as the type of breaking object, the type of bullet, and the size of the window directly influence the prediction models. In spite of the variability of the breaking events, the authors showed that the proposed statistical model is a promising tool for gathering information of the transfer of glass at time zero, which can be further used for interpretation of the evidence.

In 2011, Irwin conducted experimental testing on broken bottles and drinking glasses, providing information that could be utilized in analogous scenarios [18]. Nonetheless, there are many more factors not yet investigated that could have relevant effects in the variability of distribution and transfer of container glass.

Up to date, the study of the transfer and persistence of vehicular glass is quite limited. Therefore, the present study aims to add to that body of knowledge. Our particular study is centered around a mock kidnapping case that tackles quite a few glass breaking, transfer, and persistence specifics. The glass utilized is tempered and originated from the side window of a vehicle. Transfer and persistence was documented from recovered glass from the victim, the victim's car, three suspects with distinct positions and roles in the event, the suspects' car, as well as the exterior of the breaking scene. Additionally, the possibility of secondary transfer and cross-contamination was noted with the collection of glass from the personnel in charge of the investigation of the scenes. This case study evaluated transfer patterns and occurrences of persistence for vehicular glass that could be used for the interpretation of glass evidence in similar cases and circumstances.

MATERIALS AND METHODS

Glass recovery from the mock kidnapping scenario was broken down into six separate activities: 1) Background recovery from clothing of the participants prior to the glass breaking, 2) Automobile glass breaking and kidnapping, 3) Glass recovery from the victims and suspects, 4) Glass recovery from the vehicles and surroundings at the crime scenes, 5) Recovery of trace evidence from the suits of crime scene personnel, and 6) Recovery and analysis of glass at the laboratory. To prevent cross-contamination, four different teams were responsible for specific tasks. Background glass and other trace evidence were collected by Team 1 (clothing evidence recovery team) from clothing of the participants in the scenario, prior to the breaking activity and subsequent recovering activities. Team 2 (actors team) then commenced in the breaking activity and subsequent transfer mechanisms while being filmed on a video camera. Team 2 consisted of a victim and three suspects. Glass within and around the vehicles (the crime scenes) was recovered by two separate groups of Team 3 (crime scene investigation (CSI) team). Finally, after Team 3 finished collecting evidence from the crime scene, any glass fragments that could be detected on their suits as a result of secondary transfer were collected by Team 1. Members of the fourth team processed and analyzed the evidence at the laboratory.

The clothing evidence recovery team (Team 1) was equipped with butcher paper, disposable lab coats and disposable nitrile gloves (Fisher Scientific, NH), trace evidence collection vacuum systems (3M, Arrowhead Forensics, KS) and filters (P5 grade, Fisher Scientific, NH), clear lifting tape and forensic evidence bags (Lynn Peavey, KS), micro-spatulas and tweezers (Ted Pella, CA), digital cameras (Nikon D7200, Nikon Corp, Japan), chain of custody forms, and packing materials.

The actors (Team 2) wore full coverage safety goggles, scarves to protect their faces, full-length pants, and long-sleeved shirts. The scarves and the victim's shirt were 100% polyester while the suspects all donned 100% cotton shirts and denim jeans. The victim drove a black Mercedes Benz E320 (1997), while the suspects drove a blue Honda Civic (2009). Both vehicles were vacuumed and cleaned prior the exercise. The suspects in Team 2 used a crowbar/pointed tool to break the driver's window and duct tape (standard grade, Staples, MA) to bind the victim.

The CSI Team 3 wore non-shedding Tyvek protective suits (DuPont, ME), disposable gloves, and safety goggles (Fisher Scientific, NH), and utilized digital cameras (Nikon D7200, Nikon Corp, Japan), light sources (crime-lite, Foster and Freeman, VA), spatulas and tweezers (Ted Pella, CA), crime scene forms/sketches, chain of custody forms, and packaging materials.

Activity one: Background Recovery

The recovery of background glass from the garments being worn by the actors was conducted in a room distant from the breaking scene. White paper was placed on the sampling room floor where individuals removed their shoes for scraping/hand picking of trace evidence. External clothing layers (shirts and pants) were further scraped and vacuumed. Clean disposable paper was used to cover the sampling table prior to recovery and packaging of any evidence. Any debris or fragments were collected in paper and/or petri dishes then packed and labeled appropriately. Disposable filters were used on the vacuum system and the table, and all sampling materials were cleaned with ethanol in between items.

Activity two: Glass Breaking and Kidnapping

The breaking activity came in the form of a mock kidnapping scenario. The scenario took place at the garage at West Virginia University's crime scene complex. While the victim (V1) was parking his vehicle (Car 1) at a garage, the suspects in Team 2 blocked the entrance by backing in their vehicle (Car 2). Suspect 1 and 2 (S1 and S2, respectively) intercepted the driver/victim, S2 with a gun aimed at the victim while S1 broke the driver's side window to force the victim out of the vehicle. Figure 1 illustrates the relative position of the suspects during the breaking event. All the windows of the victim's vehicle were in the closed position. The victim was moved to the trunk of Car 2 and immobilized with tape on the wrists and ankles as well as over his head scarf. Suspects 1 and 2 did not have direct contact with the victim. Suspect 3 (S3) bound and placed the victim into the trunk. Car 2 drove about 6 blocks before being "apprehended", with S1 in the front passenger seat, S2 in the back seat, and S3 in the driver seat.

