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Cost-Benefit Analysis of 3D Imaging Technology as a Crime Scene Investigation Tool

Prepared for the Wisconsin Institute for Discovery, Living Environments Lab

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Abbreviations

CSI – Crime Scene Investigation or Crime Scene Investigator

DCSO – Dane County Sheriff's Office

LiDAR – Light Imaging, Detection, and Ranging

RGB – Red, green and blue

TST – Total System Theodolite

WID – Wisconsin Institute for Discovery

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Executive Summary

On the behalf of the Wisconsin Institute for Discovery (WID) Living Environments Laboratory, our team conducted a cost-benefit analysis of 3D capture technology in crime scene investigations. We compared two 3D scanning technology alternatives relative to traditional crime scene diagramming techniques. The first alternative is a stationary tripod mounted LiDAR scanner (represented by the FARO Focus 3D), and the second is a handheld depth camera scanner (represented by the Panoscan PointGun). We assessed the average annual net benefits of adopting each technology for use by law enforcement. We estimated that the LiDAR technology provides an average annual net benefit of $18.1 thousand (middle 95 percent of trials [$1.5, $36.9]), and the handheld depth camera provides an average annual net benefit of $14.9 thousand (middle 95 percent of trials [$6.0, $25.8]). Excluding social benefits and costs, the average annual fiscal net benefit is $21.8 thousand (middle 95 percent of trials [$8.1, $38.0]) and $14.2 thousand (middle 95 percent of trials [$5.5, $24.9]) for the LiDAR and depth camera technologies, respectively. We recommend that the DSCO adopt the LiDAR technology for diagramming crime scenes and traffic accidents because we estimated that it would yield higher annual net benefits. However, the implementation of either technology alternative would present positive net benefits.

Each 3D alternative provides net benefits compared to traditional methods of diagramming crime and crash scenes. Although the two technology alternatives may differ in ways for which our analysis was not able to account, such as micro-level accuracy, ease of use, and ease of data processing. The Panoscan PointGun offers a more affordable option for law enforcement agencies that are concerned about the up-front costs of the technology. However, agencies that can purchase the FARO Focus 3D scanner are predicted to enjoy larger positive net benefits because it can be used in a wider variety of conditions than the Panoscan PointGun.

We estimated the average social and fiscal net benefits of adopting each technology by conducting a Monte Carlo simulation. A Monte Carlo simulation is a form of sensitivity analysis that uses repeated random sampling to estimate the distribution of the final outcome, with the goal of capturing uncertainty in estimates.

Law enforcement agencies considering either scanning technology should keep in mind that the majority of the benefits come from avoided time costs because it takes less time to scan a scene than it does to measure it using traditional techniques. These differences in time are magnified with each traffic accident or crime scene that a department processes. Our estimated net benefits for the Dane County Sheriff's Office assume that the devices will be used to scan automobile crash sites as well as homicide scenes. Utilizing either alternative solely for homicide scenes would require a larger volume of homicides to obtain net benefits. Therefore, law enforcement agencies should consider the volume and type of the cases they handle when deciding whether to purchase a 3D capture device.

Introduction

Law enforcement agencies use diagrams of crime scenes and automobile crash scenes as investigative tools, visual aids during courtroom proceedings, and even as evidence under certain circumstances. These diagrams provide valuable information regarding the environments in which particular crimes and crashes take place. Crime scene investigators create these diagrams from measurements taken at a scene. The on-scene measuring process is conducted after the scene has been cleared of any hazards, inspected for physical evidence, and photographed. The measuring methods used to collect the necessary information vary according to the type of scene being diagrammed as well as the policies of the agency in charge. After the measurements are collected, investigators use them to create scaled scene diagrams either by hand or with software specifically designed for the task. Once a scene diagram is complete, it is ready to be utilized in the investigation or in court and is kept on file by the agency in charge of the case.

On-scene measuring techniques vary primarily according to the type of scene being diagrammed. Crime scenes involving indoor spaces or relatively small outdoor spaces are generally measured using traditional tape measures and, more recently, laser devices, which emit a focused beam of light in order to measure distance. Large outdoor scenes, such as automobile crash sites, are generally measured using a device known as a Total Station Theodolite (TST). A TST is an electronic/optical instrument commonly used in surveying and construction. The TST functions by emitting a modulated infrared carrier signal that reflects off the object of interest or off a specialized target placed by investigators. The modulation pattern of the returning signal is read and interpreted by a miniature computer inside of the total station. Measuring a scene using a TST generally requires three law enforcement personnel.

One of the greatest challenges that investigators face when diagramming a scene is maintaining an appropriate balance between speed and detail. Completing the on-site measuring process in a short amount of time saves resources, including investigator time, but may not generate enough information to satisfy the current and future needs of the investigation. Conversely, committing large amounts of time to the measuring process produces ample information but may prevent investigators from completing other tasks. This challenge creates a demand for measuring techniques that reduce the amount of time investigators spend on-scene while increasing the amount of information gathered.

One potential solution is the use of 3D capture technology to replace tape measures, laser measuring devices, and TST devices. 3D technologies vary by type and by manufacturer; however as a general rule, they employ cameras and focused rays of light in order to create a three-dimensional representation of a scene (Appendices A, B). 3D capture devices also provide large amounts of data from which investigators can essentially measure any relevant dimension of the scene. Although 3D capture technology presents much higher initial capital costs than traditional methods, time savings and increased data availability may justify the higher costs.

Our Task

Our team was commissioned by the Living Environments Lab at the University of Wisconsin Institutes for Discovery (WID) to conduct a cost-benefit analysis of two products for diagramming crime scenes and automobile crash scenes. We have conducted our analysis in partnership with our client as well as the Dane County Sheriff's Office (DCSO). We are comparing traditional methods of crime scene diagramming to the use of 3D scanning technology for diagramming. The two alternatives under consideration are the purchase and use of the FARO Focus 3D scanner (Appendix A), a tripod-mounted LiDAR technology, and the purchase and use of the Panoscan PointGun (Appendix B), an RGB (red green blue) depth camera technology.

The majority of the data regarding the time required to measure a scene and create a diagram using each method were contributed by the WID research team and the DCSO. Other data was collected by our team from various publicly available sources. We used this information to conduct a Monte Carlo sensitivity analysis in order to determine whether one or both of the alternatives provide net benefits over traditional methods of diagramming crime scenes and crash scenes.

Costs

Implementing 3D capture technology involves numerous costs related to hardware, software, technology infrastructure, and investigator training (**Table 1**). These costs vary depending on the type of 3D scanning device. Additional information on costs is provided in appendices A, B, D, E, and F.

***Table 1**: Cost Estimates for Alternative 1 (FARO Focus 3D) and Alternative 2 (Panoscan PointGun)*

Cost Category/Item	**Cost Estimates**		
	Low Estimate	Point Estimate	High Estimate
Initial Hardware Costs			
FARO Focus 3D Scanner	-	$37,730	-
Panoscan PointGun Scanner	-	$4,000	-
Desktop Computer	-	$2,500	-
Recurring Software Costs			
FARO Software License	-	$2,490	-
Panoscan Software License	-	$800	-
Annually Recurring Technology Infrastructure			
Server-based storage costs	$1,050	-	$3,000
Training Costs			
FARO Training			
Twenty-one-hour training (Two trainees)	-	$2,100	-
Opportunity cost of investigator time (two full-time investigators for five days)	$2,230	$4,303	$6,929
Transportation (airfare) for two trainees	-	$900	-
Lodging for two trainees (separate rooms)	-	$1,200	-
Panoscan Training			
Sixteen-hour training (Two trainees)	-	$1,000	-
Opportunity cost of investigator time (two full-time investigators for two days)	$892	$1,721	$2,772
Lodging for trainer for two nights	-	$400	-

Initial Hardware Costs

The two devices being compared in this analysis differ significantly in their initial cost. The Focus 3D scanner (Appendix A) produced by FARO Technologies costs $37,730 while the Panoscan PointGun scanner (Appendix B) produced by Panoscan Inc. costs $4,000.[1] Some agencies may not currently possess the computing capacity required to create 3D models using the data collected by the FARO Focus 3D and would therefore need to invest in additional computing capacity. Agencies that purchase the FARO Focus 3D and already possess adequate computing capacity would face lower initial capital costs. We estimate that purchasing a computer powerful enough to perform the necessary tasks would cost approximately $2,500.[2] The Panoscan PointGun does not require the same level of computing power because most of the data processing work is done by the device itself.

Recurring Software Costs

3D modeling software is necessary for viewing scans and using the 3D information. FARO Technologies and Panoscan Inc. offer software packages that are compatible with their respective devices. After the initial equipment purchase, each software package must be renewed after a certain number of years. The FARO software must be renewed every three years at a cost of $2,490.[3] The Panoscan PointGun software must be renewed every two years at a cost of $800.[4]

Technology Infrastructure Costs

Recreating crime scenes using 3D capture technology produces much larger electronic files than more traditional methods. Therefore, adopters of this technology would most likely have to expand their electronic storage capabilities. Additionally, each 3D reconstruction must be stored securely in the event that a case goes to trial or is reopened at some point in the future. The storage needs of agencies will vary widely based on current storage capacity, availability of secure options for expanding storage capacity, and the volume of 3D reconstructions being created and stored. In order to provide an estimate of the infrastructure costs that a department would bear if they adopted either 3D scanning technology, we obtained estimates for contracting the service. The first estimate is an annual fee of $3,000, and the second estimate is a minimum of $1,050 annually (Appendix E).

Training Costs

Specialized training is required because of the highly technical nature of 3D capture equipment. Manufacturers of 3D capture devices offer training courses specifically tailored to their products. A detailed description of the training costs is outlined in appendix F.

FARO Technologies, the manufacturer of the FARO Focus 3D scanner, provides a 21-hour training for two individuals for $2,100.[5] However, the training takes place in Irving, Texas. As a result, law enforcement agencies would face additional costs related to travel, travel time, and lodging. The opportunity cost of time spent in training and travel by two investigators is valued at their hourly compensation rate (Appendix C). Assuming that travel to and from the site would require one day before the training and one day after the training, the opportunity costs of two full-time investigators over three days of training and two days of travel range from $2,230 to $6,929 (Appendices C, F). Roundtrip airfare for two people from Madison, Wisconsin to Dallas, Texas costs approximately $900 based on the average observed cost of airfare. Lodging for two people in separate hotel rooms for three nights costs approximately $1,200 based on the average observed cost of a one-night hotel stay.

Panoscan Inc., the manufacturer of the Panoscan PointGun scanner, provides a 16-hour training session for $1,000 per person.[6] In our analysis, we assumed that two investigators would participate in the training. The estimated opportunity cost of the time spent in training by two investigators ranges from $892 to $2,772 (Appendices C, F). In addition to the cost of the training session, the customer is required to pay for lodging for the facilitator. We estimate the facilitator's lodging costs to be $400 for two nights based on the average observed cost of a one-night hotel stay.

Benefits

Our analysis accounts for three distinct categories of benefits gained through the implementation and utilization of 3D capture technology: avoided time costs, reduced traffic delay, and availability of additional measurement information.

Avoided Time Cost

Each 3D capture alternative provides a time savings in comparison with traditional investigation methods. This time savings may occur because the on-scene portion of the process requires less time, because the off-scene processing of the data requires less time, or because both processes require less time. This is considered a benefit because investigators can use the time not spent diagramming a scene on other productive tasks.

Reduced Traffic Delay

Reducing the amount of time spent diagramming a traffic accident can reduce traffic delay. Therefore, 3D capture alternatives are expected to decrease traffic delays related to crash scene investigations. For every minute of reduced on-scene scanning time, we expect overall traffic delay to be reduced by four minutes.[7] The time gained from reduced traffic delay is not a direct benefit to the DCSO but is a general benefit to the community and people who travel through Dane County, Wisconsin. Time spent in traffic is time not spent at work, home, or elsewhere. Therefore, reduced traffic delay is considered a social benefit.

Availability of Additional Measurement Information

Interviews with law enforcement officers revealed that, from their perspective, one of the greatest benefits of 3D capture technology is its ability to collect extremely large amounts of data because it is difficult to know exactly what will be important to a case at the time a scene is being diagrammed. 3D capture technology allows investigators to go back to a 3D crime scene model at any time and take any relevant measurement of the crime scene, regardless of whether or not they knew it would be important when the crime scene diagram was initially created. It also allows investigators and attorneys who were not at the scene to visualize it. Because, this benefit is difficult to quantify, we consulted one crime scene investigator in order to elicit his willingness to invest additional personnel time to gather the additional information provided by 3D capture technology (Appendix K)**.**

Analysis and Results

Net benefits of the Panoscan PointGun and the LiDAR FARO Focus 3D scanners were each calculated relative to the traditional methods for diagramming crime scenes and traffic accidents. As described previously, three benefit impact categories and three cost categories were the basis of the analysis. Specific inputs and calculations for costs and benefits are outlined in Appendices C – K and the R code for the analysis is included in Appendix M.

Monte Carlo Simulation

We conducted a Monte Carlo simulation with 100,000 trials to estimate a distribution of net benefits. A Monte Carlo simulation is a form of sensitivity analysis that uses repeated random sampling from assumed distributions of uncertain parameters to estimate the distribution of the final outcome. For example, the compensation for a crime scene investigator can range from about $27 per hour to $85 per hour. Instead of picking one compensation value to use in our calculations, we specified the range and distribution of values for the compensation. We did this for all of the inputs. Then, we subtracted the costs from the benefits to get the net benefits. The key component that makes this a Monte Carlo simulation is that we repeated this process of calculating the net benefits (100,000 times), and with each repetition, a value was randomly drawn from each input's distribution of values. This resulted in 100,000 net benefits estimates, which have a distribution that captures the uncertainty of the net benefit estimate.

Monetization of Benefits

Avoided time cost

To estimate the avoided cost of spending more time diagramming a site, we calculated the difference in the amount of time it takes to scan and process a scene with each scanner

(Appendix I). To monetize the time savings, we multiplied the time difference by the total compensation of the individuals who would be spending less time at the scene, namely crime scene investigators and patrol officers guarding the scene (Appendices C, I). We did a similar calculation for traffic accidents, except that it did not include patrol officer compensation rates because the scene does not need to be guarded. The per-scene dollar savings were multiplied by the number of homicides and accidents that the Dane County Sheriff's Office would handle on a yearly basis. The number of annual homicides was observed (Appendix G). Because the scanners would only be used for accidents with specific circumstances such as an accident involving a fatality, we calculated a LiDAR-specific and Panoscan PointGun-specific number of accidents (Appendix H). A key difference between the two technologies is that the Panoscan PointGun cannot be used in daylight, which reduces the number of accidents for which it can be used. Cars that cannot be scanned at the scene may be towed to a storage facility for diagramming. We did not factor this into our analysis, so it can be thought of as an excluded benefit.

Reduced traffic delay

For traffic accidents, not only is it beneficial for crime scene investigators to spend less time diagramming a site, it is also beneficial to reduce the duration of traffic delays experienced by commuters. We estimated the total reduced delay time for each scanner with the assumption that every minute that an average highway lane is closed results in four minutes of total commuter delay.[8] An estimate of the amount of delay caused by one minute of lane closure on a local street or road was not available. Therefore, we estimated that the amount of delay caused by one minute of lane closure on a local street would be between one and four minutes. To monetize the value of the reduced delay we multiplied it by half of the national average hourly compensation rate of $35.28 (Appendices C, J).

