The Accuracy of Photogrammetry vs. Hands-on Measurement Techniques used in Accident Reconstruction

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ABSTRACT

A study was conducted to assess the relative accuracy of two measurement techniques commonly used for vehicle measurements in damaged-based accident reconstruction. The traditional technique of hands-on measurement was compared with the use of photogrammetry for measurement of targeted damaged vehicles. Three undamaged vehicles were subjected to 4 impacts, resulting in 4 damaged areas (two front, one side and one rear). The study's intent was only to examine the accuracy of each measurement technique. The influence of other confounding independent variables such as selection of measurement location on the vehicle, reference line location, and definitions of what constitutes “damage”, etc. were controlled for and minimized by using predefined measurement points on the vehicles and prescribed station lines.

The points on each vehicle were measured using both techniques, and compared to baseline reference measurements obtained via a TOPCON GPT-7005i prismless imaging total station. PhotoModeler was employed as the photogrammetry technique, and photographs of the post-impact vehicles were obtained using several different cameras and photographers, including an adjuster with no formal training or instruction in photographing for photogrammetric analysis. Hands-on measurements were obtained via two groups of qualified professionals in the field of accident reconstruction, with access to both the vehicles and traditional measuring equipment such as tape measures, crush jig and plumb bobs.

The results found that both methods effectively measured the vehicle points, with a mean difference between the baseline and hands-on measurements of 0.6 ± 1.4 cm, and a mean difference between the baseline and photogrammetry measurements of 0.1 ± 1.0 cm. The accuracy of the photogrammetry method was found to be slightly greater than that for hands-on physical measurements. The results indicated that both physical inspection of a damaged vehicle and photogrammetric analysis from photographs are suitably accurate techniques for vehicle damage measurement, and in some cases the photogrammetric analysis may even yield superior results.

INTRODUCTION

Vehicle damage based accident reconstruction is an established methodology that has been employed for several decades. Largely based on the principles of conservation of energy, the approach was described in the early works of Emori [1] and Campbell [2]. These authors noted the relationship between residual vehicle crush and vehicle speed related parameters, such as impact speed, Delta V and equivalent barrier speed (EBS). These principles have since enjoyed general acceptance in accident reconstruction and vehicle impact analysis, including accident reconstruction training texts [3] and the Federal Government [4].

While the theory behind damage based reconstruction has been established for many years, the manner in which the vehicle damage is quantified has evolved somewhat over time. The Society of Automotive Engineers recommended the use of orthogonal plane measurements for coding vehicle damage [5,6]. Other initial protocols for measuring crushed vehicles included plumb bobs, tape measures, crush deformation jigs, or grids [7]. Tumbas and Smith outlined crush measurement procedures which incorporated a series of stations using graduated rods at prescribed heights [8], with similar guidelines later being followed by the NHTSA. Boddorf and Jones described a technique in which an overhead photograph of the damaged vehicle was used to estimate the damage profile [9].

Newer technologies such as optical measurement systems have introduced increased accuracy in vehicle crush measurement [10,11,12]. Other newer techniques include transducer-equipped articulated arms (FARO arms) and Moire topography.

These methods are all essentially “hands-on,” in that they require the vehicle to be physically inspected and measured in its damaged condition. In many cases, however, the reconstructionist does not have access to the vehicle in its damaged condition, as the vehicle may have been repaired or sold prior to being made available. In these cases the investigator must rely on post-impact photographs of the vehicle in order to assess damage.

For those cases in which only photographs are available, techniques involving the use of these photographs have been published. Photogrammetry involves the use of multiple two-dimensional photographs to create a three-dimensional representation of an object. Initial applications of photogrammetry in accident reconstruction often involved scene documentation, including establishment of skids and other physical scene evidence through the use of photographs [13,14,15,16,17,18,19]. More recently, photographic analysis techniques have also been used to quantify the vehicle dimensions and crush damage. Woolley et al. [10] and Breen [19] discussed a reverse camera projection technique in which a negative of the photograph of the damaged vehicle was superimposed through a camera's viewfinder on an undamaged exemplar vehicle.