Activity three: Recovery from Victims and Suspects

The recovery of the glass from the victim's and suspects' clothing was conducted over white paper specific to each participant, then picked over, taped, and vacuumed. The shoes were examined with the aid of light sources and subsequently scraped and picked at. The tape on the victim was carefully removed and placed on transparent acetate films, then sealed within an evidence bag. Any recovered debris was placed in the recovery paper or plastic petri dishes. Team 1 was performing this recovery while donning disposable lab coats and gloves. Different entrance-exit routes to and from the sampling recovery area were designed to avoid cross contamination.

Activity four: Recovery from the Crime Scenes

The CSI Team 3 was responsible for evidence recovery at the scenes (Car 1, its surrounding area, and Car 2). The team was split into two groups corresponding to the car they were responsible for processing. Photographs and/or videos of the scene were taken prior to the collection of evidence. Within Car 1, if glass was found in the vicinity of the broken window the distance was documented before collection. The floor area outside the driver's side window of Car 1 was covered with paper divided into twenty-five 1.0 meter x 0.5 meter recovery zones (Figure 1). The glass from the different sections of the car seats and the car floor were collected separately (front, back, passenger, and driver sections). Evidence on the car floor was documented and collected by hand picking followed by vacuuming. The interior of Car 2 was processed in a similar manner, with additional inspection and recovery from the trunk area.

Activity five: Recovery from CSI Suits

Team 1 recovered any secondary transfer glass from Team 3. White paper was placed on the ground and each member's entire Tyvek suit was individually packed, labeled, and sent back to the laboratory for further analysis. Their tyvek footwear covers were not examined.

Activity six: Recovery and Analysis at the Laboratory

At the laboratory, microscopes and light sources, taping, picking, scraping, and/or vacuuming were utilized. To avoid cross-contamination, items recovered from suspects and victim were processed in separate sections of the laboratory by different individuals. Due to the larger amount of glass anticipated from the items recovered from the broken vehicle and vicinity, the evidence was processed in a laboratory located on another floor of the building. Glass fragments recovered in petri dishes and/or tapings were then observed under the stereoscope and separated according to their size range (<1mm, 1mm-5mm, 5mm-10mm, >10mm). Small fragments (<5mm) were identified as glass by further inspection under a stereoscope (4-30x), observation using a compound polarized light microscope, and by the needle-test [19]. The results were corroborated by a second analyst.

RESULTS AND DISCUSSION

Backward Fragmentation

In order to evaluate the backward fragmentation pattern from the broken driver's side tempered window, glass fragments were collected from each of the 25 zones of paper placed on the immediate floor area around the impact site (Figure 1).

As one might intuitively suspect, the largest and most significant quantities of glass were found in closer proximity to the broken window, both on the interior and exterior of the vehicle. Glass fragments were found and collected up to 3.6 meters away from the breaking point. As the distance from the breaking site increased, the size and amount of shards decreased. Zones 2, 3, 4, 7, 8, and 9, which were all located within 1 to 2 meters from the breaking site, contained the majority of glass fragments. The observed fragment distributions illustrate the travel direction of backward fragmentation (Figures 1 & 2). Glass fragments of all four-size ranges were transferred to the floor, with the majority of the glass smaller than 5mm traveling further away than the bigger fragments (Figure 2).

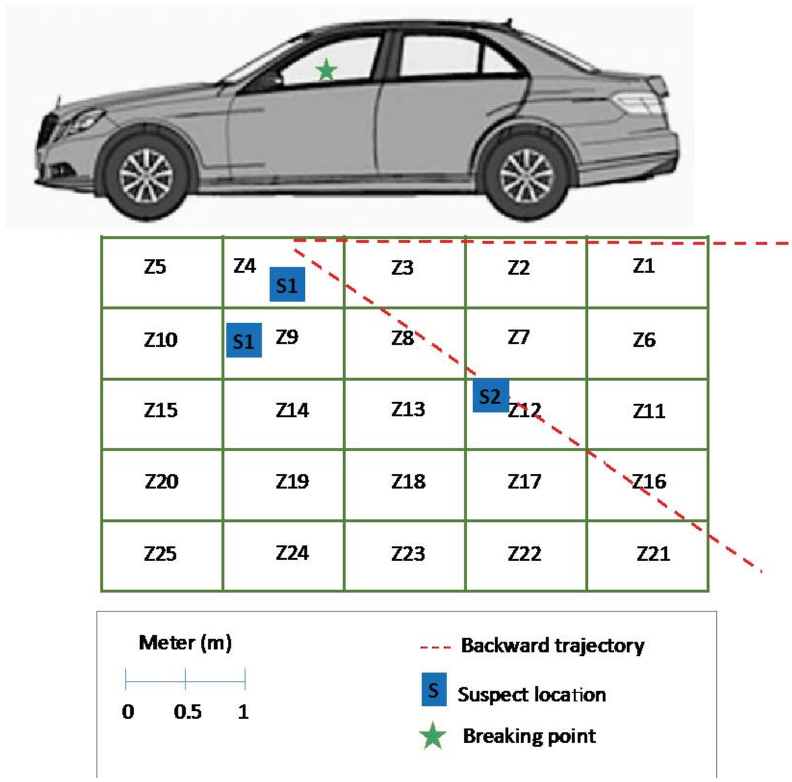

Figure 1: 2D diagram of the setup of 25 zones on the floor outside of Car 1. S1 and S2 represent the location of the suspects at the time of the breaking. Suspect 1 positioned the right foot in zone 4 and the left foot in zone 9.