Availability of Additional Measurement Information

Another advantage of diagramming a site with these scanners is that they capture a 3D representation of a scene. Once diagrammed, the location of any object or the length of any distance can be measured on a computer. With traditional techniques, only essential distances are measured and documented. The value of the additional information provided by the scanners is realized when investigators need different measures of the scene because of a new development in a crime investigation.

We elicited the value of this additional information through a questionnaire filled out by a crime scene investigator (Appendix K). Briefly, the investigator was asked how much time he would be willing to spend diagramming a scene beyond the time he spends taking essential measurements to obtain the same amount of information provided by a 3D device. Based on the hours and number of personnel at the scene indicated in the elicitation, we calculated the total value of additional information per investigation by multiplying the hours by the compensation of an investigator and a patrol officer (Appendices C, K). We only considered this benefit for homicides because the question was phrased for a crime scene investigation. We assumed both technologies would offer the same value of information.

Monetization of Costs

Equipment

The cost of the scanner, its software, and a computer comprised this cost category. The computer was included in the LiDAR costs because computing power beyond the typical office computer is required to process LiDAR scans (**Table 1**). We estimated annual costs of each component by dividing by an annuity factor (Appendix D). We assumed a 3.5 percent interest rate and a 5 to 10-year lifetime of the scanners.

Technology Infrastructure

Departments that adopt 3D scanning technology would likely have to expand server space to store, protect, and archive the scans from each scene. We estimated the cost of data storage using quotes for contracting that service through two University of Wisconsin computing centers (Appendix E). We assumed the same annual contracting costs would apply to both technologies.

Training

Training costs included training session costs, travel to the site, and the opportunity cost of the investigators that go through the training (Appendix F). Annual training costs were calculated by dividing by an annuity factor. We assumed a 3.5 percent interest rate and that training costs would have the same lifetime as the technology (5 to 10 years).

Cost and Benefit Estimates

The average annual net benefits for the FARO Focus 3D LiDAR scanner and Panoscan PointGun scanner were positive (**Table 2**, **Figure 1**). The avoided time costs dominated benefits for both technologies. Equipment costs dominated the costs for the LiDAR technology, while the technology infrastructure was the largest cost for the depth camera technology. The information value benefit and the technology infrastructure costs were the same for both alternatives. For the FARO Focus 3D, the costs are approximately one-third of the benefits, and for the Panoscan PointGun, the costs are approximately one-fifth of the benefits.

Table 2*:* *Mean annual benefits and costs for the LiDAR FARO Focus 3D and the Panoscan PointGun scanners. The range of middle 95% trials represents the bounds (in thousands of dollars) that demarcate the middle 95% portion of a cost or benefit distribution.*

	LiDAR FARO Focus 3D		**Panoscan PointGun**	
	Mean (1000s of Dollars)	Range of Middle 95% of Trials	Mean (1000s of Dollars)	Range of Middle 95% of Trials
Benefits	**29.7**	**13.0, 48.6**	**18.6**	**9.7, 29.6**
Avoided Time Cost Savings	27.2	13.6, 42.5	11.7	6.0, 17.6
Reduced Traffic Delay	-3.7	-6.6, -1.1	0.7	0.5, 0.9
Information Value	6.3	1.2, 14.1	6.3	1.2, 14.1
Costs	**11.6**	**9.0, 14.0**	**3.7**	**2.6, 4.7**
Equipment	8.0	6.3, 9.7	1.1	0.9, 1.3
Training	1.5	0.9, 2.1	0.5	0.3, 0.8
Technology Infrastructure	2.0	1.1, 3.0	2.0	1.1, 3.0
Net Benefits	**18.1**	**1.5, 36.9**	**14.9**	**6.0, 25.8**

We estimated the average annual net benefit for the FARO Focus 3D to be about $3,000 more than that of the Panoscan PointGun. Approximately 1 percent of the LiDAR net benefits extend below $0, whereas the Panoscan PointGun net benefits are consistently positive (**Figure 1**). This is also seen in the overlapping costs and benefits for LiDAR and the completely separated costs and benefits of the Panoscan PointGun (**Figure 2**). This means that the LiDAR technology has a small potential for yielding a negative net benefit, and the Panoscan PointGun more consistently offers a positive net benefit.

We examined the individual benefit and cost categories to understand what influenced the net benefit estimates. The specific cost and benefit category figures are in Appendix L. Most of the benefits for the LiDAR and Panoscan PointGun come from the reduced time it takes to diagram a crime scene or an accident (**Table 2**, **Figure 6**, **Figure 7**). This seems to be driven by the number of accidents we estimated the DCSO would process using each scanner. We explore this in our sensitivity analysis below.

Specific Benefits

Interestingly, the reduced traffic delay benefit was positive for the Panoscan PointGun and negative for the LiDAR technology (**Table 2**, **Figure 6**, **Figure 7**). This results from the way crash scenes are traditionally diagrammed. The traditional technique involves three people measuring an accident, which results in a slightly shorter time of lane closure than when one person is diagramming the scene with the FARO Focus 3D scanner. The Panoscan PointGun scan takes less time than the traditional technique. Of course, the total person-time it takes to measure a crash scene with traditional techniques is longer than with either of the scans, and this was accounted for in the avoided time cost. The per-accident cost of traffic delay for the FARO Focus 3D scanner ranges from approximately -$30 to $0, while the benefit per accident for the Panoscan PointGun ranges from $5 to $15. These values are small for a single accident but can become substantial when many accidents are processed.

The value of having detailed measurements for a crime scene was less than the avoided time costs and more than the traffic delay benefit. Curiously, the annual value of extra information exceeds the total costs of the Panoscan PointGun alternative (**Table 2**). The estimate of information value is based on one response to our elicitation questionnaire which outlined a hypothetical scenario (Appendix K); therefore, we do not have great confidence that the elicited price reflects the true value of having more detailed information. We include a sensitivity analysis removing this benefit from the estimate.

Specific Costs

Expenditures on equipment dominated total costs for the FARO Focus 3D alternative (**Table 2**, **Figure 8**; Appendix E). The training costs were the lowest fraction of total costs for the FARO Focus 3D. However, they were higher than the PointGun training costs mainly because the FARO Focus training is off-site and required air travel and a several-day hotel stay (Appendix F). The middle cost was the yearly expenditure on the technology infrastructure where scan data would be maintained. For the Panoscan PointGun, the highest cost was the technology infrastructure, followed by the equipment costs, and training costs, in descending order (**Table 2**, **Figure 9**; Appendices D - F).

Sensitivity Analysis

The avoided time cost benefit was very influential on the net benefits and this is related to the number of traffic accident scenes that we assumed would be processed by the 3D scanners. Of the accidents that occur in Dane County, we estimated that 65 to 85 accidents per year would justify use of the Panoscan PointGun scanner and 221 to 265 accidents per year would justify use of the FARO Focus 3D scanner (Appendix H). The Panoscan PointGun number of accidents is lower because it cannot be used in daylight, and approximately two-thirds of accidents occur during the day. The net benefits presented above were calculated assuming the Dane County Sheriff's Office would process these numbers of accidents. Processing 65 to 85 accidents per year is plausible but 221 to 265 may not be. With one scanner, these accidents would have to occur on separate days or at separate times during the day for the investigators to be able to process all of them. Therefore, we first estimated how many homicides the Sheriff's Office would need to process to break even on the costs of the technology if they did not process any accidents. We added a second component to this analysis: the exclusion of the information value benefit. The value of having detailed measurements for a homicide is very uncertain, so we wanted to see how much of a difference excluding it would make. Including the information value benefit, the DSCO would break even with the costs of the scanning technology if they processed at least 4 homicides per year for the LiDAR technology and 2 per year for the Panoscan PointGun (**Table 4**). However, if that benefit is excluded, then the number of homicides goes up to 107 for the FARO Focus 3D and 28 for the Panoscan PointGun. This large increase in the number of homicides needed to break even with the costs after the exclusion of the information value benefit is surprising. However, when we examine the elicitation of the willingness to pay for this information, we can see that the information value per homicide is high. In our elicitation, the investigator answered that he would be willing to devote 10 hours of one crime scene investigator's time taking traditional measurements and 10 hours of two patrol officers' time guarding the scene over two days if it were possible to get the same level of information as a 3D scanner. If we multiply these hours by the compensation of the individuals (Appendices C, K), we get an average information value per homicide of approximately $2.8 thousand, which is much larger than the per-homicide values for the other benefits (**Table 3**). With the total average annual costs of the LiDAR technology being $11.6 thousand and the PointGun being $3.7 thousand, the stark difference in the number of homicides when excluding this benefit is no longer surprising.

Table 3*: Mean benefit per homicide or per accident for the FARO Focus 3D and the Panoscan PointGun. Values are in dollars.*

	LiDAR FARO Focus 3D	Panoscan PointGun
Avoided Time Cost Per Homicide	108	135
Avoided Time Cost Per Accident	110	157
Reduced Delay Per Accident	-15	9
Information Value Per Homicide	2,853	2,853

The break-even number of homicides including the information value is in the range of what DSCO handles on a yearly basis (0 to 5 homicides per year). However, if the information value benefit is excluded, the number of homicides is high, and the DCSO may need to rely on the savings from processing traffic accidents with a scanner.

Table 4*: Number of homicides the DCSO would need to process with a scanner every year to break even with costs if no accidents were processed with the scanning technology.*

	Information Value Benefit	
	Including	Excluding
LiDAR FARO Focus 3D	4	107
Panoscan PointGun	2	28

We did a second analysis to find the fewest number of accidents (on average) the Sheriff's Office would have to diagram on a yearly basis for benefits to just equal the costs of the technologies (**Table 5**). As with the first sensitivity analysis, we also assessed the break-even point excluding the information value benefit. We did a second sub-analysis excluding the benefits from reduced traffic delay, which is a social benefit and not a direct benefit to the

Sheriff's Office. A third sub-analysis looked into benefits if no homicides were processed with the scanners. The most conservative estimate of the number of accidents the DSCO would need to process per year to break even is 122 for the LiDAR technology and 24 for the Panoscan PointGun (**Table 5**). Excluding the traffic delay component did not influence the break-even estimates of accidents very much. However, the information value benefit had a large influence. The number of accidents that would need to be processed with a LiDAR scanner went up from 2 with the information value benefit to 34 (excluding costs of delay) or 35 (including costs of delay) without it. Again, this is due to the relatively high information value (**Table 3**). Likewise, the number of accidents for the Panoscan PointGun went from 1 with the information value benefit to 9 (excluding reduced delay) or 8 (including reduced delay) without it. If homicides are excluded (by default the information value is excluded too because we only applied it to homicides), the number of accidents increases even more. For the LiDAR technology, the numbers increased to over 100, while the Panoscan PointGun number of accidents ranges from 23 (including reduced delay) to 24 (excluding reduced delay). The break-even accident estimates reveal that the value of having detailed homicide scene information can significantly affect the benefits.

***Table 5**: Number of accidents DCSO would need to handle every year to break even with the costs of having a LiDAR or Panoscan scanner.*

			Including Homicides Handled by DCSO (0 – 5 Homicides)		**No Homicides**
			Information Value Benefit		
			Including	Excluding	
LiDAR	**Costs from Increased Traffic Delay**	Including	2	35	122
		Excluding	2	34	105
Panoscan	**Benefits from Reduced Traffic Delay**	Including	1	8	23
		Excluding	1	9	24

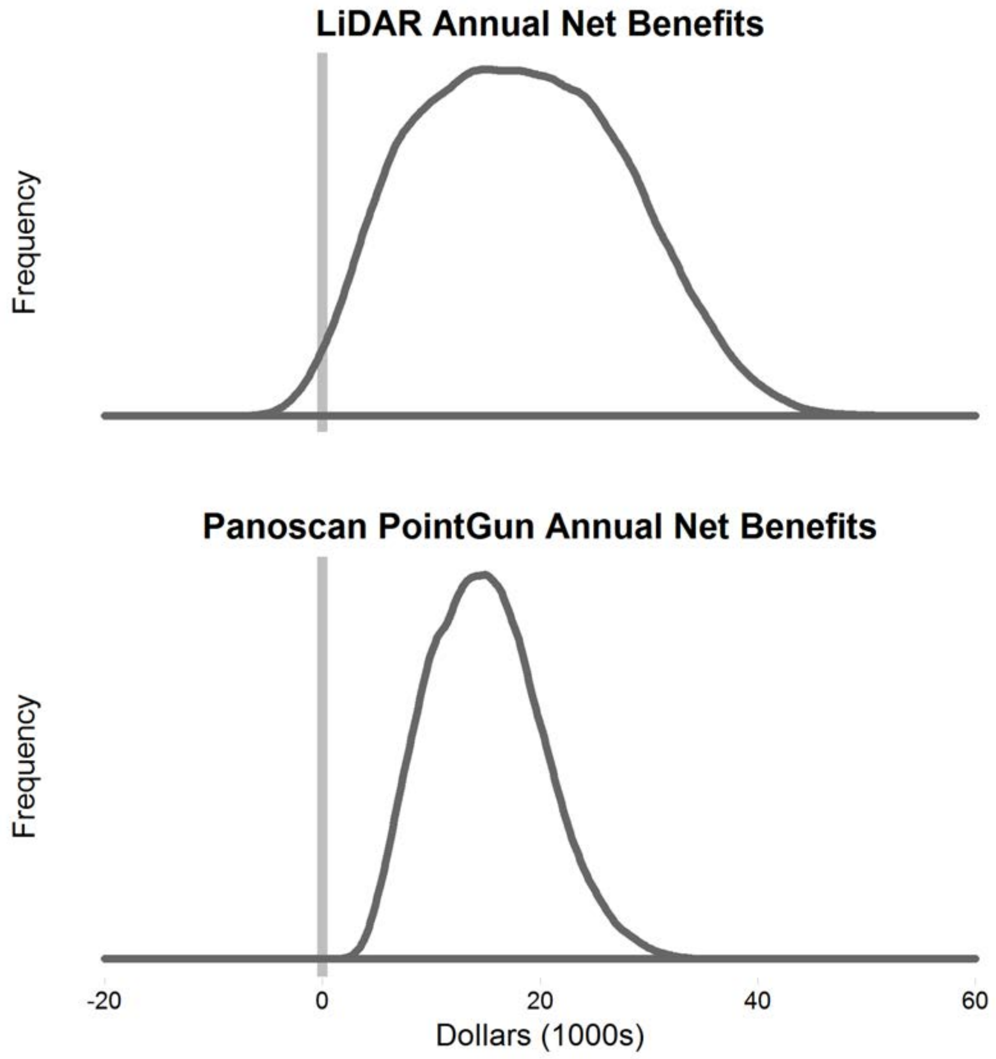

***Figure 1**: Annual Net Benefits for the FARO Focus 3D LiDAR scanner and the Panoscan PointGun. Dollar amounts are on the x-axis, and the y-axis is the frequency of Monte Carlo trials (n = 100,000). The vertical line demarcates negative and positive net benefits. Approximately 1% of trials fall below 0.*