More sophisticated analytical photogrammetry has been applied to accident reconstruction involving vehicle measurements. Some of the earliest work in this regard was conducted by Bryner [13], who found an inch of difference between the measured and the photogrammetry results in measuring vehicle dimensions and crush damage. Lie et al. [20] used photogrammetry to document vehicle crush, and reported the accuracy of the method to be within 1.5 cm for most measurements, with photogrammetry also reported as being significantly more accurate than what could be achieved using a measuring tape. Pepe et al. [15] noted photogrammetric accuracy for vehicle measurement to be within 2 inches. Kullgren et al. [21] reported accuracies of better than 10 mm for photogrammetric analysis of vehicle deformation.

Fenton et al. [22] found measurement errors of 1-2% when comparing vehicle dimensional measurements obtained through photogrammetry to published vehicle specification measurements. O'Shields et al. [23] used photogrammetry to estimate vehicle crush from NHTSA crash tests, ultimately estimating the Equivalent Barrier Speed (EBS) for comparison to the actual tests. They found an error of less than 7% in the predicted versus actual EBS for a series of NCAP tests.

Rucoba et al. [24] estimated vehicle crush via a 3 dimensional wireframe model of a vehicle, deformed so as to mimic the crush as seen in photographs. The resulting crush profile was compared to that determined by tapes/gridlines or total station. Average differences between photogrammetry and total station crush measurements were 1.1-1.2 cm.

While the literature clearly supports the use of photogrammetric techniques for vehicle deformation evaluation in accident reconstruction, of interest is a direct quantitative comparison between photogrammetry and traditional “hands-on” methods currently accepted in both the forensic and research arenas. Toward this end, the current study compared the accuracy of a photogrammetry technique relative to a standard, accepted “hands-on” physical inspection technique, for a series of damaged vehicles under prescribed conditions.

METHOD

Three automobiles were used in the study. The first vehicle was a purple 1995 Ford Thunderbird, the second was a silver 1987 Nissan Maxima, and the third was a gold 2001 Hyundai Accent. None of the vehicles exhibited pre-existing deformation to any of their body panels, with the exception of some minor cosmetic blemishes. Prior to testing, 19 mm circular adhesive labels containing printed on central black 4 mm diameter circles were affixed to the entire vehicle, to be used as measurement targets. The targets were placed at 6 inch (15.2 cm) intervals along the length of the vehicle structure in the area that was to be impacted. The targets were placed at multiple vertical heights that correlated with the anticipated damage pattern. In areas away from the projected damage, the targets were simply placed in a manner that aided in the creation of a 3-D model of the vehicle.

Pre-impact photos of each vehicle were taken by several different investigators at various points around the vehicle and at varying heights, to be later used in the photogrammetric analysis. The cameras used were a Nikon D700 with a Nikon Nikkor 20.0 mm fixed lens, a Nikon D100 with a 28 mm-200 mm Nikkor lens set to 28 mm (Accent front and rear only) and a Canon EOS Digital Rebel XTi with a Canon EF-S 18-55 mm lens set to18 mm.

The vehicles were each subjected to at least one impact. The first impact was between the front of the Thunderbird and the driver's side of the stationary Maxima at approximately 32 km/h in an essentially perpendicular impact. The second series of impacts included a front and rear impact of the Accent into a concrete Jersey-type barrier. The Accent underwent a rearward perpendicular impact into the barrier at 13.4 km/h. The Accent also underwent a 14.9 km/h angled frontal impact (30 degrees) into the barrier with the right front corner. Four areas of damage were thus created for analysis - the front of the Thunderbird, the driver's side of the Maxima, the rear of the Accent, and the front of the Accent.

Hands-On Measurement

Hands-on measurements were obtained by volunteer professionals who worked in the field of accident reconstruction. All the participants were either law enforcement professionals or engineers in the industry (many of whom with advanced degrees), and most were ACTAR (Accreditation Commission for Traffic Accident Reconstruction) accredited. Levels of experience in the field of accident reconstruction ranged from 5 years to over 30 years.