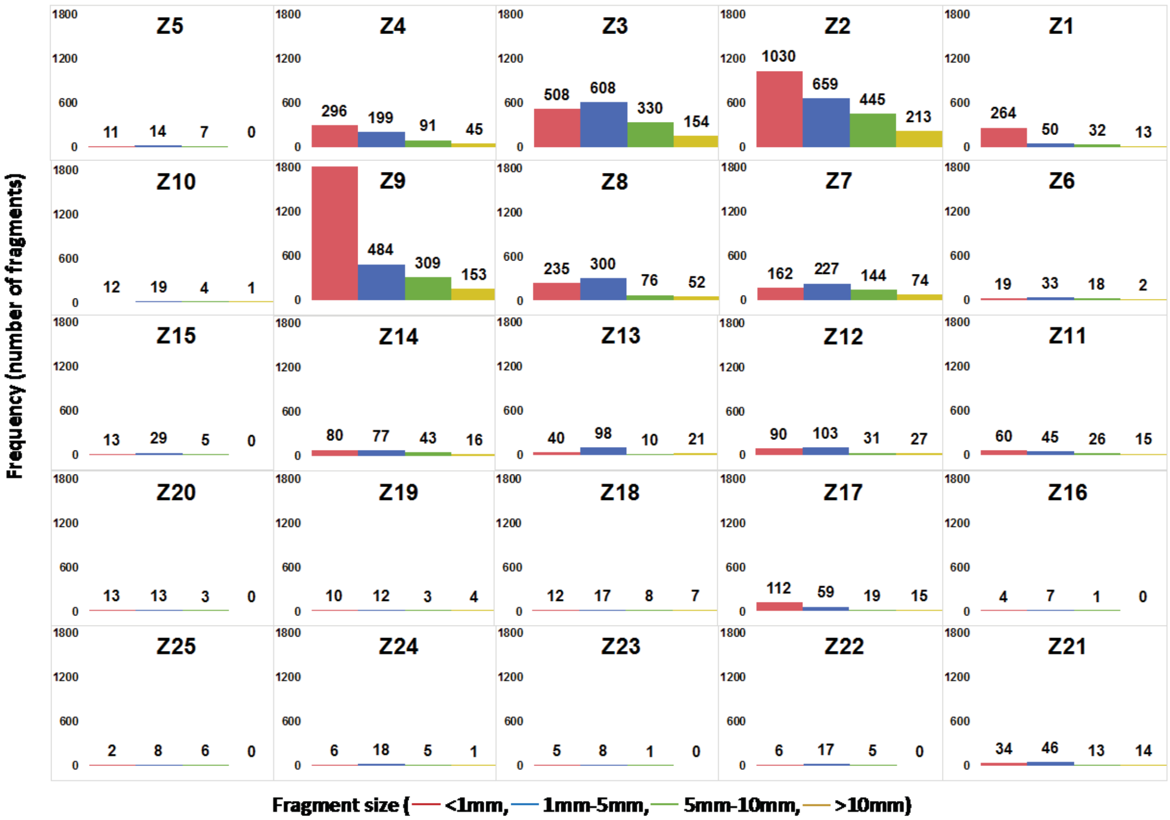

Figure 2: Color specific histograms revealing the distribution and concentration of glass fragments found in each zone.

The suspect breaking the glass was located at about 0.5 meter from the window (zones 4 and 9) during the breaking activity. The suspect moved the crowbar with a baseball-like swing motion, moving the arms from back to front while maintaining their feet in a fixed location. As a result, the sharp edge of the crowbar hit the window at an angle of approximately 45 degrees. The photographs in Figure 3 illustrate the trajectories of the tool and the broken fragments. The sphere image is shown to facilitate the 3-D visualization of the movement of the tool (red dots). The blue axis represents the relative location of the suspect's torso, the green vertical line represents the window's plane, and the red arrows represent the direction of the force and the respective reverse trajectory of the broken glass.

The pattern distribution of the recovered glass shows that the majority of the glass followed a dispersion cone of approximately 45 degrees towards the rear of the vehicle, moving from Z4 to Z12. This trajectory was the result of the ejection of the glass in the opposite direction of the breaking force as observed in Figure 3 and videos evaluated in low speed mode. However, the glass recovered from zone 9 deviated from this pattern. This suggests a secondary breaking pattern from the car window, which was later confirmed by the video to be glass that originated from breaking due to the opening of the door, rather than from the main impact. This secondary pattern is depicted by the heat maps in Figure 4, representing the fragment quantity distribution by fragment size. The heat maps are a dimensional representation of data, where the x-axis and the y-axis represent the location of each zone on the floor and a colored scale represents the amount of glass in each zone. As indicated by the scale, darker shades represent a relatively higher number of fragments. The heatmaps show the largest concentration of glass was found within 1 to 2 meters from the breaking point, and on zone 9 from the secondary breaking of glass (see Figure 1 for identification of zones). The additional breaking of glass when the vehicle's door was opened highlights the importance of considering uncontrolled factors during the evaluation of transference of broken glass. Although in a real case it is not practical to count and sort fragments due to the time involved, observations and relative estimations of spatial distribution of glass could become key during interpretation of the evidence.