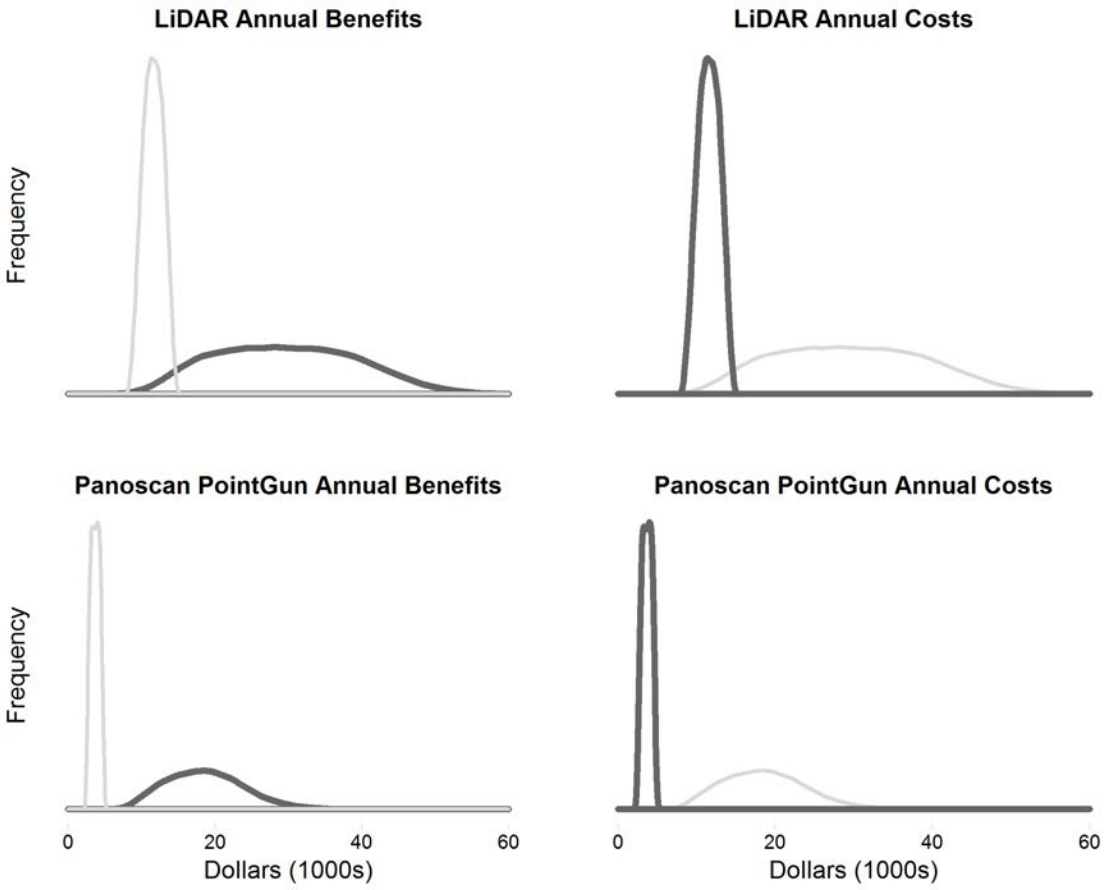

***Figure 2**: Total costs and total benefits for the FARO Focus 3D LiDAR scanner and the Panoscan PointGun scanner. Dollar amounts are on the x-axis, and the frequency of Monte Carlo trials (n = 100,000) is on the y-axis. The cost or benefit corresponding to each panel's title is represented by a thicker and darker line.*

Limitations

The use of 3D capture technology in crime scene investigations is a relatively new and understudied subject. In the absence of previously conducted cost-benefit analyses on the subject, our team faced the challenge of creating a framework for estimating the relevant costs and benefits. Understandably, this challenge creates a variety of limitations.

First, our analysis compares two products representing two types of 3D capture technology. The FARO Focus 3D tripod mounted scanner represents LiDAR technology (Appendix A), while the Panoscan PointGun represents RGB depth camera technology (Appendix B). The costs and capabilities associated with these devices may not accurately reflect the costs and capabilities of other devices on the market. Therefore, our findings should not be generalized to the use of other 3D capture devices without further investigation.

Additionally, the estimates of the time required to recreate a scene using each method are based on a limited number of trials and settings. The estimated time required to recreate a homicide scene using 3D technology is based on the results of two identical trials with each device. We were unable to secure data regarding the use of the Panoscan PointGun to recreate automobile crash scenes. Therefore, we created a time estimate based on the ratio of time required to recreate a homicide scene using the FARO Focus 3D over the time required to recreate a homicide scene using the Panoscan PointGun. We then applied this ratio to the amount of time required to recreate an automobile crash scene using the FARO Focus 3D (Appendix I). Although this estimate is not based on field trials where the Panoscan PointGun was used to recreate an automobile accident, it is the best estimate we could make based on the available data. Overall, the relatively small sample size of scene re-creations and the fact that the size and characteristics of individual crime scenes can differ immensely will result in benefit variability.

The net benefits of using 3D capture technology in crime scene investigations depend largely on the number of times it is used and the settings in which it is used, and our net benefits estimates are based on predicted usage by the Dane County Sheriff's Office (Appendices G, H). Dane County-specific data were used when available and supplemented with state and national-level data whenever necessary. Therefore, the results of this analysis should not be applied to other agencies and jurisdictions without recognizing differences with the Dane County Sheriff's Office. Additionally, using state and national-level data to estimate the net benefits of an intervention in a particular county diminishes the internal validity of the analysis.

Our break-even sensitivity analysis used the cost and time estimates specific to the DCSO and the two 3D scanner models. Law enforcement agencies should carefully consider the types of crime scenes that they would be using the device for, whether they handle enough scenes of that type to justify the purchase of a device, and whether the number of cases that they would need to utilize the device for in order to achieve net benefits is physically feasible based on the number of scenes that could be scanned using a single device in a given year. Once again, due to variations between agencies and jurisdiction, caution should be taken in generalizing these results beyond Dane County and the Dane County Sheriff's Office. Our analysis only includes automobiles crashes that can be scanned immediately following the crash. Because of weather and light conditions, this is not always the case. However, some agencies may choose to utilize 3D capture technology for all automobile crashes by transporting damaged vehicles to a storage site until the vehicles and the site can be scanned separately when conditions improve. Additional analysis should be conducted in the future to examine the net benefits of this practice.

In order to estimate the value of the detailed information collected by 3D capture devices, we consulted one crime scene investigator to elicit his willingness to pay for the additional data. This was accomplished using an elicitation composed of a single question (Appendix K). The elicitation described a scenario in which 3D capture technology was not available and asked the participant to choose, from a list, the largest amount of resources that he would be willing to commit to a crime scene investigation, after traditional measurements had been taken, in order to gather the same amount of data that is collected by a 3D scanner. This method should be treated as providing only a rough estimate of the value of more complete information.

Our analysis tends to underestimate the potential benefits of 3D capture technology because of a lack of available data. For example, our analysis does not account for costs borne by individuals whose homes and businesses are inaccessible during an investigation and therefore underestimates the potential benefits of the technology. Our analysis also tends to underestimate the impact of 3D capture technology on traffic delays caused by crash investigations. First, our estimate assumes that each vehicle passing a given crash site contains only one adult passenger. Therefore, we are unable to account for time savings or loss experienced by adults travelling as passengers. Also, we valued commuter time at half of the average hourly compensation rate, but people commuting as part of their job should be valued at the full rate. Second, we were unable to find an estimate of traffic delay time for lane closures on local roads. Therefore, we assumed that the delay associated with a one-minute lane closure on a local road would be smaller than the same delay on a highway. Because a one-minute lane closure on a highway results in a total traffic delay of four minutes, we hypothesized a triangular distribution for the delay time caused by a one-minute lane closure on a local road with a range of one to four minutes. Third, our analysis does not consider the potential impacts that the use of 3D capture technology could have on vehicle exhaust related pollution levels. However, because of the time required to scan a scene with each device, we expect that utilizing the Panoscan PointGun would provide a net reduction in vehicle exhaust related pollution, while utilizing the FARO Focus 3D would provide a net increase in vehicle exhaust related pollution.

Finally, new technological advancements will likely cause the costs of purchasing these and similar products to decline steadily over time. Such changes, as well as changes in the capabilities of the devices, will eventually make this analysis obsolete. Therefore, cost-benefit estimates should be updated regularly to maintain accuracy and relevance.

Recommendations

According to our analysis, both alternatives provide overall positive net benefits in comparison with traditional methods for diagramming crime and crash scenes. The Panoscan PointGun provides positive benefits for all three benefit categories. The FARO Focus 3D provides positive benefits for two of the three benefit categories. It reduces personnel time costs and increases the amount of data available to investigators. However, it yields negative net benefits for the third benefit category because it requires more time on the accident scene than traditional methods. This is predicted to increase the amount of investigation related traffic delay experienced by commuters. Although both devices provide overall positive net benefits, we recommend the FARO Focus 3D because it provides larger positive net benefits. However, the Panoscan PointGun offers a more affordable option for agencies concerned about the up-front capital costs of investing in 3D capture technology.

Our estimated net benefits are primarily driven by the assumption that the Dane County Sheriff’s Office would use either device to scan automobile crashes as well as homicide scenes. Utilizing either device solely for homicide scenes would require a larger volume of homicides in order to obtain net benefits. Additionally, our analysis does not account for other potentially relevant considerations, such as differences in the micro-level accuracy of each device, the ease of use of each device, and ease of data processing provided by each alternative. For example, the PointGun can be used more easily in small areas, such as under a table. Additional research is needed to account for these considerations.

This cost-benefit analysis is primarily concerned with determining whether the Panoscan PointGun and the FARO Focus 3D would provide the Dane County Sheriff's Office with positive net benefits in comparison with traditional investigation methods. However, our analysis also offers insights for other agencies considering an investment in 3D capture technology. Our break-even analysis estimates how many scenes an agency would have to scan with each device in order for the net benefits to equal zero. Any scenes scanned beyond the break-even point would represent positive net benefits to the agency.

Before making a decision based on this analysis, law enforcement agencies should consider three key investigation personnel decisions that contribute to costs: how many investigators they will choose to train in 3D capture techniques, how many investigators they currently utilize when investigating a single scene using traditional methods, and how many patrol officers they currently utilize as crime scene guards at a single scene while an investigation is underway. The Dane County Sheriff's Office has decided to train two investigators in 3D capture techniques, utilizes two investigators in order to investigate a single scene using traditional methods, and utilizes two patrol officers as crime scene guards at a single scene while the investigation is underway. This analysis is based on the personnel decisions made by the Dane County Sheriff's Office; therefore, other agencies should consider how their personnel decisions might impact the costs and benefits related to adopting 3D capture technology. Additionally, law enforcement agencies should consider the volume and type of the cases they are involved in when deciding whether or not to purchase a 3D capture device. Agencies that do not handle an adequate volume of applicable cases may consider cooperating with nearby agencies to purchase a device and train investigators.

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[1] Wisconsin Institute for Discovery Living Environments Lab. (2017, September 18). Personal interview.
[2] *Ibid*.
[3] *Ibid.*

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[4] Lehmann, S. (2017, October 25). Personal interview.
[5] Wisconsin Institute for Discovery Living Environments Lab. (2017, September 18). Personal interview.
[6] Lehmann, S. (2017, October 25). Personal interview.
[7] National Traffic Incident Management Coalition. (2011). Benefits of traffic incident management.
[8] National Traffic Incident Management Coalition. (2011).

Appendix A: Technology Alternative 1 - FARO Focus 3D

The FARO Focus 3D is a 3D capture device manufactured by FARO Technologies. The device uses LiDAR (Light detection and ranging) technology to create a scaled photo-realistic 3D model of a target area.

LiDAR Technology[i,ii,iii]

Light detection and ranging (LiDAR) technology integrates a digital camera and a laser emitter in to capture images as well as highly accurate measurements of objects and scenes. Distance is measured by recording the amount of time required for the laser beam to reflect off an object in its path and return back to the device. Each time the laser beam reflects off an object, a data point is created. The device repeats this process millions of times to create a point cloud that is then matched with photographic images of the scene.

FARO Focus 3D[iv,v]

The FARO Focus 3D consists of a tripod mounted scanner that automatically rotates to capture the surrounding environment. The cost of the device is $37,730 and includes a back-up battery and tripod.

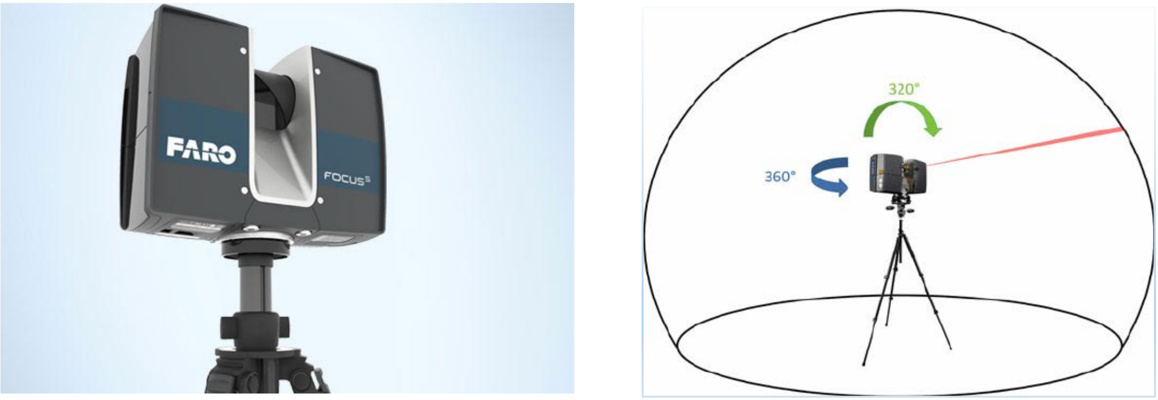

Figure 3: *Images of FARO Focus 3D scanning device (Left) and the range of visual capture (Right).*[vi]

On-scene scanning

Depending on the scene being measured, a single scan may take 7 to 38 minutes to complete. A crime scene may need to be scanned multiple times from a variety of angles in order to capture all of the important details. The level of photo quality can be adjusted and affects the scanning speed. A single trained operator is needed to set up the device and begin the scanning process. Once the process begins, the device rotates automatically and scans 360° horizontally and 320° vertically.

Limitations

The device cannot be operated in adverse weather conditions like rain, snow, and sleet. It also cannot correctly recreate mirrors or the surface of a body of water because these reflective surfaces tend to disturb the trajectory of the laser. However, errors caused by reflective surfaces can be corrected during the processing stage. The bulkiness of the tripod can make it difficult to use the device in small spaces. Although the device can be used in the dark, it cannot capture accurate photographs in the absence of natural or artificial light. However, measurements collected in the dark can still be used to create 3D models of the surrounding environment.

Data Processing and Software

Once the scanning process is complete, the acquired data are entered into the FARO Scene software in order to generate a 3D model of the site. Operating the necessary software requires a powerful desktop or laptop computer. Also, the software license must be renewed every three years at a cost of $2,490.