The study's intent was to examine the accuracy of each measurement technique. The influence of other confounding, non studied, independent variables such as selection of measurement location (height and spacing), reference line location, variation in definitions of what constitutes “damage” (induced, direct contact, airgap, etc), were controlled for and minimized by using predefined measurement location points on the vehicles, and predefined station lines. This method assured that everyone was measuring the same exact points on the vehicles from the same starting point or reference line, thus allowing a direct point-by-point comparison. Therefore, the accuracy of the measurement techniques could be specifically assessed without being significantly confounded by the influence of other independent variables which were not being studied.

Predefined measurement points were identified on each of the vehicles for inclusion in the study. Twenty-five points were measured on the driver side of the Maxima, from the leading edge of the front door to the trailing edge of the rear door, along two lines which correlated with the rocker panel and the lower-to-mid-door level. In a similar fashion, the Thunderbird measurement points included 22 points along the front edge of the hood and the lower portion of the front bumper. Accent front measurements included 13 points at three levels of the right front portion of the vehicle, and rear measurements consisted of 11 points along the top portion of the rear bumper cover.

Each participant was asked to measure linear distances from a prescribed station line to these points for each vehicle. The station line was established in accordance with standard accident reconstruction practice. Provided inspection equipment included multiple tape measures, a crush deformation jig, string and plumb bobs. Participants were provided a form on which to document their measurements, and were simply encouraged to make and report the measurements in a manner consistent with their normal forensic practice. Appendix A contains an example of the documentation form.

A group of 14 participants measured to the points on the Maxima, with 13 of those participants also measuring to the points on the Thunderbird. A second group of 14 participants measured to the points on the front and rear of the Accent.

Photogrammetry Measurement

Two sets of post-impact photographs of each vehicle were taken by two different investigators from a wide variety of different camera locations and angles, with the same cameras as used for the pre-impact photographs. Additionally, an independent automobile damage appraiser took post-collision photographs of all three vehicles, instructed only to take the photographs in accordance with his typical appraisal protocol. The camera properties were not known for the adjuster photographs.

PhotoModeler was selected as the software tool for photogrammetric analysis, having been found an appropriate and accurate software for reconstruction purposes [22,23,27,28]. Three separate individuals, including an independent PhotoModeler instructor, used the post-impact photographs in order to complete a 3-D model of the vehicle and the measurement points, using the inverse camera feature in PhotoModeler in conjunction with control points. Upon completion of each PhotoModeler project, a 3-D DXF of the model was exported. The 3-D DXF model was overlaid onto a baseline model, obtained using total station points from the undamaged areas of the vehicle, and matched in a CAD program. Measurements were taken from the predefined damage points along an axis perpendicular to the station line in the CAD program. The result was a 2-D representation of the vehicle measurement in the vehicle X-Y plane [25,26] at the prescribed heights. This method of vehicle measurements conform with those set forth by the Society of Engineers [5] and those used in vehicle damage analysis [4,8]. Figures 1,2,3,4 show an example from one of the PhotoModeler projects for the Maxima, Thunderbird, front of the Accent and rear of the Accent, respectively. Figures 3 and 4 show the prescribed station line that was used in the analysis

Figure 1. Maxima driver's side damage and measurement points

Figure 2. Thunderbird front damage and measurement points

Figure 3. Accent front damage, measurement points and station line

Figure 4. Accent rear damage, measurement points and station line

Baseline Total Station Measurements

The post impact body profiles of the test vehicles were established with a TOPCON GPT-7005i imaging total station that was used in non-prism mode. These profiles served as the baseline for comparison with the hands-on measurements and the photogrammetry analysis. This particular total station was chosen as the baseline for several reasons. It was capable of taking direct measurements to the center of the dot locations on the adhesive labels without the use of a prism that could potentially introduce additional human error. The total station also captures a zoomed digital image of each point taken, which can then be later viewed on a point by point basis to assess the location of the specific captured point and determine if the correct point was captured. Therefore, any questions about the exact location of a point could be answered by simply opening up the project drawing. This particular total station was a newer model and was recently serviced and calibrated.