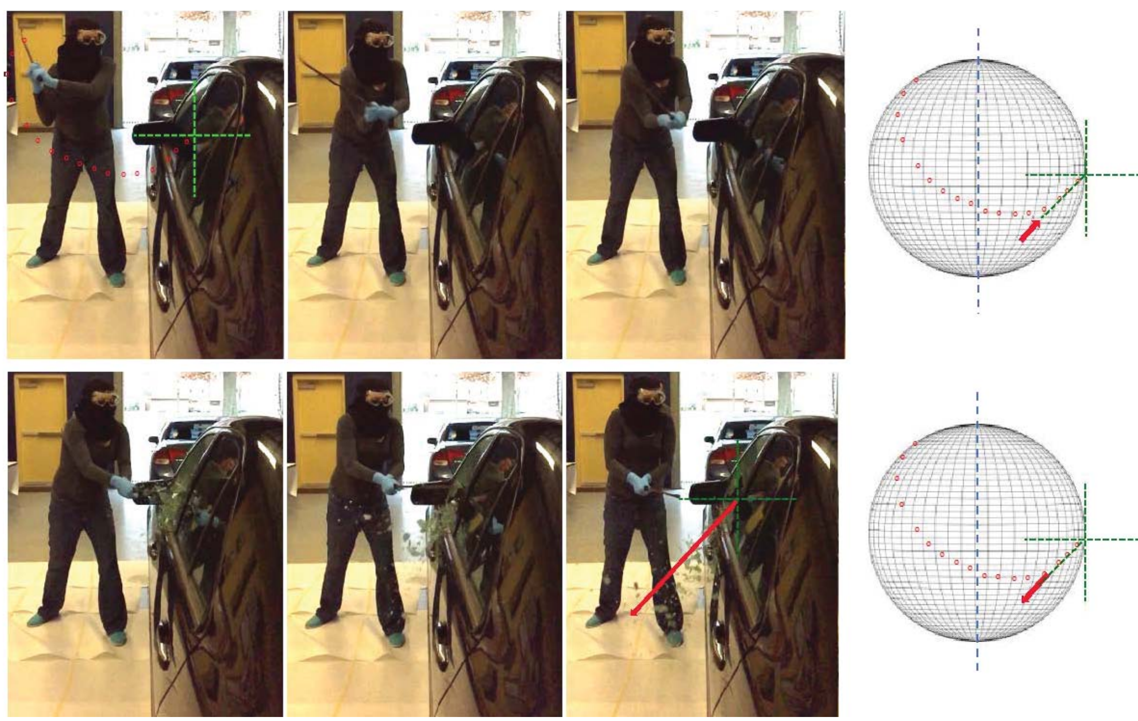

Figure 3: Photographs of the trajectory of the breaking force (top) and the backward fragmentation (bottom). The spheres illustrate the observed paths relative to the location of the suspect and vehicle window.

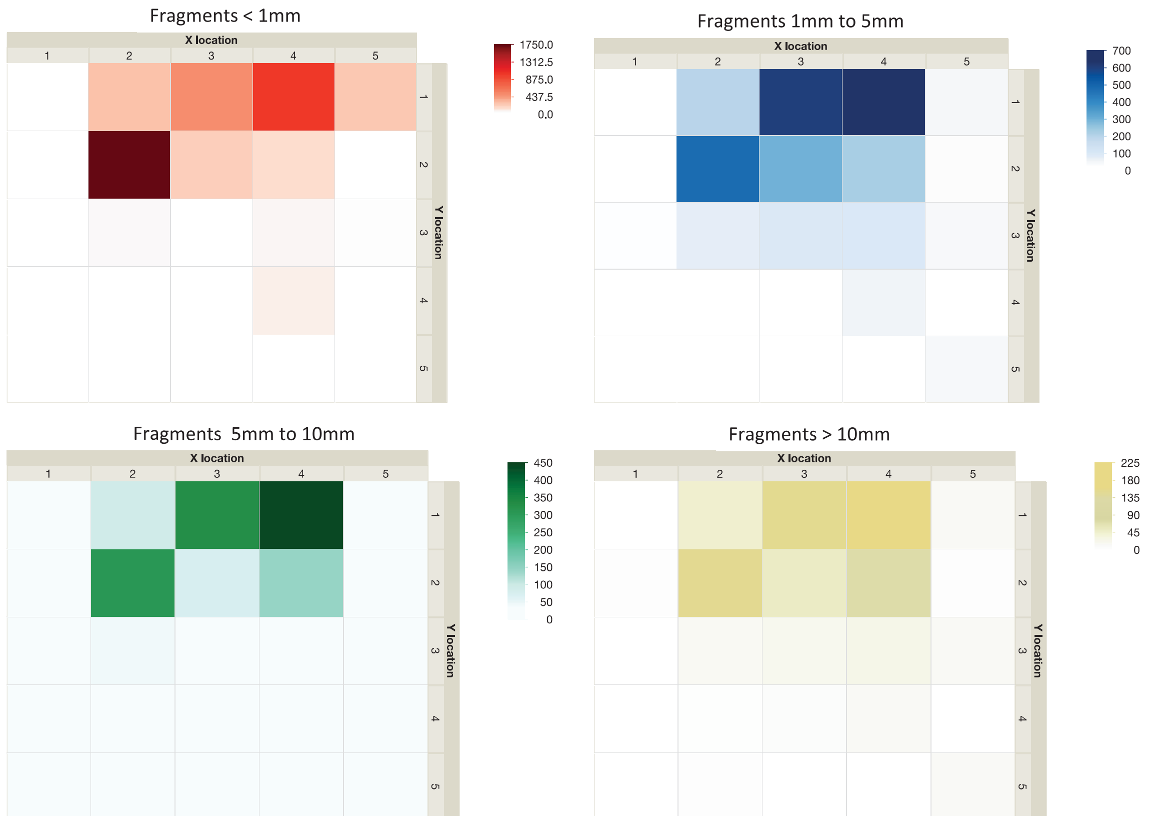

Figure 4: Heat maps of the distribution of glass fragments by zone according to fragment size. Each x,y location represents the respective zone identified in Figure 1 (e.g., location x1,y1 represents zone 5 while x5,y5 represents zone 21)