The processing stage involves a variety of tasks including rectifying erroneous data points and outliers and identifying and classifying objects and surfaces in order to produce final deliverables. The time required to create a 3D model using the data collected depends on the number of scans being used. The final product is a 3D model of the site that was scanned. The model can be viewed on almost any computer equipped with the appropriate software.

Personnel Training

In order to operate the device and properly utilize the data collected, investigators must complete twenty-one hours of training provided by the manufacturer. The training takes place in Irving, Texas and costs $2,100 per trainee. For additional training related cost considerations see **Table 1** in the body of the paper.

Figure 4: *3D model of a house created using the Faro Focus 3D (Top left)*[vii], *2D Floorplan created using traditional methods (Top right)*[viii], *Photograph of a body at a crime scene (Bottom left)*[ix], *and a 3D reconstruction corresponding with the previous photograph (Bottom right)*[x]

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[i] Rider, R. R. (2017). *The impact of new technology on crash reconstruction* (Doctoral dissertation, Tarleton State University).

[ii] Colwill, S. (2016). *Low-cost crime scene mapping: reviewing emerging freeware, low-cost methods of 3D mapping and applying them to crime scene investigation and forensic evidence.*

[iii] Chang, J.C., M. K. (2015). *Infrastructure investment protection with LiDAR.* North Carolina: North Carolina Department of Transportation.

[iv] Rider, R. R. (2017). *The impact of new technology on crash reconstruction* (Doctoral dissertation, Tarleton State University).

[v] FARO. (2017). Retrieved from www.faro.com: https://www.faro.com/products/construction-bim-cim/faro-focus/

[vi] Ibid.

[vii] Colwill, S. (2016). *Low-cost crime scene mapping: reviewing emerging freeware, low-cost methods of 3D mapping and applying them to crime scene investigation and forensic evidence.*

[viii] Ibid.

[ix] Ibid.

[x] Ibid.

Appendix B: Technology Alternative 2 – Panoscan PointGun

The Panoscan PointGun is a hand-held 3D scanner that uses RGB depth camera technology to capture high density color cloud data with speed and reliability. The PointGun is not intended to replace traditional crime scene photography, but to augment and support standard photographs with panoramic imaging.

RGB Depth Camera Technology[i]

Red Green Blue (RGB) depth camera technology captures RGB images and per pixel depth information that is used to measure distance. This combination can be used to create 3D models of an environment that incorporate accurate measurements as well as photorealistic visual representations.

Panoscan PointGun[ii,iii]

The PointGun is composed of an RGB depth camera, an LED light source, a detachable Android tablet, and an interchangeable rechargeable battery. The device costs $4,000 which includes one tablet and two batteries.

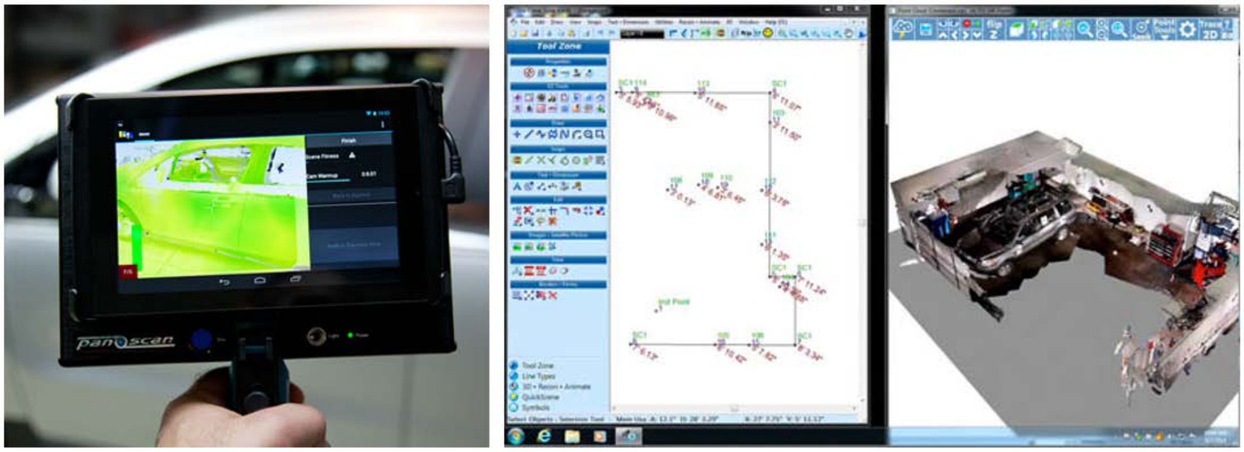

***Figure 5**: The Panoscan PointGun (Left) and a 3D model created using the device (Right).*[iv]

Set-up and Calibration

The PointGun requires very little setup and does not need to be calibrated before use like most other 3D capture devices. This saves time during crime scene investigations, reducing labor costs.

Data Capture

To collect data, a single operator holds the device and slowly moves around the environment being scanned in order capture the entire scene. The PointGun is able to capture real-time data, instantly creating a colored 3D point cloud. This allows capture of approximate 20 million colored data points per session which is faster than competing devices. Additionally, the scanner can be used continuously for over three hours on a single charge, while sending data to an Android tablet, freeing up storage. The tablet that is sold with the device can store over 2,000 individual scans.

Capabilities and Limitations

The Panoscan cannot be operated in adverse weather conditions like rain, snow, and sleet. The device can be operated indoors at any time using artificial light and outdoors at night using artificial light. However, due to the type of technology used to capture the data, it cannot be operated outdoors during daylight. This significantly decreases the number of automobile accidents that can be scanned using the device. The PointGun is light and portable making it very useful for scanning small spaces.

Software Requirements and Processing

The data produced by the PointGun is compatible with a variety of standard industry software programs. However, Panoscan Inc. provides its own data processing software which is available for a licensing fee of $800. The software license must be repurchased every two years.

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[i] Henry, P., Krainin, M., Herbst, E., Ren, X., & Fox, D. (2010). *RGB-D mapping: Using depth cameras for dense 3D modeling of indoor environments.* In In the 12th International Symposium on Experimental Robotics (ISER).

[ii] Panoscan Inc. (2017). *PointGun*. Retrieved from: *http://www.panoscan.com/PointGun/*

[iii] National Institute of Justice. (2013). *Technical Advances in the Visual Documentation of Crime Scenes: An Overview.*

[iv] Panoscan Inc. (2017).

Appendix C: Compensation

Compensation was included in the avoided cost benefit, reduced delay benefit, and the training cost calculations to take into account the personnel time that would be needed while processing information at the crime scene or personnel time lost during training.

As the hourly wage of crime scene investigators and patrol officers varies, we included the national values of hourly wage as a range from \$20.30 (bottom 10 percent) to \$63.08 (top 10 percent), and \$16.46 (bottom 10 percent) to \$47.36 (top 10 percent), respectively.[i] We then multiplied the wage by 1.373 to account for benefits as a component of total compensation. We chose 1.373 because a conservative estimate of a total benefits package for private sector workers is 28% of compensation.[ii]

Compensation was calculated as follows:

$$\textit{Compensation rate} = 1.373 * \textit{hourly\_wage}$$

Therefore, the employer's total compensations costs for crime scene investigators and patrol officers range from \$27.87 to \$86.61, and \$22.60 to \$65.03 per hours worked, respectively.

Table 6: *Compensation of Crime Scene Investigator and Patrol Officer (\$/hour)*

	Minimum	**Maximum**	**Average**
Crime Scene Investigator	27.87	86.61	53.79
Patrol Officer	22.60	65.03	43.82

These values were included in the Monte Carlo simulation as *CSI_comp* and *patrol_comp* variables, where *CSI_comp* is the hourly compensation rate for a crime scene investigator and *patrol_comp* is the hourly compensation rate for a patrol officer. Both wage ranges were modeled as uniform distributions.

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[i] U.S. Bureau of Labor Statistics. (2017). *Occupational employment and wages, May 2016 33-3021 detectives and criminal investigators.*

[ii] U.S. Bureau of Labor Statistics. (2017). *Employer costs for employee compensation – June 2017* [Press release].

Appendix D: Equipment Costs

Equipment costs are divided into three components: the 3D scanner and any necessary accessories such as a battery or tripod, the software for processing the scans, and the computer used to view and process 3D scans (**Table 7**). Because a typical office computer can process the Panoscan PointGun scans, we assumed no computer would be purchased with the PointGun alternative.

Table 7: *Equipment costs for the FARO Focus 3D and the Panoscan PointGun.*

	FARO Focus 3D	**Panoscan PointGun**
Scanner	37,730	4,000
Software	2,490	800
Computer	2,500	-

We calculated annual costs (**Equation 1**) for each equipment component by dividing the total cost (**Table 7**) by an annuity factor (**Equation 2**). We assumed a 3.5% interest rate. The number of periods in the annuity factor reflects the assumed lifetime of the equipment (**Table 8**). The lifetime for the software is a fixed value representing the length of the software license. We assumed a 5 year lifetime for the computer. The scanners were assumed to last between 5 and 10 years and were modeled with a triangular distribution with a mode of 5 years.

Equation 1*: Annual value calculation*

$$Annual\ Value = \frac{Total\ Value}{Annuity\ Factor}$$

Equation 2: *Annuity factor formula.*

$$Annuity\ Factor = \frac{1 - (1 + Interest\ Rate)^{-\ Lifetime}}{Interest\ Rate}$$

Table 8: *Lifetime of equipment used to calculate the annuity factor. Values are in years.*

	FARO Focus 3D			**Panoscan PointGun**		
	Minimum	Maximum	Mode	Minimum	Maximum	Mode
Scanner	5	10	5	5	10	5
Software	-	-	3	-	-	2
Computer	-	-	5	-	-	-

Annual costs were summed to estimate the total equipment costs for each technology.

FARO Focus 3D:

Annual Equipment Cost =
Annual Scanner Cost + Annual Software Cost + Annual Computer Cost

Panoscan PointGun:

Annual Equipment Cost = Annual Scanner Cost + Annual Software Cost

Appendix E: Technology Infrastructure Costs

Storing electronic versions of the models produced using 3D capture technology requires much more storage space than storing crime scene diagrams created with traditional methods. Law enforcement agencies that do not currently possess adequate storage capabilities will need to invest in additional storage space. Due to the magnitude of the storage space that is needed, expanding capacity by adding additional physical hard drives is not a feasible solution. Therefore, in order to estimate the cost of expanding storage capacity, we present two alternatives for server-based storage solutions. For the purposes of this analysis we assume that all law enforcement agencies will need to invest in server-based storage in order to utilize 3D capture technology. However, agencies that already possess sufficient storage capacity will experience larger net benefits by avoiding the costs of additional storage.

The sensitive nature of crime scene evidence necessitates the use of secure servers for data storage. Therefore, we obtained two estimates of the cost of secure server-based storage. The first estimate was produced by the Social Sciences Computing Cooperative at the University of Wisconsin-Madison and features an annual initial cost of $1,050 as well as a per gigabyte storage cost of $1 after the first twenty gigabytes. We used this as our low-end estimate and therefore assume that the annual cost of server-based storage will be at least $1,050.[i] Our second estimate of the cost of server-based storage was obtained from our client, the Learning Environments Lab, and featured an annual total cost of $3,000.[ii] We used this as our high-end estimate of the cost of server-based storage. In order to incorporate both cost estimates into our Monte Carlo analysis, we created a uniform distribution ranging from $1,050 to $3,000.

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[i] Social Sciences Computing Cooperative. (2017, November 22). Personal interview.

[ii] Wisconsin Institute for Discovery Living Environments Lab. (2017, September 18). Personal interview.

Appendix F: Training Costs

Training costs include the reported cost of training and facilitators for each of the two types of 3D scanning technology alternatives being evaluated. The training cost is a one-time cost.

The **LiDAR training session** costs $2,100 for 1 to 2 people.[i] In our calculation we assumed 2 people would be sent to the training. The LiDAR training takes 21 hours (three 7-hour days).[i] Staff must also travel to the LiDAR training location, which is held in either Irving, Texas, or Exton, Pennsylvania.[i] Therefore, the travel cost and time traveling were also included in the LiDAR training session calculation. We estimated a $450 round-trip flight from Madison, Wisconsin to Dallas, Texas and a $200 hotel stay per night for three nights.

Training cost for the LiDAR scanning technology was calculated as follows:

$$\mathit{lidarTrainingCost} = \mathit{lidarSessionCost} + \mathit{lidarTravelCost} + \mathit{lidarOpportunityCostOfficer}$$

where *lidarTrainingCost* is the total cost of the LiDAR training session, which includes *lidarSessionCost*, the cost of the LiDAR training session; *lidarTravelCost*, the cost of the hotel and airfare per person; and *lidarOpportunityCostOfficer*, the compensation the staff will receive while getting paid to go to these trainings.

$$\mathit{lidarTravelCost} = ((\mathit{hotel} * \mathit{numNight}) + \mathit{flight}) * \mathit{numPpl}$$

where numPpl is the number of staff sent to the training, *hotel* is the cost of the stay per night, *flight* is the cost of a round trip flight from Madison, WI, to Dallas, TX, and numN*ight* is the number of nights staying at the hotel.

$$\mathit{lidarOpportunityCostOfficer} = \mathit{CSI\_comp} * \mathit{numPpl} * (\mathit{timeAtLidarTraining} + \mathit{lidarTravelTime})$$

where *CSI_comp* is the compensation rate of the crime scene investigator calculated in Appendix C, *timeAtLidarTraining* is the time staff will spend at the LiDAR training session, and *lidarTravelTime* is the time staff will spend traveling to and from the session.

The **Panoscan PointGun training session** costs $1000 per person. The training takes 16 hours (two 8-hour days). For the Panoscan PointGun scanner, the sales representative comes to train the crime scene investigators at a location near them. The customer has to pay for lodging for the facilitator.[ii] Therefore, the facilitator's lodging cost was also included in the Panoscan PointGun training session calculation. We estimated a $200 hotel stay per night for two nights.

Training cost for the **Panoscan PointGun** was calculated as follows:

panoTrainingCost = panoSessionCost + panoTravelCost + panoOpportunityCostOfficer

where *panoTrainingCost* is the total cost of the Panoscan PointGun training, which includes *panoSessionCost,* the cost of the Panoscan PointGun training session*;* *panoTravelCost*, the cost of lodging for the training representative*;* and *panoOpportunityCostOfficer*, the compensation the staff will receive while getting paid to go to these trainings.

*panoOpportunityCostOfficer = CSI_comp * numPpl * timeAtPanoTraining*

where *CSI_comp* is the compensation rate of the crime scene investigator calculated in Appendix D, *timeAtPanoTraining* is the time staff will spend at the Panoscan PointGun training session, and *lidarTravelTime* is the time staff will spend traveling to and from the session.

We calculated annual costs for the training costs for both technologies by dividing the total cost by the annuity factor. We assumed a 3.5 percent interest rate. The number of periods in the annuity factor reflects the assumed lifetime value of the equipment (Appendix D). This was modeled as a triangular distribution.