Measurements were taken from the predefined damage points along an axis perpendicular to the station line in the CAD program. The result is a 2-D representation of the vehicle measurement in the vehicle X-Y plane [25,26] at the prescribed heights. This method of vehicle measurement conforms with those set forth by the Society of Engineers [5] and those used in vehicle damage analysis [4,8].

Using the total station measurement profiles as baselines, the hands-on measurements were compared with those obtained from PhotoModeler analysis, in order to determine the relative efficacy of both methods.

RESULTS

The hands-on measurements for all participants were grouped for each of the 4 damaged vehicle measurement areas. Mean and standard deviations were calculated for each measurement point, and compared to those obtained from the total station (baseline). Similarly, photogrammetry measurement point means and standard deviations were also calculated for each of the 4 damaged vehicle areas.

Figures 5 and 6 show the results for measurement points on the rear of the Hyundai Accent from hands-on measurement and photogrammetric analysis, respectively. The error bars denote the standard deviation of the measurements. The values on the Y-axis represent the measurement distance from the prescribed station line and the values on the X-axis represent the distance between the measurements along the station line. Figure 7 shows the mean values for the measurement points obtained from both methods, as compared to the baseline total station measurements. Any gaps in the data in the following figures represent points that were not measured by a given method because they were not visible.

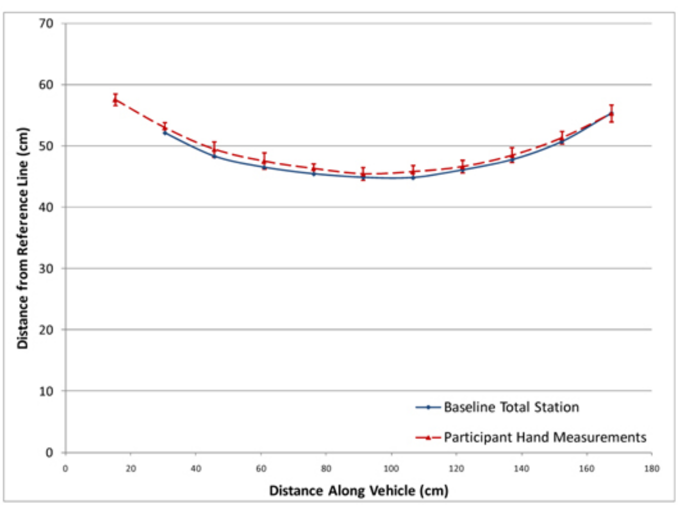

Figure 5. Accent rear bumper cover participant measurement mean and standard deviation comparison to baseline total station

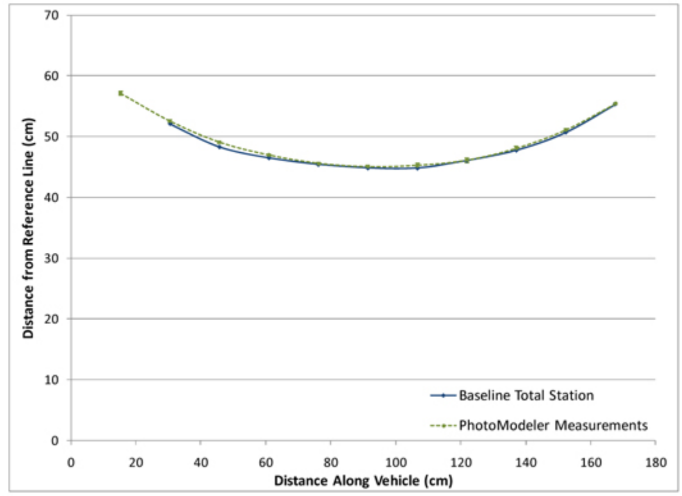

Figure 6. Accent rear bumper cover PhotoModeler mean and standard deviation measurement comparison to baseline total station