Forward Fragmentation and Transfer of Glass (Car 1)

The impact of the window breaking sent the glass fragments throughout the vehicle, depositing fragments of various sizes (Figure 5). The most significant amount of fragments was discovered in the front half of the car. The locations with the overall greatest amounts of glass were the driver's seat, the broken window frame, and the front passenger's seat, in that order. The passenger's seat did, in fact, surpass the driver's seat in the quantities of <1mm and 1mm to 5mm fragments. However, it is important to note that a large amount of these size fragments were transferred to the victim in the driver's seat (and not included in the Figure 5 glass count).

Pieces larger than 5mm were discovered in the back driver's side area at low quantities. The back passenger side accumulated the fewest fragments, but still had fragments in the sizes of <1mm, 1mm-5mm, and 5mm-10mm. Consequently, it would appear that anyone inside the car in addition to the driver would have had at least some glass transferred onto their garments. Given the direction of the breaking force in this scenario, the majority of the glass shards were projected toward the front side of the vehicle. However, it is worth nothing that a change in angle and direction of force would have a direct impact in the relative number of glass fragments ejected to the back areas.

These results stress the relevance of considering factors that could influence glass transfer in a particular case. Even though an accurate reconstruction of events is not easy to attain, the evaluation of glass fragment distributions could provide valuable contextual insights about potential interpretation of the evidence.

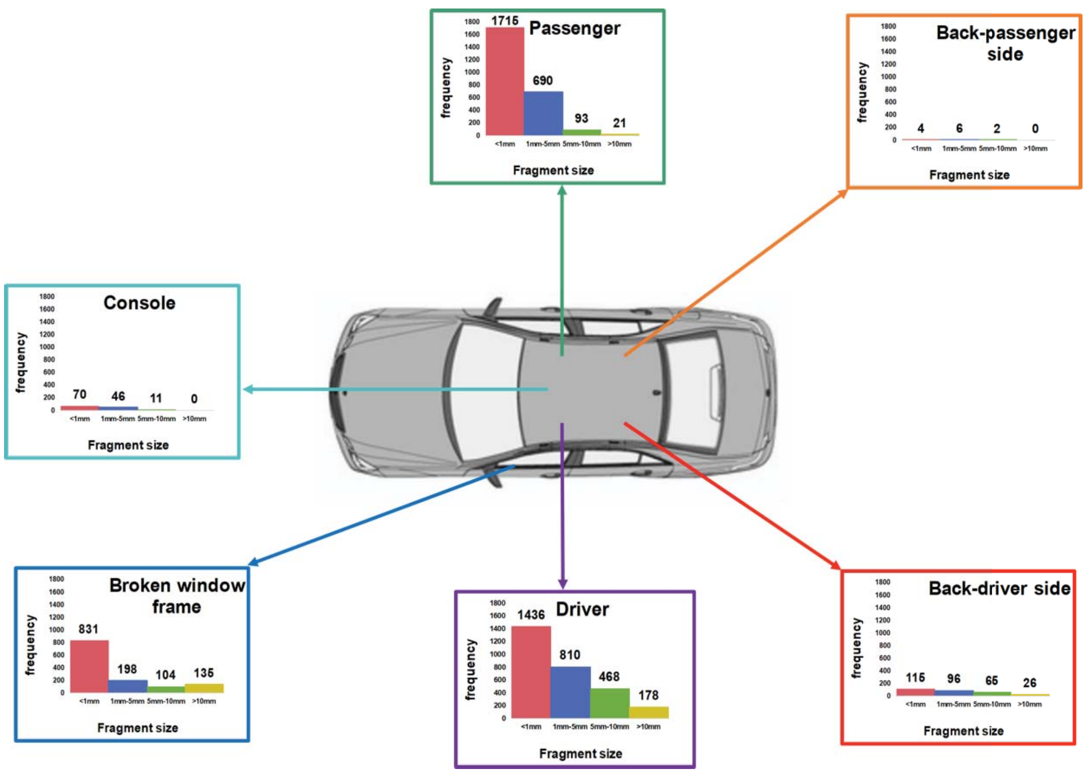

Figure 5: Histograms of forward fragmentation of glass in Car 1 by location in vehicle.

Background, Primary, and Secondary Transfer of Glass on Clothing and Footwear

No glass was recovered from any of the articles of participant's clothing (V1, S1, S2, and S3) during the background collection. All of the shoes were bare, save for embedded glass recovered from the shoe soles of two of the participants (10 shards and 1 shard, respectively, Table 1 and 2). The individual that had the most glass on her shoes is often exposed to broken glass at West Virginia University's Forensic and Investigative Science crime scene complex, which probably accounts for the larger number of fragments collected from her shoes. This does support the conclusions of other published studies noting the importance of considering the subject's normal background environment and the decreased significance afforded to glass embedded into the soles of footwear.

The post-breaking activity collections for transfer revealed the majority of the glass fragments were recovered from the victim, with the greatest amount on his shirt (1414 fragments), followed by the suspect who broke the window, with the majority of glass on her shoes (140 fragments). The bulk of the fragments recovered from the victim's shirt were smaller than 1mm. It is expected that the majority of the glass recovered from the S1 and S2 suspect's clothing was a result of primary transfer. Nonetheless, it is worth noting that secondary transfer from the victim-suspect interaction is possible, in particular for suspect 3 who had direct contact with the victim.