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[i] Data provided by the Wisconsin Institute of Discovery, Living Environments Lab
[ii] Data provided by the Dane County Sheriff's Office

Appendix G: Usage Estimates - Homicide Scenes

According to our contacts within the Dane County Sheriff's Office (DCSO), 3D capture devices would primarily be used to recreate homicide scenes because they often require the largest amount of information collection. The following tables describe the number of homicide scenes handled by each law enforcement agency in Dane County, over the past five years and the estimated number of homicides at which the Dane County Sheriff's Office would utilize a 3D capture device in a given year. We modeled the number of homicides with a triangular distribution from the values in **Table 10**.

***Table 9**: Dane County Homicides by Agency*[i]

Agency	2012	2013	2014	2015	2016
Belleville PD	0	0	0	0	0
Blue Mounds PD	0	0	0	0	0
Cottage Grove PD	0	0	0	0	0
Cross Plains PD	0	1	0	0	0
Dane Co Sheriff's Office	**1**	**0**	**2**	**5**	**0**
Dane PD	0	0	0	0	0
DeForest PD	0	0	0	0	0
Fitchburg PD	3	0	2	1	0
Madison PD	3	0	5	6	8
Madison Town PD	0	0	1	0	1
Maple Bluff PD	0	0	0	0	0
Marshall PD	0	0	0	0	0
Mc Farland PD	0	0	0	0	0
Middleton PD	0	5	0	0	0
Monona PD	0	0	0	0	0
Mount Horeb PD	1				
Oregon PD	0	0	0	0	0
Shorewood Hills PD	0	0	0	0	0
Stoughton PD	0	2	0	1	0
Sun Prairie PD	0	0	0	1	0
UW-Madison PD	0	0	0	0	0
Verona PD	0	0	0	0	0
Waunakee PD	0	0	0	0	0
YEARLY TOTALS	**8**	**8**	**10**	**14**	**9**

***Table 10**: Estimated Annual Usage for Homicide Scenes (DCSO)*[ii]

	Low	**Mean**	**High**
Estimate	0	1.6	5

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[i] Wisconsin Department of Justice, Uniform Crime Reporting, accessed Oct 2017.
[ii] *Ibid.*

Appendix H: Usage Estimates – Automobile Crash Scenes

According to our contacts within the Dane County Sheriff's Officer (DCSO), a 3D capture device would only be used to recreate automobile crashes in which the operator of a motor vehicle injures or kills one or more individuals other than himself, due to the fact that these cases generally require the greatest amount of investigation and information. Additionally, the 3D capture devices being evaluated in this study can only be used effectively under certain weather and light conditions. Therefore, we calculate the number of crash scenes at which the DCSO would utilize 3D capture technology as a function of: the number of crashes resulting in a fatality or injury that are handled by the Dane County Sheriff's Office in a given year, the proportion of injury and fatality crashes in Wisconsin that occur during acceptable weather conditions in a given year, and the proportion of injury and fatality crashes in Wisconsin that occur during acceptable light conditions in a given year (light conditions only apply to the Panoscan PointGun).

Number of Injury/Fatality Crashes Handled by the DCSO

The following two tables show the number of injury and fatality crashes handled by the DCSO over the five most recent years for which data are available as well as the estimated number of injury/fatality crashes that the DCSO will handle in a given year.

Table 11: *Annual Injury/Fatality Crashes Handled by the DCSO*[i,ii,iii,iv,v]

Year	Injury Crashes	Fatality Crashes	Total Injury/Fatality Crashes
2013	429	19	448
2012	434	14	448
2011	433	15	448
2010	402	15	417
2009	391	15	406

Table 12: *Estimated Annual Usage for Crash Scenes (DCSO)* [i,ii,iii,iv,v]

	Low	Mean	High
Estimates	406	433.4	448

Proportion of Wisconsin Crashes Involving an Injury/Fatality Caused by another Driver

As stated previously, the Dane County Sheriff's Office would only use a 3D capture device to scan a crash scene if the scene involved an injury or fatality caused by another driver. The Wisconsin Department of Transportation (WI DOT) collects data regarding the type of collision that each reported crash is classified as. We classify a crash as being an appropriate collision type if it involves a collision with another motor vehicle in transit, a pedestrian, a bicycle, a motor vehicle in transport on another roadway, or a train. Based on this classification, the following tables show the proportion of fatality or injury crashes in Wisconsin over the five most recent years for which data are available that are categorized as being an appropriate collision type as well as the estimated number of crashes that will be categorized as being an appropriate collision type in a given year.

Table 13: *Proportion of Annual Injury/Fatality Crashes Categorized as Appropriate Collision Type* [i,ii,iii,iv,v]

Year	Proportion
2013	0.685
2012	0.674
2011	0.673
2010	0.678
2009	0.664

Table 14: *Range of Proportion of Crashes Categorized as Appropriate Collision Type* [i,ii,iii,iv,v]

	Low	Mean	High
Estimates	0.664	0.675	0.685

Proportion of Wisconsin Injury/Fatality Crashes Occurring During Acceptable Weather Conditions

The Wisconsin Department of Transportation (WI DOT) collects data regarding the weather conditions at the time of each reported crash. The weather conditions tracked by the WI DOT include: clear, cloudy, rain, sleet/hail, snow, severe crosswinds, fog/smog/smoke, blowing sand/dirt/snow, other, and unknown. Based on the capabilities of the Panoscan PointGun and the FARO Focus 3D, we have classified clear, cloudy, severe crosswinds, other, and unknown as acceptable weather conditions. Based on this classification, the following tables show the proportion of crashes in Wisconsin that have occurred during acceptable weather conditions over the five most recent years for which data are available as well as the estimated number of crashes that will occur during acceptable conditions in a given year.

Table 15*: Proportion of Annual Injury/Fatality Crashes Occurring During Acceptable Weather Conditions* [i,ii,iii,iv,v]

Year	Proportion
2013	0.815
2012	0.867
2011	0.829
2010	0.865
2009	0.830

Table 16: *Range of Proportion of Crashes Occurring during Appropriate Weather Conditions* [i,ii,iii,iv,v]

	Low	Mean	High
Estimates	0.815	0.841	0.867

Proportion of Wisconsin Injury/Fatality Crashes Occurring During Acceptable Light Conditions

While the FARO Focus 3D is not affected by light conditions, the Panoscan PointGun cannot be utilized outdoors during daylight hours. Therefore, the proportion of crashes occurring during acceptable light conditions is only applicable for the Panoscan PointGun. The Wisconsin Department of Transportation (WI DOT) collects data regarding the light conditions at the time of each reported crash. The light conditions tracked by the WI DOT include: daylight, dark (lit), dark (unlit), dusk, dawn, and unknown. Based on the capabilities of the Panoscan PointGun, we have classified dark (lit), dark (unlit), and dusk as appropriate light conditions for the use of the device. Based on this classification, the following tables show the proportion of crashes in Wisconsin that have occurred during acceptable light conditions over the five most recent years for which data are available as well as the estimated number of crashes that will occur during acceptable conditions in a given year.

Table 17: *Proportion of Annual Injury/Fatality Crashes Occurring During Appropriate Light Conditions* [i,ii,iii,iv,v]

Year	Proportion
2013	0.288
2012	0.291
2011	0.297
2010	0.299
2009	0.311

Table 18*: Range of Proportion of Crashes Occurring during Appropriate Light Conditions* [i,ii,iii,iv,v]

	Low	Mean	High
Estimates	0.288	0.297	0.311

Calculating the Number of Crash Scenes that Can Be Scanned by Each Device

Panoscan PointGun

Pano Appropriate Crash Scenes =
Number of Fatality/Injury Crashes * p_appropriateCollisionType * p_appropriateWeather * p_appropriateLight

Where the “p_” prefix refers to proportion. We modeled the number of a fatality/injury crashes and the three proportions as triangular distributions using values presented in tables 12, 14, 16, and 18.

FARO Focus 3D

FARO Appropriate Crash Scenes =

> Number of Fatality/Injury Crashes * p_appropriateCollisionType * p_appropriateWeather

Where the “p_” prefix refers to proportion. We modeled the number of a fatality/injury crashes and the three proportions as triangular distributions using values presented in tables 12, 14, and 16.

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[i] Wisconsin Department of Transportation. (2010). 2009 Wisconsin Traffic Crash Facts.

[ii] Wisconsin Department of Transportation. (2012). 2010 Wisconsin Traffic Crash Facts.

[iii] Wisconsin Department of Transportation. (2013). 2011 Wisconsin Traffic Crash Facts.

[iv] Wisconsin Department of Transportation. (2014). 2012 Wisconsin Traffic Crash Facts.

[v] Wisconsin Department of Transportation. (2015). 2013 Wisconsin Traffic Crash Facts.

Appendix I: Benefits of Avoided Time Costs

The benefits of avoided time costs, or time savings, were calculated based on the personnel time differences between the traditional method and LiDAR scanning technology method (FARO Focus 3D) and between the traditional method and RGB depth camera technology method (Panoscan PointGun). The time it takes to measure a crime scene includes both on-scene (field) time and in the office ("processing") time. The time savings between these methods was further compared between two different crime scene types, a homicide and a traffic accident, as these are the only types of situations where the technologies would be used by the DCSO. We are assuming that all homicides can be scanned by either scanner but only certain traffic accidents can be scanned (Appendix H).

Number of Staff

The number of staff taking on-scene measurements and processing the measurements can vary depending on the type of scene. For the traditional method, we assume two crime scene investigators will always be taking the measurements on-scene. While crime scene investigators are measuring the scene, patrol officers are also needed to monitor and guard the scene to prevent anyone else from entering. Therefore, the time spent on scene by the patrol officers is also considered in our calculations.

> *numCSI* and *numPatrol* are the number of crime scene investigators taking measurements on-scene or doing the processing work and patrol officers guarding the scene while on-scene measurements are being taken.

Crime Type – Homicide

The data for the homicide traditional method measurement times and the RGB depth camera scanning measurements are based on times provided by the DCSO, and the FARO Focus 3D scanning measurement times are based on two scanning trials conducted by the WID Team. We are able to use the times that measured "Bedroom 1" and "Bedroom 2" at the crime scene education house located in Platteville, Wisconsin, to reflect the two scanning trials.

On-scene measurements

For the **traditional method**, it took 60 minutes to measure Bedroom 1 and 16 minutes to measure Bedroom 2.[i] However, since the traditional method involved two investigators, the scanning time was doubled to represent the total personnel time required (**Table 19**).

***Table 19**: Traditional method on-scene processing times for a homicide*

	Point Estimate	
	minutes	*hours*
Bedroom 1	60	1
Bedroom 2	32	0.534

These values were included in the Monte Carlo as *tradScene 1* and *tradScene2* variables*,* where *tradScene1* is the time it took to measure Bedroom 1 and *tradScene2* is the time it took to measure Bedroom 2 with traditional methods.

For the **FARO Focus 3D**, we used the data from two scanning trials to determine minimum and maximum scanning times for Bedroom 1 and Bedroom 2. We also added together the times of multiple scans used to complete a bedroom for a total scan time. Bedroom 1 took a minimum of 7 minutes and maximum of 30 minutes.[ii] Note that the number of scans taken per room, the number of rooms, and resolution of the scan can further vary the time required to scan a scene (**Table 20**).

***Table 20**: LiDAR on-scene processing times for a homicide*

	Minimum		Maximum		Average	
	minutes	*hours*	*minutes*	*hours*	*minutes*	*hours*
Bedroom 1	7	0.117	30	0.5	18	0.308
Bedroom 2	24	0.4	38	0.63	31	0.516

These values were included in the Monte Carlo as *lidarScene1* and *lidarScene2* variables*,* where *lidarScene1* is the time it took to measure Bedroom 1 and *lidarScene2* is the time it took to measure Bedroom 2 with the LiDAR scanning technology. These scanning time ranges were modeled as triangular distributions.

For the **Panoscan PointGun**, it took 23 minutes to measure Bedroom 1 and 8 minutes to measure Bedroom 2 (**Table 21**).[ii]

***Table 21**: Panoscan Pointgun on-scene processing times for a homicide*

	Point Estimate	
	minutes	*hours*
Bedroom 1	23	0.383
Bedroom 2	8	0.133

These values were included in the Monte Carlo as *panoScene1* and *panoScene2* variables*,* where *panoScene1* is the time it took to measure Bedroom 1 and *panoScene2* is the time it took to measure Bedroom 2 with the Panoscan PointGun.

The **on-scene time difference** between the **traditional method** and the **LiDAR scanning technology** for a homicide was calculated as follows:

lidarDiffTime_1 = tradScene 1 - lidarScene1

where *lidarDiffTime_1* is the difference in scan time between the traditional method and the LiDAR scanning technology for Bedroom 1.

lidarDiffTime_2 = tradScene2 - lidarScene2

where *lidarDiffTime_2* is the difference in scan time between the traditional method and the LiDAR scanning technology for Bedroom 2.

We assume a 50 percent chance that either bedroom will be representative of a crime scene, where *p_scene1* was the probability and was modeled as a Bernoulli distribution.

The **on-scene time difference** between the **traditional method** and the **Panoscan PointGun** for a homicide was calculated as follows:

panoDiffTime_1 = tradScene 1 - panoScene1

where *panoDiffTime_1* is the difference in scan time between the traditional method and the Panoscan PointGun for Bedroom 1.

panoDiffTime_2 = tradScene2 - panoScene2

where *panoDiffTime_2* is the difference in scan time between the traditional method and the Panoscan PointGun for Bedroom 2.

Again, we assume a 50 percent chance that either bedroom will be representative of a crime scene, where *p_scene1* was the probability and was modeled as a Bernoulli distribution.

Processing measurements

For the **traditional method**, processing took 90 minutes (**Table 22**).[i]

Table 22*: Traditional method processing times for a homicide*

	Point Estimate	
	minutes	*hours*
Bedroom 1	90	1.5
Bedroom 2	90	1.5

Where *tradProcessingTime* was the traditional method processing time. This scanning time was modeled as a point estimate.

For the **LiDAR scanning technology**, we were given one processing time for the entire house (instead of specific times per bedroom), so we had to develop a ratio to determine the assumed times to process the scanning of Bedroom 1 and Bedroom 2 (**Table 23**). This ratio was calculated as follows below:

(bedroom 1 scanning time / entire house scanning time) = (unknown bedroom 1 processing time / entire house processing time)

Table 23*: LiDAR processing times for a homicide*

	Minimum		**Maximum**		**Average**	
	minutes	*hours*	*minutes*	*hours*	*minutes*	*hours*
Bedroom 1	3	.052	19	.32	11	.186
Bedroom 2	11	.179	25	.408	18	.294

Where *lidarProcessingScene1* and *lidarProcessingScene2* were the LiDAR scanning technology processing times for Bedroom 1 and Bedroom 2, respectively. These scanning time ranges were modeled as triangular distributions.

For the **Panoscan PointGun**, the processing time took 2 to 3 minutes per scene (**Table 24**).[i]

Table 24*: Panoscan PointGun processing times for a homicide*

	Minimum		**Maximum**		**Average**	
	minutes	*hours*	*minutes*	*hours*	*minutes*	*hours*
Bedroom 1	2	.033	3	.05	2.5	.042
Bedroom 2	2	.033	3	.05	2.5	.042

Where *panoProcessScene* was processing time for both Bedroom 1 and Bedroom 2 with the Panoscan PointGun. These scanning time ranges were modeled as triangular distributions.