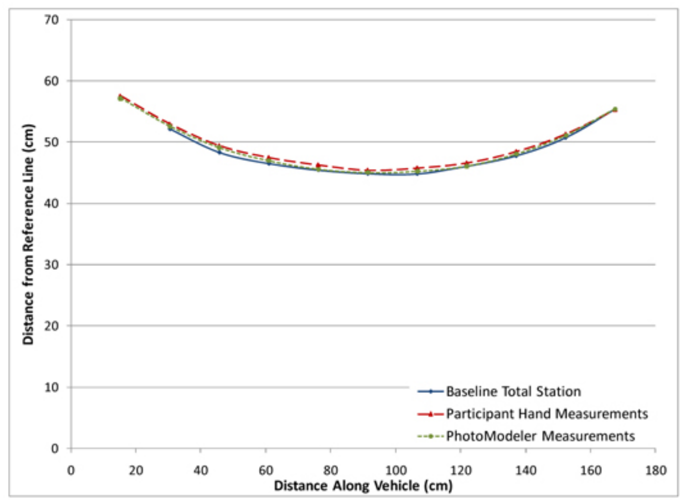

Figure 7. Accent rear bumper cover measurement method comparison

Figures 8,9,10 show similar results for the side of the Maxima.

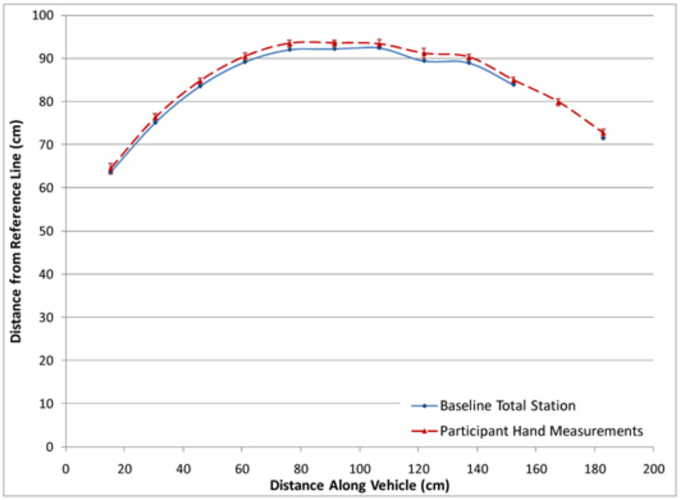

Figure 8. Maxima side door participant measurement mean and standard deviation comparison to baseline total station

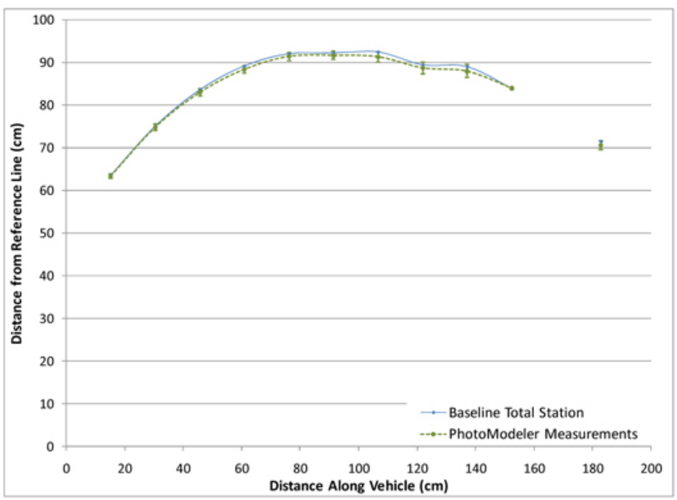

Figure 9. Maxima side door PhotoModeler measurement mean and standard deviation comparison to baseline total station