Given the short time elapsed between the breaking and the arrest along with the limited activities executed by the suspects, it was unexpected to find very low persistence of glass on their clothing. The study shows that the low amount of glass found on the S1 and S2 suspect's clothing was a result of their position relative to the backward fragmentation trajectory and the post-breaking activity. For instance, the suspect breaking the glass was just 0.5 meter away from the window but her body was positioned at the left edge of zone four and, therefore, outside of the main trajectory of the backward fragmentation. The video recorded showed that most of the glass found on her shoes and pants may have originated from glass that fell when she opened the broken door. However, most of that glass was further lost during the post-breaking activity, with the vast majority of the remaining fragments being smaller than 1mm. On the other hand, the second suspect that was holding the gun (S2) was located about 1.5 meters away from the breaking window (zone 12) but still within the main trajectory of the backward fragmentation, which explains the glass recovered from the shirt and shoes. The third suspect was not near the breaking activity, resulting in a relatively low number of glass fragments transferred to his clothing. However, he did participate in binding and transferring the victim into the car's trunk, which could be a secondary transfer source for the glass recovered from his gloves, and tertiary transfer to the drivers seat.

The highest amount of glass found on the Tyvek suits was for CSI team members who worked on Car 1 (90 to 139 fragments, Table 2). The fragments on the Tyveks reveal how much glass was subjected to potential secondary transfer and possible cross-contamination had the CSIs been responsible for recovery in both scenes. These observations are in agreement with a previous study that showed that indirect transfer of glass from personnel attending a scene can persist up to at least 60 minutes after the original contact with the broken glass [20].

Table 1: Pre-Breaking and Post-Breaking glass recovered from clothing and footwear from Victim and Suspects-Team 2

Individual		Suspect 1	Suspect 2	Suspect 3	Victim
Pre-Breaking	Shoes	10	0	0	0
	Shirt	0	0	0	0
	Pants	0	0	0	0
	Scarf	0	0	N/A	0
	Shoes	140	12	0	4

Post-Breaking	Shirt	4	29	1	1414
	Pants	4	1	1	16
	Scarf	4	5	N/A	0
	Gloves	2	0	3	0
	Paper	27	18	0	1
	Tyveks	N/A	N/A	N/A	N/A
Main Activity		Glass Breaking	Near Breaking	Driver	Victim

Table 2: Pre-Breaking and Post-Breaking glass recovered from clothing and footwear from Evidence Recovery Team 3

Individual		CSI – Car 1	CSI – Car 1	CSI – Car 2	CSI – Car 2
Pre-Breaking	Shoes	0	0	1	0
	Shirt	0	0	0	0
	Pants	0	0	0	0
	Scarf	0	0	0	0
Post-Breaking	Shoes	N/A	N/A	N/A	N/A
	Shirt	N/A	N/A	N/A	N/A
	Pants	N/A	N/A	N/A	N/A
	Scarf	N/A	N/A	N/A	N/A
	Gloves	N/A	N/A	N/A	N/A
	Paper	N/A	N/A	N/A	N/A
	Tyveks	139	90	2	0
Main Activity		Glass recovery from Car 1-victim's broken window and surroundings	Glass recovery from Car 1-victim's broken window and surroundings	Glass recovery from Car 2 – suspect's vehicle	Glass recovery from Car 2 – suspect's vehicle

Secondary Transfer to Car 2

Within Car 2, the largest sized and greatest amount of fragments were transferred to the passenger side by the suspect who broke the victim's window (S1). The passenger's floor and seat contained fragment sizes of both <1mm and 5mm to 1mm (Figure 6). The only fragments found on the driver's side were <1mm and transferred by the suspect that was furthest away from the breaking site (S3). However, as mentioned earlier, this suspect did interact with the victim while placing him in the trunk. The suspect near the breaking site (S2) transferred 46 fragments of <1mm size to the back seat. The results show that a larger amount of glass was found in the suspect's vehicle than on the suspect's clothing, suggesting that a large portion of the transferred glass was lost either during the short walking activity or the seating activities via either secondary or tertiary transfer to the car's seats and floor mats. Secondary transfer is expected from glass initially transferred to suspects near the breaking site to the respective car seat and mat. Tertiary transfer is probable from suspect 3, who was not close to the breaking scene but had substantial direct contact with the victim.

The trunk of the car possessed fragment sizes of <1mm and 1mm-5mm, while both the tape roll and the breaking tool had a few <1mm fragments. The tape from the victim's face (head scarf) and hands had fragment sizes of <1mm, 1mm-5mm, and 5mm-10mm, while the ankle tape had all four-fragment sizes retrieved (Figure 6). As expected, the adhesive of the tape retained a large amount of glass fragments, even some larger pieces that are not commonly kept on the surface of regular fabrics after some post-breaking activity. This site in the suspect's vehicle was exposed to the largest amount of secondary transfer from the victim, which was expected given the amount of glass on the victim and the movement inside the vehicle's trunk.