The **processing time difference** between the **traditional method** and **the LiDAR scanning technology** for a homicide was calculated as follows:

lidarProcessTimeDiff1 = tradProcessingTime - lidarProcessingScene1

where *lidarProcessTimeDiff1* is the difference in processing time between the traditional method and the LiDAR scanning technology for Bedroom 1.

lidarProcessTimeDiff2 = tradProcessingTime - lidarProcessingScene2

where *lidarDiffTime_2* is the difference in scan time between the traditional method and the LiDAR scanning technology for Bedroom 2.

We assumed a 50 percent chance that either bedroom would be representative of a crime scene, where *p_scene1* was the probability and was modeled as a Bernoulli distribution.

The **processing time difference** between the **traditional method** and the **Panoscan PointGun** for a homicide was calculated as follows:

panoProcessTimeDiff = tradProcessingTime – panoProcessScene

where *panoProcessTimeDiff* is the difference in the processing time between the traditional method and the Panoscan PointGun.

Scene Type – Traffic Accident

The data for the traffic accident scanning times are based on a Tarleton State University study[iii] measuring traffic accident scanning time with the traditional method and LiDAR scanning technology and our own estimates for the Panoscan PointGun.

On-scene measurements

For the **traditional method**, we used data from the Tarleton State University study which measured three traffic accident events. We used these three events to determine minimum and maximum traditional measurement times for a traffic accident, which were 150 minutes and 168 minutes, respectively (**Table 25**).[iii]

***Table 25**: Traditional method on-scene processing times for a car accident*

	Minimum		**Maximum**		**Average**	
	minutes	*hours*	*minutes*	*hours*	*minutes*	*hours*
Traffic Accident	150	2.50	168	2.80	159	2.66

tradAutoTime was the time it took to measure a traffic accident with traditional methods. These processing time ranges were modeled as triangular distributions.

For the **LiDAR scanning technology**, we used data from the Tarleton State University study, which measured three traffic accident events. We used these three events to determine minimum and maximum measurement times for a traffic accident, which were 55 minutes and 84 minutes, respectively (**Table 26**).[iii]

Table 26*: LiDAR on-scene processing times for a car accident*

	Minimum		**Maximum**		**Average**	
	minutes	*hours*	*minutes*	*hours*	*minutes*	*hours*
Traffic Accident	55	.917	84	1.4	70	1.16

lidarAuto was the time it took to measure a traffic accident with LiDAR scanning technology. These processing time ranges were modeled as triangular distributions.

For the **Panoscan PointGun**, we assumed 43 minutes for measuring a traffic accident. Due to lack of data for this technology alternative, we estimated time by applying the ratio of the Panoscan PointGun to the LiDAR scanning technology from the two crime scenes types and processing times to the LiDAR scanning time for an accident (**Table 27**). This calculation was as follows:

Average LiDAR on-scene time for both bedrooms
= (*lidarScene1* + *lidarScene2*) / 2
= (0.308 + 0.516) / 2 = 0.412 hours

Average Panoscan PointGun scanning on-scene time for both bedrooms
= (*panoScene1* + *panoScene2*) / 2
= (0.383 + 0.131) / 2 = 0.257 hours

Ratio of Panoscan PointGun to LiDAR: 0.257 / 0.412 = 0.624 hours
LiDAR average crash scene time: 1.16 hours
Estimated Panoscan PointGun scanning time for crash scene scan: 0.624 * 1.16 = 0.724

Table 27*: Panoscan PointGun method on-scene processing times for a car accident*

	Point Estimate	
	minutes	*Hours*
Traffic Accident	43	0.724

where *panoAuto* was the time it took to measure a traffic accident with Panoscan PointGun.

The **on-scene time difference** between the **traditional method** and the **LiDAR scanning technology** for a traffic accident was calculated as follows:

lidarDiffTime_auto = tradAutoTime - lidarAuto where *lidarDiffTime_auto* is the difference in scan time between the traditional method and the LiDAR scanning technology for a traffic accident.

The **on-scene time difference** between the **traditional method** and the **Panoscan PointGun** for a traffic accident was calculated as follows:

panoDiffTime_auto = tradAutoTime - panoAuto

where *panoDiffTime_auto* is the difference in scan time between the traditional method and the LiDAR scanning technology for a traffic accident.

Processing measurements

For the **traditional method**, processing a traffic accident took a minimum of 44 minutes and a maximum of 60 minutes (**Table 28**).[iii]

***Table 28**: Traditional method processing times for a car accident*

	Minimum		**Maximum**		**Average**	
	minutes	*hours*	*minutes*	*hours*	*minutes*	*hours*
Traffic Accident	44	.733	60	1	54	.911

Where *tradProcessingAuto* was the traditional method processing time.

For the **LiDAR scanning technology**, processing of a traffic accident took a minimum of 15 minutes and a maximum of 40 minutes (**Table 29**).[iii]

***Table 29**: LiDAR processing times for a car accident*

	Minimum		**Maximum**		**Average**	
	minutes	*hours*	*minutes*	*hours*	*minutes*	*hours*
Traffic Accident	15	.25	40	.667	25	.416

Where *LiDARProcessingrAuto* was the time it took to measure a traffic accident with LiDAR scanning technology.

For the **Panoscan PointGun**, we assumed it would take 4 minutes to process a traffic accident. Due to lack of data for this technology alternative, we estimated it by applying the ratio of the Panoscan PointGun processing times to the LiDAR scanning technology processing times to the LiDAR scanning time for an accident. The ratio was obtained from the two scene types and processing times. The calculation is as follows:

Average LiDAR processing time for both bedrooms

= (*lidarScene1* + *lidarScene2*) / 2

= (0.186 + 0.294) / 2 = 0.240 hours

Average Panoscan PointGun processing time for both bedrooms

= (*panoProcessScene* min + *panoProcessScene* max) / 2

= (0.033 + 0.05) / 2 = 0.042 hours

Ratio of Panoscan PointGun to LiDAR: 0.042 / 0.240 = 0.175 hours
LiDAR average crash scene processing time: 0.416 hours
Estimated Panoscan PointGun scanning time for crash scene scan: 0.416 * 0.175 = 0.073 hours

***Table 30**: Panoscan PointGun processing times for a car accident*

	Point Estimate	
	minutes	*hours*
Traffic Accident	4	0.073

Where *panoProcessAuto* was the time it took to measure a traffic accident with the Panoscan PointGun.

The **processing time difference** between the **traditional method** and the **LiDAR scanning technology** for a traffic accident was calculated as follows:

lidarDiffTime_auto = tradAutoTime - lidarAuto

where *lidarDiffTime_auto* is the difference in processing time between the traditional method and the LiDAR scanning technology for a traffic accident.

The **processing time difference** between the **traditional method** and the **Panoscan PointGun** for a traffic accident was calculated as follows:

panoProcessTimeDiffAuto = tradProcessingAuto - panoProcessAuto

where *panoProcessTimeDiffAuto* is the difference in processing time between the traditional method and the Panoscan PointGun for a traffic accident.

Avoided Time Costs Calculation – Homicide

The final avoided time costs for the **LiDAR scanning technology** for a homicide was calculated as follows:

$$
\begin{aligned}
&\mathit{lidarSavingsPerHomicide} \\
&\quad = ((\mathit{lidarProcessTimeDiff1} * \mathit{p\_scene1} + \mathit{lidarProcessTimeDiff2} * (1 - \mathit{p\_scene1})) * \\
&\quad (\mathit{CSI\_comp} + (\mathit{patrol\_comp} * \mathit{numPatrol} / \mathit{numCSI}))) \\
&\quad + \\
&\quad ((\mathit{lidarProcessTimeDiff1} * \mathit{p\_scene1} + \mathit{lidarProcessTimeDiff2} * (1 - \mathit{p\_scene1})) * \\
&\quad \mathit{CSI\_comp})
\end{aligned}
$$

where *lidarSavingsPerHomicide* is the difference in total on-scene and processing personnel compensation from the traditional method and the LiDAR scanning technology for homicides.

The final avoided time costs for the **Panoscan PointGun** for a homicide was calculated as follows:

$$
\begin{aligned}
&\mathit{panoSavingsPerHomicide} \\
&\quad = ((\mathit{panoDiffTime\_1} * \mathit{p\_scene1} + \mathit{panoDiffTime\_2} * (1 - \mathit{p\_scene1})) * \\
&\quad (\mathit{CSI\_comp} + (\mathit{patrol\_comp} * \mathit{numPatrol} / \mathit{numCSI}))) \\
&\quad + \\
&\quad (\mathit{panoProcessTimeDiff} * \mathit{CSI\_comp})
\end{aligned}
$$

where *panoSavingsPerHomicide* is the difference in total on-scene and processing personnel compensation from the traditional method and the Panoscan PointGun technology for homicides.

Avoided Time Costs Calculation – Traffic Accident

The final avoided time costs for the **LiDAR scanning technology** for a traffic accident was calculated as follows:

$$\mathit{lidarSavingsPerAccident} = (\mathit{lidarDiffTime\_auto} + \mathit{lidarProcessTimeDiffAuto}) * \mathit{CSI\_comp}$$

where *lidarSavingsPerAccident* is the difference in total on-scene and processing personnel compensation from the traditional method and the LiDAR scanning technology for a traffic accident.

The final avoided time costs for the **Panoscan PointGun** for a traffic accident was calculated as follows:

$$panoSavingsPerAccident = (panoDiffTime\_auto + panoProcessTimeDiffAuto) * CSI\_comp$$

where p*anoSavingsPerAccident* is the difference in total on-scene and processing personnel compensation from the traditional method and the Panoscan PointGun technology for a traffic accident.

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[i] Data provided by the Dane County Sheriff's Office

[ii] Data provided by the Wisconsin Institute of Discovery, Living Environments Lab

[iii] Rider, R. R. (2017). *The impact of new technology on crash reconstruction* (Doctoral dissertation, Tarleton State University).

Appendix J: Estimating Reduced Traffic Delay Time

We estimate the impact of potential reductions in time spent in traffic by commuters as a function of the difference in time required to scan a scene with a 3D capture device as opposed to traditional methods, the amount of traffic delay caused by a one-minute lane closure, the proportion of crashes occurring on highways versus local roads, and half of the average U.S. worker's hourly compensation.

On-Scene Data Collection Time Differences

The first step in estimating reduced traffic delay time is determining the difference in the amount of time required to scan a crash scene with each 3D capture device and traditional investigation methods (Appendix I). Scanning a crash scene with the Panoscan PointGun is estimated to require less time on average than traditional methods. Therefore, net benefits related to changes in the amount of traffic delay time experienced by commuters will be positive for crash scenes scanned with this device. On the other hand, scanning a crash scene with the FARO Focus 3D is estimated to require more time on average than traditional methods. Therefore, net benefits related to changes in the amount of traffic delay time experienced by commuters will be negative for crash scenes scanned with this device.

Impact of Lane Closure on Traffic Delay Time

According to the National Traffic Incident Management Coalition, each minute a highway lane is closed results in four minutes of total delay for commuters on that roadway.[i] Therefore multiplying difference in the time required to scan a scene by four will provide the change in highway commuter delay time that can be attributed to each device. No such data is currently available regarding the amount of delay caused by a one-minute lane closure on local roads or streets. However, we assume that the amount of delay time per minute of lane closure will be smaller for crashes on local streets and roads than for crashes on highways because local streets and roads generally support fewer vehicles, and there are usually more alternative routes for commuters travelling on local roads than for commuters travelling on highways. Therefore, we estimate the delay time caused by one minute of lane closure on a local road using a triangular distribution with a minimum of one minute, a maximum of four minutes, and a mean of two and a half minutes.

Estimating Usage by Road Type

In order to estimate the potential changes in traffic delay caused by using a 3D capture device, we must first determine how many crashes occur on highways and how many occur on local streets and roads. The Wisconsin Department of Transportation (WI DOT) collects county level data regarding the number of crashes that occur on each type of road. The following tables show the number of injury and fatality crashes occurring on each type of road in Dane County over the five most recent years for which data are available as well as the estimated proportion of injury and fatality crashes that will occur on each type of road in Dane County in a given year.

Table 31: Dane County Injury/Fatality Crashes by Road Type (Count) [ii,iii,iv,v,vi]

Year	Local Street/Road	Highway	Total
2013	1311	1096	2407
2012	1301	1088	2389
2011	1323	1156	2479
2010	1455	1085	2540
2009	1454	1040	2494

Table 32: Dane County Injury/Fatality Crashes by Road Type (Proportion) [ii,iii, iv, v, vi]

	Low	Mean	High
Highways *(County HWY, State HWY, and Interstate)*	0.417	0.444	0.466
Local Roads	0.534	0.556	0.583

We estimate the proportion of crashes occurring on highways and local roads using a triangular distribution for each road type. Each distribution is based on the high, low, and mean values of the proportion of crashes occurring on that type of road. These distributions are then multiplied by the estimated number of crashes scenes that each device would be used for (established in Appendix H) in order to determine how many crash scenes would potentially be scanned with each device on each type of road.

Calculating Changes in Traffic Delay Time

Using the information discussed above, we calculated the change in traffic delay time that would occur by using each device on each road type.

Panoscan PointGun

Pano Change in Traffic Delay_HWY
*= numPanoAccidents * p_HWY * ScanTimeDifference * 4minDelay*

Pano Change in Traffic Delay_Local Roads
*= numPanoAccidents * p_Local Roads * Scan Time Difference * 1to4minDelay*

Pano Total Change in Traffic Delay
= Pano Change in Traffic Delay_HWY + Pano Change in Traffic Delay_Local Roads

Where *numPanoAccidents* is the number of accidents that justify use of the PointGun, *p_HWY* is the proportion of accidents that occur on a highway, *p_LocalRoads* is the proportion of accidents that occur on local roads, *ScanTimeDifference* is the difference between the time it takes to measure a scene with traditional techniques and with the PointGun, and *4minDelay* or *1to4minDelay* represents the traffic delay for every minute of lane closure.

FARO Focus 3D

FARO Change in Traffic Delay_HWY
*= numFAROAccidents * p_HWY * ScanTimeDifference * 4minDelay*

FARO Change in Traffic Delay_Local Roads
*= numFAROAccidents * p_Local Roads * Scan Time Difference * 1to4minDelay*

FARO Total Change in Traffic Delay
= FARO Change in Traffic Delay_HWY + FARO Change in Traffic Delay_Local Roads

Where *numFAROAccidents* is the number of accidents that justify use of the FARO Focus 3D, *p_HWY* is the proportion of accidents that occur on a highway, *p_LocalRoads* is the proportion of accidents that occur on local roads, *ScanTimeDifference* is the difference between the time it takes to measure a scene with traditional techniques and with the FARO Focus 3D, and *4minDelay* or *1to4minDelay* represents the traffic delay for every minute of lane closure

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[i] National Traffic Incident Management Coalition. (2011). Benefits of traffic incident management.
[ii] Wisconsin Department of Transportation. (2010). 2009 Wisconsin Traffic Crash Facts.
[iii] Wisconsin Department of Transportation. (2012). 2010 Wisconsin Traffic Crash Facts.
[iv] Wisconsin Department of Transportation. (2013). 2011 Wisconsin Traffic Crash Facts.
[v] Wisconsin Department of Transportation. (2014). 2012 Wisconsin Traffic Crash Facts.
[vi] Wisconsin Department of Transportation. (2015). 2013 Wisconsin Traffic Crash Facts.