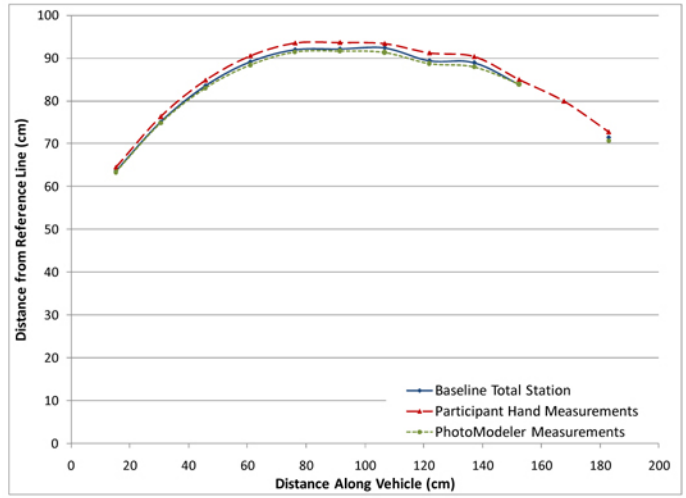

Figure 10. Maxima side door measurement method comparison

Figures 11 and 12 contain comparisons for the lower edge of the front bumper of the Thunderbird and the upper edge of the right side front bumper cover of the Accent, respectively.

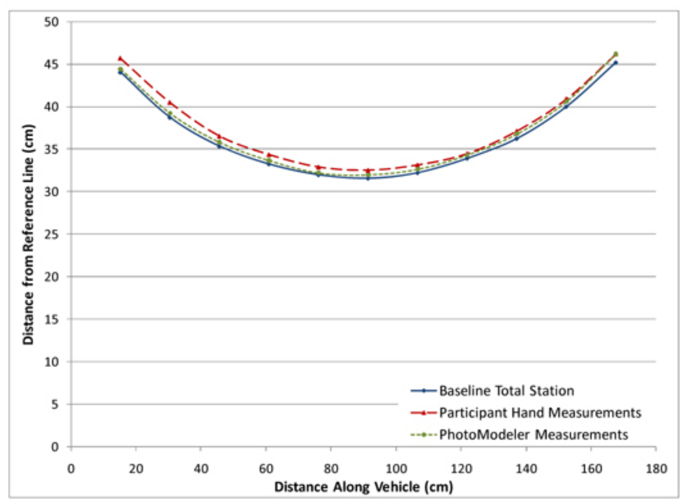

Figure 11. Thunderbird front bumper cover measurement method comparison

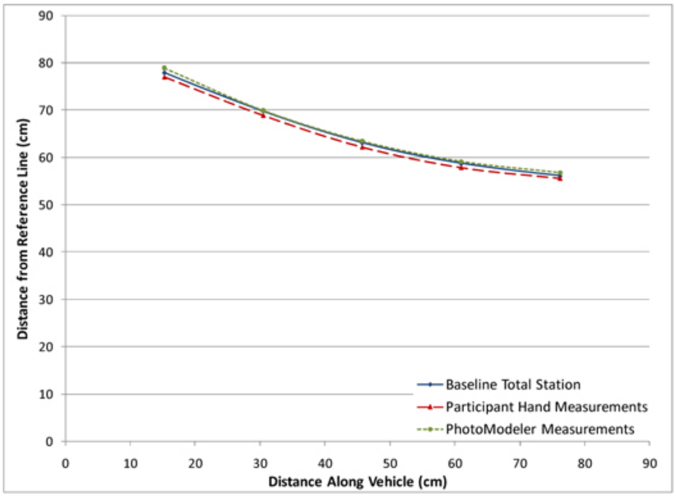

Figure 12. Accent front bumper cover measurement method comparison

A statistical analysis was performed comparing the participant hands-on measurements and the PhotoModeler measurements (PM), as referenced to the baseline total station measurements. Measurements were grouped according to vehicle region (front, side and rear), and for all regions combined (Table 1).

Table 1. Measurement Differences as Compared to Total Station Baselines

	Frontal		Side		Rear		All Regions	
	Participant	PM	Participant	PM	Participant	PM	All Participant	All PM
Mean (cm)	0.3	0.4	0.8	-1.0	0.7	0.4	0.6	0.1
Standard Deviation (cm)	1.5	0.4	1.3	1.3	1.1	0.2	1.4	1.0
Minimum (cm)	-6.2	-0.4	-7.1	-5.1	-2.7	-0.1	-7.1	-5.1
Maximum (cm)	7.0	2.0	4.6	1.8	3.2	0.9	7.0	2.0
Count	436	114	322	70	120	30	878	214

Table 2 shows these differences expressed as a percentage of the actual measurement length from station line to measurement point.