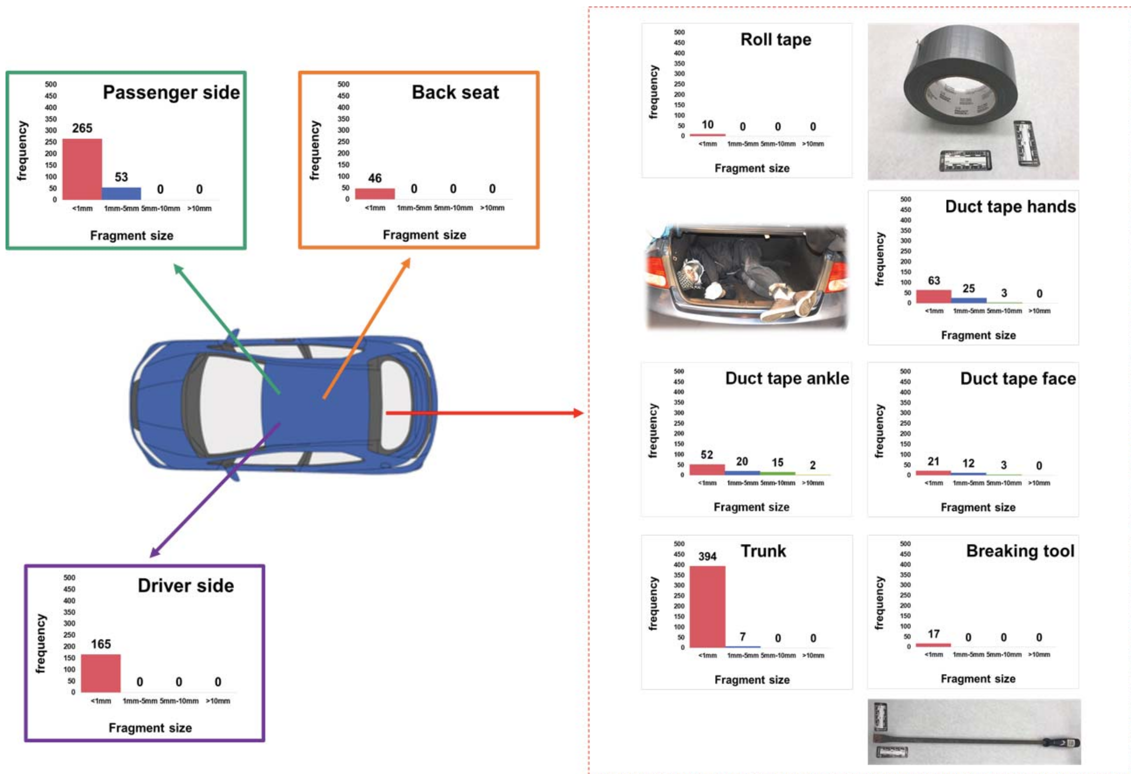

Figure 6: Histograms of Secondary Transfer to Car 2 by location.

CONCLUSIONS

This case study provides valuable information that can be used for interpreting the significance of glass fragments recovered in cases involving the breaking of tempered vehicle side windows. It demonstrates how the fragments could transfer to victims, suspects, the primary scene location, and secondary locations.

With regards to backward fragmentation, the majority of glass fragments transferred to the vicinity of the broken glass and to the suspects near the breaking activity were smaller than 1mm. These fragments were ejected in the opposite direction of the force that struck the driver's window in an approximate forty-five degree arc towards the rear of the vehicle. They were scattered primarily within a 1-2 meter radius from the breaking point. The maximum distance glass fragments were found away from the car was approximately 3.6 meters.

A significant second transfer pattern was created by the force of slamming the driver's door open which caused the remaining glass attached to the window frame to detach and shatter onto the door and the ground. The observation of a second breaking event points out the significance of documenting and/or elucidating the sequence of events in a case, as similar situations may influence the transfer of glass in cases where a CSI or first responder causes or is exposed to glass transfer during the opening of a door with a broken glass window.

Moreover, during the collection of the glass fragments, those in the Tyvek suits acquired relatively large amounts of glass shards from the scene, regardless of the low-persistence properties of their protective coveralls. These results highlight the importance of scene contamination polices and investigators taking the necessary steps to prevent cross-contamination prior to transitioning from different parts of a scene or different scenes entirely.

The data acquired from glass produced by forward fragmentation inside the victim's vehicle indicates the majority of the fragments were distributed to the front seats of the vehicle, with similar amounts on the driver and front passenger seats. Therefore, careful considerations must be taken when evaluating relative positions of the driver/passenger given the fact that the space inside a vehicle is relatively confined. This provides opportunities for a large transfer of glass across the vehicle areas. There was considerably less glass in the back row of the vehicle; however, fragments of all four-size ranges were present. Thus, there is a potential for any occupant within the vehicle to have glass transferred to their garments. Observations of relative amounts of glass during a case investigation could provide valuable context information during the interpretation of collected and analyzed glass evidence, keeping in mind the previous cautions.

The proximity an object or subject has to the breaking point and its relative location to the trajectory of the broken fragments are related to the size and amount of transferred fragments. Therefore, being further away from the breaking point decreases the expected size and amount of fragments that will be transferred to the subject(s). The transfer of forward fragmentation glass fragments, those traveling in the direction of the breaking force, was understandably most substantial to the victim. The amount and size of backscattered fragments that persisted on the suspects was fairly small, since the great majority of the glass that was apparently showered upon the suspects S1 and S2 was lost via activity and secondary transfer, leaving mostly fragments about 100um in size retained on their clothing.