Appendix K: Estimating Crime Scene Investigator's Willingness to Pay for More Complete Data

According to our contacts in the Dane County Sheriff's Office, one of the largest benefits of using 3D capture technology to recreate crime scenes, particularly homicide scenes, is the fact that it provides very large amounts of data that can easily be accessed in the future if necessary. This is significant because investigators do not always know what information will be important to the investigation when they are evaluating the scene. In comparison, traditional methods of diagramming crime scenes are very time intensive and are therefore only used to create basic reconstructions of a scene. In order to estimate the value of the more complete information provided by 3D capture technology, we distributed the following elicitation to a crime scene investigator employed by the Dane County Sheriff's Office. We asked the respondent to choose an amount of personnel time that he or she would be willing to invest in the scene diagramming process using traditional methods, assuming that that amount of time would yield the same amount of information provided by 3D capture technology.

Elicitation Text

Scenario: You are responsible for allocating personnel in order to obtain measurements and diagrams of a homicide scene. **The standard physical measurements of important scene characteristics have already been taken.**

Imagine that you could match the amount of data gathered by the Panoscan by committing more time to taking physical measurements. How much time and personnel resources would you be willing to invest in order to obtain the same amount of data that is collected by the Panoscan? In this hypothetical situation, allocating additional time to mapping the crime scene will ensure you have measurements that were initially considered unimportant but might be important in the future.

REMEMBER that assigning personnel to this task means that they are unavailable for other tasks like investigating other crimes, responding to calls, or going out on patrol. Please be as realistic as possible.
Choose the largest amount of resources that you would be willing to commit **if the amount of time listed would provide the same amount of data as the Panoscan**. Assume that taking additional measurements at the scene will require one crime scene investigator and two crime scene guards.

Think about the options in this way: "I would invest _____ hours of resources into taking additional physical measurements if it provided the same level of information as the Panoscan."

☐ No additional resources
☐ 2 hours in a single day
☐ 4 hours in a single day
☐ 6 hours in a single day
☐ 8 hours in a single day
☐ 10 hours over two days
☐ 12 hours over two days
☐ 14 hours over two days
☐ 16 hours over two days
☐ 18 hours over three days
☐ 20 hours over three days
☐ 22 hours over three days
☐ 24 hours over three days
☐ 26 hours over four days
☐ 28 hours over four days
☐ 30 hours over four days
☐ 32 hours over four days

Willingness to Pay (WTP) Calculation

The single response to the elicitation revealed that the investigator would be willing to invest ten hours of investigator time over two days, assuming that this amount of time would yield the same amount of information provided by 3D capture technology. We estimate the monetary value of this investment as a function of time spent on-scene by the investigator, the hourly compensation of an investigator, the time spent-on scene by two patrol officers assigned to guard the scene, and the hourly compensation of a patrol officer. Two patrol officers must be onsite to guard the crime scene at all times in order to preserve the integrity of the scene.

- Investigator Time On-Scene: Ten hours, determined by the elicited response.
- Crime Scene Investigator Hourly Compensation (CSI-Comp): We estimate hourly compensation for a crime scene investigator using a range between $27.87 per hour and $86.61 per hour (Appendix C).
- Patrol Officer Time On-Scene: Two patrol officers are required to be on-site for as long as the scene is active. We assume that ten hours of measuring and diagramming over two days will require the scene to remain open for a total of twenty-six hours. This assumption is based on eight hours of diagramming to be completed on day one, two hours of diagramming to be completed on day two, and eighteen hours of time during which the scene must be guarded overnight between day one and day two. This twenty-six-hour time period must them be multiplied by the number of patrol officers that are required to be on-site at all times (two). The total estimated number of hours spent on-site by patrol officers will be fifty-two hours.

- Patrol Officer Hourly Compensation (Patrol_Comp): We estimate hourly compensation for a patrol officer using a range between $22.60 per hour and $65.03 per hour (Appendix C).

The following equation illustrates the steps required to monetize the cost of committing ten additional hours to the on-scene measuring and diagramming process:

$$\text{Investigator WTP} = 10 \text{ hours} * \text{CSI\_Comp} + 26 \text{ hours} * \text{Patrol\_Comp} * 2 \text{ Patrol Officers}$$

The results of this calculation can be found below in **Table 33**.

Table 33: *Mean Willingness to Pay for More Complete Data per Homicide. Values are in dollars.*

	Minimum	Maximum	Mean
Information Value	1,459	4,240	2,852

It is important to remember that this elicitation was only administered to a single respondent and is therefore a very rough estimate of the value of additional information.

Appendix L: Supplementary Cost and Benefit Figures

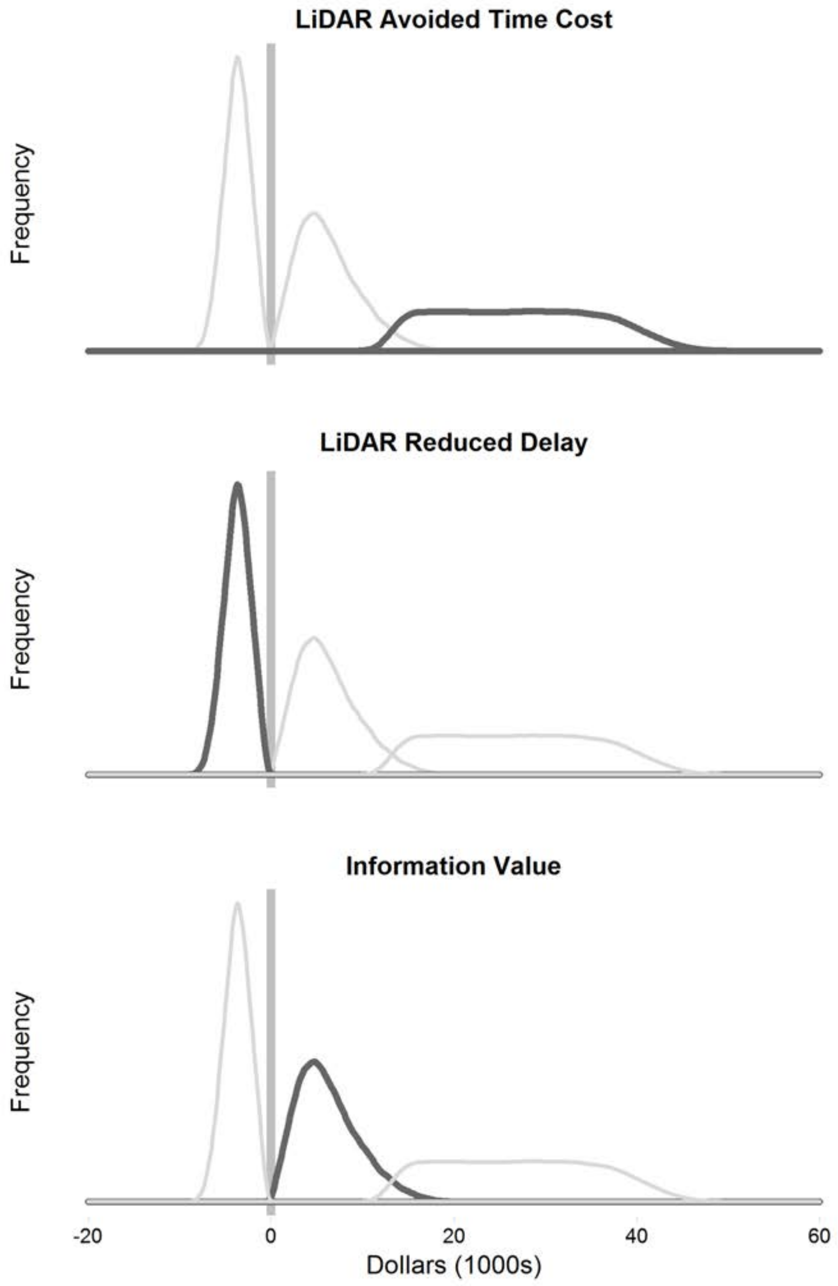

***Figure 6**: Individual benefits for the FARO Focus 3D LiDAR scanner. Dollar amounts are on the x-axis, and the frequency of Monte Carlo trials (n = 100,000) is on the y-axis. The benefit corresponding to each panel's title is represented by a thicker line. The vertical grey line marks $0.00.*

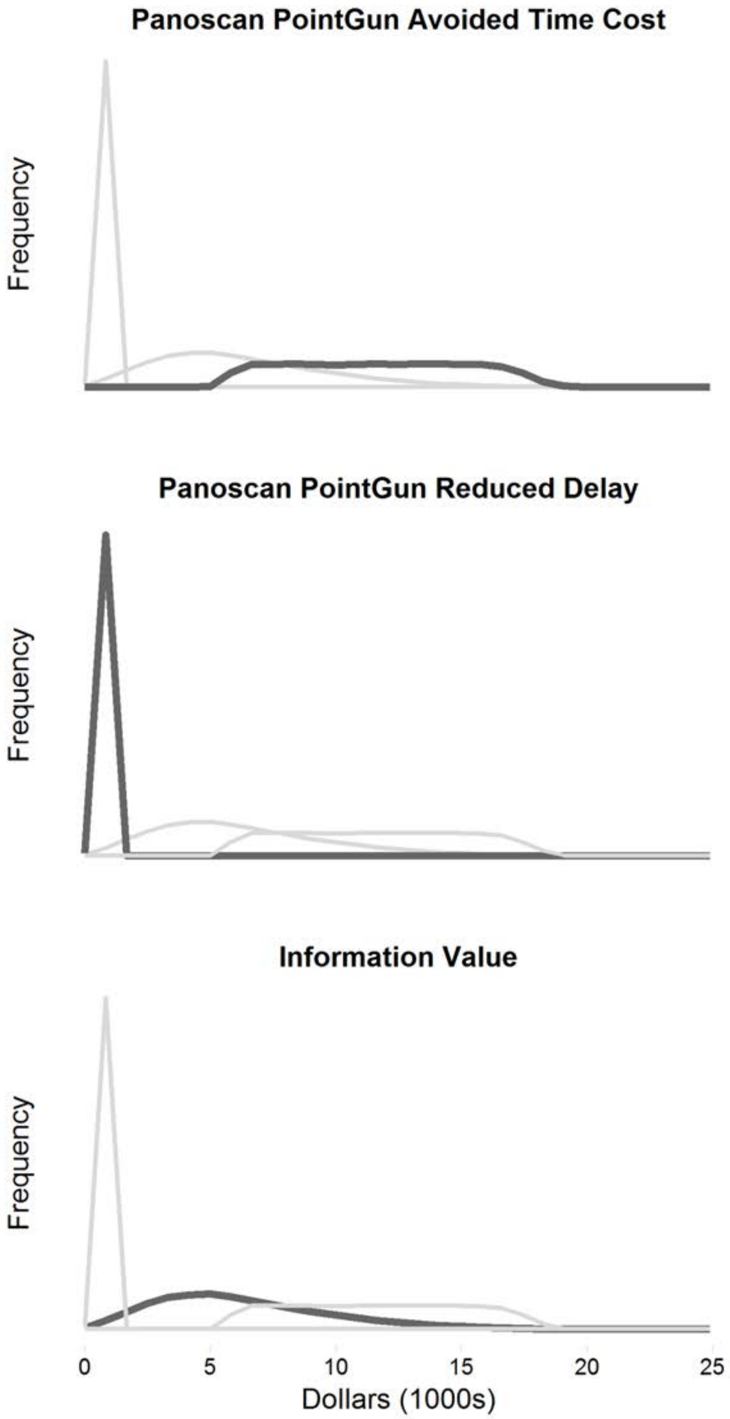

***Figure 7**: Individual benefits for the Panoscan PointGun scanner. Dollar amounts are on the x-axis, and the frequency of Monte Carlo trials (n = 100,000) is on the y-axis. The benefit corresponding to each panel's title is represented by a thicker line.*

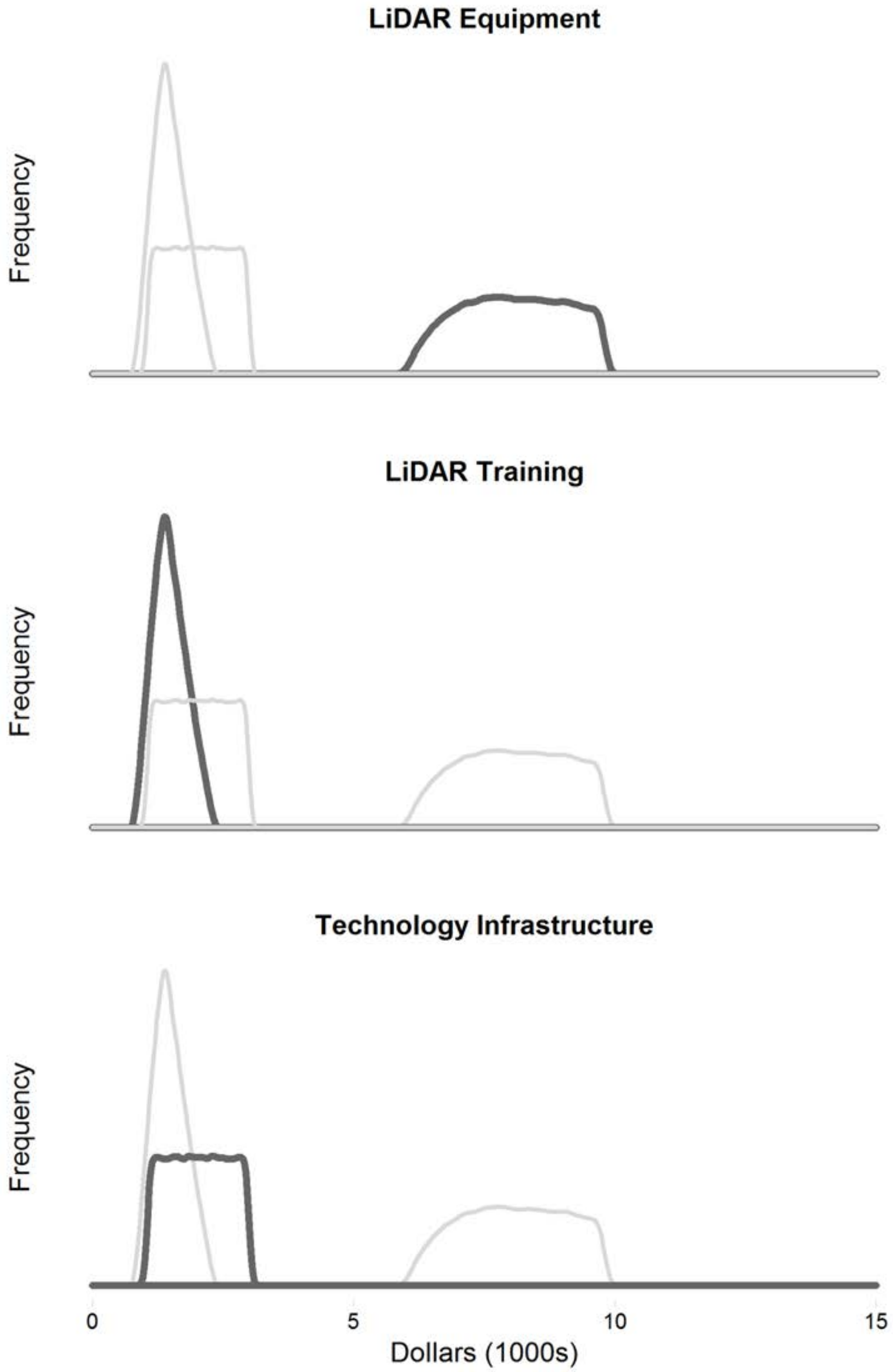

***Figure 8**: Individual costs for the FARO Focus 3D LiDAR scanner. Dollar amounts are on the x-axis, and the frequency of Monte Carlo trials (n = 100,000) is on the y-axis. The cost corresponding to each panel's title is represented by a thicker and darker line.*