Table 2. Percent Measurement Differences as compared to Total Station Baselines

	Frontal		Side		Rear		All Regions	
	Participant	PM	Participant	PM	Participant	PM	All Participant	PM
Mean (%)	1.0	0.8	1.1	-1.2	1.6	0.8	1.1	0.2
Standard Deviation (%)	2.8	0.7	1.8	1.6	2.3	0.5	2.4	1.4
Minimum (%)	-9.4	-0.8	-10.4	-5.7	-5.7	-0.2	-10.4	-5.7
Maximum (%)	18.1	3.0	7.0	2.6	6.5	2.0	18.1	3.0
Count	436	114	322	70	120	30	878	214

DISCUSSION

Qualitative examination of both participant hand measurements and PhotoModeler measurement data showed a strong agreement with the baseline total station measurements, as depicted in Figures 5,6,7,8,9,10,11,12. Based on these measurement sets, it appears that both methods are appropriate for accident reconstruction and damage analysis.

The rear of the Accent (Figures 5,6,7) showed the best overall agreement in measurement profiles for both the participants and PhotoModeler measurements, with the standard deviations for both essentially encompassing the baseline measurements. The largest difference between the mean participant measurement and the baseline total station measurement was 3.2 cm, while the largest difference between the mean PhotoModeler measurement and the corresponding baseline total station measurement was 0.9 cm, indicating a greater accuracy for the PhotoModeler method. The standard deviation for the PhotoModeler measurements was also considerably lower than that for the participants (0.2 to 1.1 cm)

The driver side of the Maxima (Figures 8,9,10) showed the worst overall agreement in the measurement profiles and relative error for both the participants and PhotoModeler measurements. Both measurement methods again showed relatively good agreement with the baseline total station, even for this worst case, with the PhotoModeler analysis again appearing slightly more accurate than the participant measurement technique.

When looking at the measurement data as a whole, the general trend was that the measurement error expressed as a percentage of the expected measurement and the values for the mean, standard deviation and maximum deviations were all greater in the participant hand measurements (0.6 ± 1.4 cm) compared to the PhotoModeler (0.1 ± 1.0 cm). The PhotoModeler method was thus found to be statistically more accurate than hands-on measurements taken by qualified accident reconstructionists, for this study involving targeted damaged vehicles.

With respect to the percentage error of the measurements, the participant hand measurements exhibited a mean error of 1.1 ± 2.4%, indicating that 95 percent of the hand measurements were within approximately ±5% of the actual measurement of the vehicle. Photogrammetric measurements were again found superior to hand measurements in this regard, with a mean error of 0.2 ±1.4%, indicating that 95 percent of all photogrammetric measurements would be within approximately ±3% of the actual measurement of the vehicle.

The current study assessed the measurements of the known points with the assumption that the participant hand measurements were taken perfectly perpendicular to the fixed point on the vehicle from the reference plane. If a participant's individual measurement was not taken perpendicular to the plane, it would introduce a slightly larger than expected measurement. Since the PhotoModeler and total station measurements were taken in a CAD program, such errors did not exist for those measurements.

The PhotoModeler measurement errors in the current study were found to be similar to, or less than, those found in previously published studies [13,15,20,21,22,24,27,28]. In addition to being more accurate than hand measurements, the use of photogrammetric analysis has other attributes that potentially make it a preferable option to physically measuring a crushed vehicle. An accurate photogrammetry analysis can be completed without physically inspecting the damaged vehicle (assuming that the photos used are of adequate quality). The use of photogrammetry also permits the investigator to re-analyze the damage at any time, as the photos and the project will always be available, whereas a damaged vehicle may be sold, repaired or disposed of after an initial inspection. Additionally, the associated photogrammetry project file can be preserved indefinitely and examined by other experts to independently evaluate the accuracy of the measurements.

Photogrammetry can also be a viable alternative to the use of a total station in some cases. Photogrammetry permits the user to essentially re-inspect a damaged vehicle at any time. The visual nature of photogrammetry permits the user to see any potential mistakes, as evidenced by the visualized physical locations of the points, and fix them if needed. When using a total station, points that were potentially not obtained properly, or any missed points, may not be detected until the investigator subsequently downloads and analyzes the data, making it difficult to go back and correct, especially if the vehicle is no longer available.