Once initial breaking of the glass was complete, the following activities induced secondary glass transfers. When the victim was bound, gagged, and thrown into the trunk of the suspect's car, a significant amount of mainly <1mm glass was transferred from the victim to the trunk and to the duct tape. The glass recovered from the interior of the suspect's car suggests pronounced secondary transfer from the suspects to the car upon reentry. Suspect 3, who was far away from the breaking point, was responsible for binding and gagging the victim as well as driving the suspect vehicle, so it is hypothesized that he gathered most of the fragments during his interaction with the victim and then lost most of them to the vehicle, specifically to the driver's seat and floor mat area. This hypothesis is formulated because being so far away from the breaking point, it is unlikely that any of the glass was transferred to the driver suspect via primary transfer. This would suggest that the glass that ended up in the driver's seat of Car 2 was transferred to Suspect 3 by secondary transfer through his interaction with the victim.

The background collection of glass on the clothing and footwear of the victim, suspects, and CSIs prior to the breaking event revealed there to be no glass fragments recoverable from any of their clothing. Out of the seven individuals, only two had glass fragments embedded in the soles of their shoes.

The results of this study demonstrate the relevance of interpreting glass evidence within particular case content, and although in many cases it may be difficult to reveal details about the events, the evaluation of glass distribution near the breaking activity can provide useful information during the investigation and subsequent interpretation in court. In general, this study confirms that a) persistence of glass in individuals not involved with broken glass is low, b) primary, secondary, and tertiary transfer of glass could help to link a suspect and/or victim to an event, c) secondary transfer during collection of glass must be carefully considered to avoid any cross-contamination of the evidence, d) the transfer and persistence of glass in small confined areas such as vehicles should be carefully evaluated given the breaking events and post-breaking activities, and e) while the transfer of glass is abundant during a breaking, the fragments are lost very easily during common post-breaking activities. Consequently, finding large quantities of glass on an object or individual is an indication of recent transfer of glass from a broken source.

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REFERENCES

1. ASTM E2927-17. Standard Test Method for Determination of Trace Elements in Soda-Lime Glass Samples Using Laser Ablation Inductively Coupled Plasma Mass Spectrometry for Forensic Comparisons. West Conshohocken, PA: ASTM International. 2017.

2. ASTM E2926 -13, Standard Test Method for Forensic Comparison of Glass Using Micro X-ray Fluorescence (μ-XRF) Spectrometry, ASTM International, West Conshohocken, PA, 2013.
3. Koons RD, Buscaglia J, Bottrell M, Miller ET. Forensic glass comparisons. In Forensic Science Handbook, 2nd ed. Upper Saddle River, New Jersey: Prentice-Hall; 2002. Volume 1, p. 161-213.
4. Curran JM, Hicks Champod TN, Buckleton JS, Evett I, Lambert J, Almirall J. Forensic interpretation of glass. Boca Raton: CRC Press; 2000. Chapter 5, Transfer and persistence studies; p. 107-136.
5. Nelson DF, Revell BC. 1967. Backward fragmentation from breaking glass. J. Forensic Sci. Soc. 7(2):58-61.
6. Luce RJW, Buckle JL, McInnis I. 1991. A study on the backward fragmentation of window glass and the transfer of glass fragments to individual's clothing. Can. Soc. Forensic Sci. J., 24(2):79-89.
7. Locke J, Unikowski JA. 1991. Breaking of flat glass - part 1: size and distribution of particles from plain glass windows. Forensic Sci. Int. 51:251-262.
8. Locke J, Unikowski JA. 1992. Breaking of flat glass - part 2: effect of pane parameters on particle distribution. Forensic Sci. Int. 56:95-106.
9. Locke J, Scranage JK. 1992. Breaking of flat glass - part 3: surface particles from windows. Forensic Sci. Int. 57:73-80.
10. Allen TJ, Locke J, Scranage JK. 1998. Breaking of flat glass - part 4 size and distribution of fragments from vehicle windscreens. Forensic Sci. Int. 93:209 - 218.
11. Allen TJ, Scranage JK. 1998. The transfer of glass - part 1 transfer of glass to individuals at different distances. Forensic Sci. Int. 93:167 - 174.
12. Allen TJ, Hoefler K, Rose S. 1998. The transfer of glass - part 2 a study of the transfer of glass to a person by various methods. Forensic Sci. Int. 93:175-193.
13. Allen TJ, Hoefler K, Rose S. 1998. The transfer of glass - part 3 The transfer of glass from a contaminated person to another uncontaminated person during a ride in a car. Forensic Sci. Int. 93:195 - 200.
14. Hicks T, Vanina R, Margot P. 1996.Transfer and persistence of glass fragments on garments. Sci. Justice., 36: 101-107.
15. Underhill, M. 1997. The acquisition of breaking and broken glass. Sci. Justice. 37: 121-127.
16. Allen TJ, Cox AR, Barton S, Messam P, Lambert JA. 1998. The transfer of glass - part 4 The transfer of glass fragments from the surface of an item to the person carrying it. Forensic Sci. Int. 93: 201 - 208.
17. Hicks T, Schutz F, Curran JM, Triggs CM. 2005. A model for estimating the number of glass fragments transferred when breaking a pane: experiments with firearms and hammer. Sci. Justice. 45(2):65-74.
18. Irwin M. 2011. Transfer of glass fragments when bottles and drinking glasses are broken. Sci. Justice. 51:16-18.

19. Curran JM, Hicks Champod TN, Buckleton JS, Evett I, Lambert J, Almirall J. Forensic interpretation of glass. Boca Raton: CRC Press; 2000. Chapter 1, Examination of glass; p. 6–31.
20. Cooper G. 2013. The indirect transfer of glass fragments to a jacket and their subsequent persistence. Sci. Justice. 53:166–170.