The purpose of this study was to determine the differences in measurement techniques typically used in accident reconstruction to determine vehicle crush. The study was carefully constructed to minimize the confounding differences in the measurements that can often be introduced when different operators set up and measure a crushed vehicle. A prescribed station line and exact locations on the vehicles were used so that a direct point-by-point comparison of the actual measurements from a baseline total station, PhotoModeler projects and participant hand measurements from qualified participants could be compared. Crushed vehicles were chosen as the objects to be measured, however any 3-D object could have been used.

Note that the accuracies reported here may not be representative of those encountered during actual reconstruction practice. Any hands-on measurement of a damaged vehicle for accident reconstruction purposes is also dependent on the individual examining the vehicle and their determination of the location of the points and how the points are measured. Similarly, the accuracy of a photogrammetry project is also influenced by the quality of the photographs available, both in resolution of the image and how the photographs are taken. In addition, the photogrammetry technique in this study employed photographs containing targets affixed to the damaged vehicles, whereas in practice photos of untargeted vehicles may only be available, potentially reducing the accuracy of the photogrammetry method.

The use of a prescribed station line also served as a limitation in this regard. However, the intent of the study was to simply compare the relative accuracy of two measurement techniques, and toward this end, the influence of other potentially confounding variables was eliminated. Inclusion of these other variables would likely reduce the accuracy of both methods, particularly the hand measurement technique. Bartlett et al. [29] demonstrated the significant influence of these variables for the hand measurement techniques. Nonetheless, it is felt that the photogrammetric technique would likely still produce more accurate results than hand measurements. Future studies may want to explore the influence of these other variables in evaluating measurement techniques.

SUMMARY/CONCLUSIONS

1. Both hand and photogrammetric measurement techniques provided measurements of targeted damaged vehicles with errors well below generally accepted ranges for accident reconstruction.

2. The photogrammetric measurements were statistically found to be more accurate than those obtained via hands-on measurement by qualified professionals in the field of accident reconstruction, both in terms of the relative differences and percent accuracy.

3. The photogrammetric measurement errors in the current study were consistent with those found in published studies using photogrammetry for vehicle damage measurements.

4. This study supports the use of photogrammetry with targeted damaged vehicles as an accurate and reliable method for the assessment of vehicle crush. The use of only photographs in a photogrammetry analysis can be used to accurately assess vehicle damage, and may even reduce potential errors due to the visual nature of the analysis.

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APPENDIX A

Crush Measurement Form (NISSAN)

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PLEASE TAKE THESE MEASUREMENTS AS ACCURATELY AS POSSIBLE SINCE THEY WILL BE UTILIZED FOR A SCIENTIFIC STUDY! PERFORM THE MEASUREMENTS IN THE SAME MANNER AS IF YOU HAD BEEN RETAINED AS AN EXPERT TO RECONSTRUCT THE ACCIDENT INVOLVING THIS VEHICLE. EACH PARTICIPANT WILL REMAIN ANONYMOUS! DO NOT WRITE YOUR NAME OR ANY IDENTIFYING INFORMATION ON THIS SHEET. WHEN FINISHED, PLACE IN SEALED BOX MARKED "*CRUSH MEASUREMENTS*."

- -

Measuring device (***Please circle all that apply***)

25' tape; Pocket Rod; Folding Wood Ruler; Jig; Other ____________;

Was plumb bob used (***Please circle one***)? **Y N**

What unit of measurement was utilized (***Please circle one***)? **in ft mm m**

1986 Nissan Maxima (left side) measurements.

Please measure **specific** points listed below perpendicular (i.e. crush depth) from **given reference line**.

Point #	Measurement Value	Point #	Measurement Value
59		72	
60		73	
61		74	
62		75	
63		76	
64		77	
65		78	
66		79	
67		80	
68		81	
69		82	
70		n/a	
LR Axle		LF Axle	

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