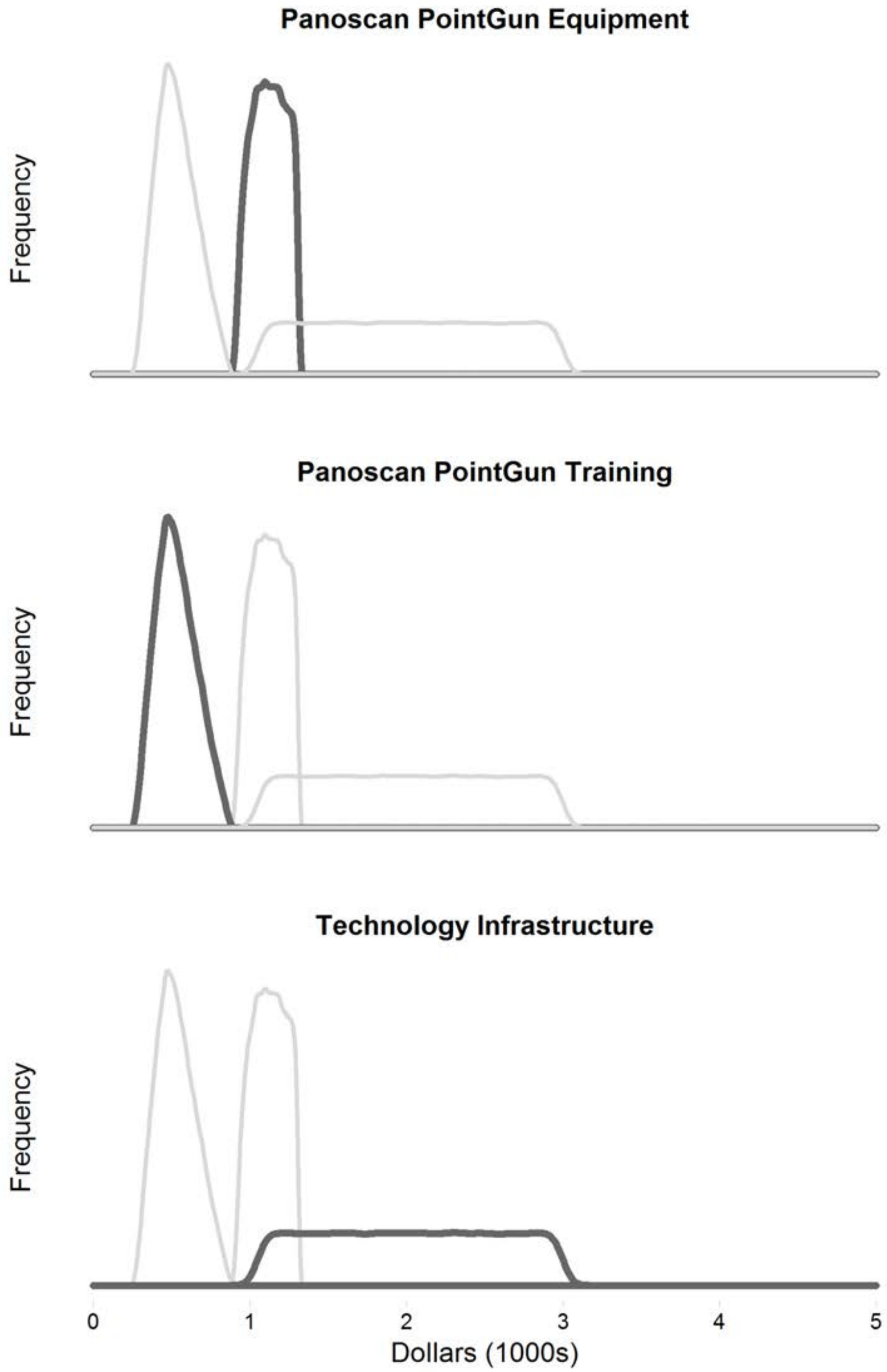

***Figure 9**: Individual costs for the Panoscan PointGun scanner. Dollar amounts are on the x-axis, and the frequency of Monte Carlo trials (n = 100,000) is on the y-axis. The cost corresponding to each panel's title is represented by a thicker and darker line.*

Appendix M: R Code for Monte Carlo Simulation

```
# libraries
library(ggthemes)
library(gridExtra)
library(tidyverse)

#~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
# Monte Carlo Simulation - number of iterations
ITER <- 100000

# Random number generator seed
set.seed(123)

#~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
# Triangular Distribution Function ~~~~~~~~~~
  # Create a triangular distribution for the given values:
  # Enter the minimum, maximum, and mode of the desired triangular distribution
  # Also, enter the number of iterations for the Monte Carlo simulation
  # Returns a variable "triDist" with a numITER number of values corresponding
  # to a triangular distribution

makeTriDist <- function(min, max, mode, numITER) {
  # density function midpoint
  midpoint <- (mode - min) / (max - min)

  # generate triangular distribution variable: multiply by uniform dist.
  tempUniform <- runif(numITER, min = 0, max = 1)
  triDist <- ifelse(tempUniform < midpoint,
                    min + sqrt(tempUniform * (mode - min) * (max - min)),
                    max - sqrt((1 - tempUniform) * (max - mode) * (max - min))
                   )

  return(triDist)
}

#~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
# Annual Value Function:
#   - calculates the annual value of item based on expected lifetime and
#     interest rate
#
# Inputs:
#   totalValue: total cost and benefit that needs to be converted to an annual
#               value
#   lifetime: length in years that the cost or benefit is expected to last
#   interestRate: interest rate to use in the annuity factor (as a decimal)
#
# Return:
#   annualValue: the annual value of the cost or benefit

calcAnnualValue <- function(totalValue, lifetime, interestRate){
  annuityFactor <- (1 - (1 + interestRate) ^ (-lifetime)) / interestRate
  annualValue <- totalValue / annuityFactor

  return(annualValue)
}

###############################################################################
#
#       VARIABLE SETUP
#
###############################################################################
```

```
#~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
# BENEFITS
#~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

# 1. Avoided Time Costs ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
#     Assumptions:
#       - For the traditional diagraming method in Dane County, we assume 2
#         crime scene investigators will always be taking the measurmements.
#         This matters when measuring the time spent by patrol officers.
#         If it takes 3 hours for 2 CSI officers to measure a scene, the patrol
#         officers will spend 3 hours at the scene.  However, if only 1 CSI
#         officer measured the scene, he/she would be there for 6 hours, which
#         would require the presence of a patrol officer for 6 hours.
#       - We are assuming that all homicides can be scanned by either scanner.

#   ~ Traditional techniques measurement times (hours)
#       For 2 people it takes: 0.5hrs for scene 1 and 0.267 hours for scene 2
#       To get the total personnel time, we multiply those by 2
        tradScene1 <- 1
        tradScene2 <- 0.534

        # We have the time it takes three people to scan an accident scene
        # min = 0.833, max = 0.933, ave = 0.887
        # times 3 personnel: min = 2.499 , max = 2.799, mode = 2.661
        tradAutoTime <- makeTriDist(min = 2.499, max = 2.799, mode = 2.661, ITER)

#   ~ LiDAR Time Differences (hourly)
#       lidarDiffTime_1: difference in scan time between traditional and LiDAR
#                        for bedroom 1
        lidarScene1 <- makeTriDist(min = 0.117, max = 0.5, mode = 0.308, ITER)
        lidarDiffTime_1 <- tradScene1 - lidarScene1

#       lidarDiffTime_2: difference in scan time between traditional and LiDAR
#                        for bedroom 2
        lidarScene2 <- makeTriDist(min = 0.4 , max = 0.63 , mode = 0.516, ITER)
        lidarDiffTime_2 <- tradScene2 - lidarScene2

#       probability of scene 1: we assume that there is a 50% chance that either
#       bedroom will be representative of a crime scene
        p_scene1 <- rbinom(ITER, 1, p = 0.5)

#       lidarDiffTime_auto: difference in scan time between traditional and
#                           LiDAR for a traffic accident #numbers from study
        lidarAuto <- makeTriDist(min = 0.917, max = 1.4, mode = 1.16, ITER)
        lidarDiffTime_auto <- tradAutoTime - lidarAuto

#       lidarProcessTimeDiff: difference in post-measurement processing of
#                             information between traditional and LiDAR
#                             measurements (hours)
          tradProcessingTime <- 1.5 # processin gtime for one scene
          # processingtime for an accident information
          tradProcessingAuto <- makeTriDist(min = 0.733, max = 1, mode = 0.911, ITER)

          lidarProcessingScene1 <-
              makeTriDist(min = 0.052, max = 0.32, mode = 0.186, ITER)
          lidarProcessingScene2 <-
              makeTriDist(min = 0.179, max = 0.408, mode = 0.294, ITER)
          lidarProcessingAuto <-
            makeTriDist(min = 0.25, max = 0.667, mode = 0.416, ITER)

          lidarProcessTimeDiff1 <- tradProcessingTime - lidarProcessingScene1
          lidarProcessTimeDiff2 <- tradProcessingTime - lidarProcessingScene2
          lidarProcessTimeDiffAuto <- tradProcessingAuto - lidarProcessingAuto

#   ~ Panoscan Time Differences (hourly)
#       panoDiffTime_1: difference in scan time between traditional and Panoscan
```

```
#                       for scene 1
        panoScene1 <- 0.383
        panoDiffTime_1 <- tradScene1 - panoScene1

#       panoDiffTime_2: difference in scan time between traditional and Panoscan
#                       for scene 2
        panoScene2 <- 0.133
        panoDiffTime_2 <- tradScene2 - panoScene2

#       panoDiffTime_auto:  difference in scan time between traditional and
#                           Panoscan for a traffic accident
#         We don't have scan times for the Panoscaner for an accident, so we
#         are going to apply the ratio of the Panoscan to LiDAR scan from the
#         two crime scenes and processing times to the LiDAR scanning time for
#         an accident.
#
#         Average LiDAR time for two scenes (0.308 + 0.516) / 2 = 0.412
#         Average Panoscan time for two scenes (0.383 + 0.131) / 2 = 0.257
#         Ratio of pano to Lidar: 0.257 / 0.412 = 0.624
#         LiDAR average crash scene time: 1.16
#         Estimated Pano time for crash scene scan: 0.624 * 1.16 = 0.724

        panoAuto <- 0.724
        panoDiffTime_auto <- tradAutoTime - panoAuto

#       panoProcessTimeDiff: difference in post-measurement processing of
#                            information between traditional and Panoscan
#                            measurements
#           The Panoscan processing time is the same for the two scenes
#           trad: 1.5hrs (for processing crime scene)
#           Pano, low: 0.033, high: 0.05, average: 0.0415 (for processing crime scene)
        panoProcessScene <- makeTriDist(min = 0.033, max = 0.05, mode = 0.042, ITER)
        panoProcessTimeDiff <- tradProcessingTime - panoProcessScene

#         We don't have processing times for the Panoscaner for an accident, so we
#         are going to apply the ratio of the Panoscan to LiDAR processing times
#         to the LiDAR processing time for an accident to get the Panoscan processing
#         time for an accident.
#
#         Average LiDAR time for processing (0.186 + 0.294) / 2 = 0.0.240
#         Panoscan time for processing 0.042
#         Ratio of pano to Lidar: 0.042 / 0.240 = 0.175
#         LiDAR average crash scene procesing time: 0.416
#         Estimated Pano time for crash scene scan: 0.416 * 0.175 = 0.073
        panoProcessAuto <- 0.073
        panoProcessTimeDiffAuto <- tradProcessingAuto - panoProcessAuto

#   ~ Compensation rates for personel (hourly)
#       CSI_comp: Hourly compensation rate (includes benefits) for a CSI
#                 investigator (national estimate from BLS)
#           low: 27.87, high: 86.61, average: 53.79
        CSI_comp <- runif(ITER, min = 27.87, max = 86.61)

#       numCSI: Number of CSI investigators taking traditional measurements
        numCSI <- 2

#       patrol_comp:  Hourly compensation rate for a patrol officer who would
#                     guard the crime scene (only factored into homicides)
#           low: 22.60, high: 65.03, average: 41.42
        patrol_comp <- runif(ITER, min = 22.6, max = 65.03)

#       numPatrol:  Number of patrol officers gurarding the scene
        numPatrol <- 2

#   ~ Number of Homicides
#       numHomicides: number of homicides in Dane Co.
```

```
#       last five years: high = 5, low = 0, ave = 1.6
        numHomicides <- makeTriDist(min = 0, max = 5, mode = 1.6, ITER)

#   ~ Number of Accidents
#       totalAccidents: Total number of accidents in Dane County averaged over
#                       a five year period. From looking at the statistics,
#                       there seems to be a plateau in the accident numbers
#                       over this period.
#       last five years accidents with injury or fatality handled by Dane Co.:
        totalAccidents <- makeTriDist(min = 406, max = 448, mode = 433.4, ITER)

#     Factors affecting scanner use for accidents:
#       p_appropriateCollision: Dane Co. Sheriff's Office will only use scanners
#           for particular kinds of accidents
#         Proportion of accidents that are a:
#          - collision with another vehicle
#          - collision with a pedestrian
#          - collision with a bicycle
#          - collision with a motor vehicle in transport on another roadway
#          - collision with a train
        p_appropriateCollision <- makeTriDist(min = 0.664, max = 0.685, mode = 0.675, ITER)

#       p_goodWeatherAccid:  Proportion of accidents that happen in non-inclement
#                       weather. Scanners cannot be used in the rain or other
#                       bad weather.
        p_goodWeatherAccid <- makeTriDist(min = 0.815, max = 0.867, mode = 0.841, ITER)

#       p_nightAccid: Proportion of accidents that happen at night. The
#                   Panoscan scanner cannot be used in the daytime unless a
#                   vehicle is towed to a garage.
        p_nightAccid <- makeTriDist(min = 0.288, max = 0.311, mode = 0.297, ITER)

#     Scanner-specific number of accidents:
#       lidarNumAccidents:  number of accidents for which a LiDAR scanner
#                           would be used
        lidarNumAccidents <-
              totalAccidents * p_appropriateCollision * p_goodWeatherAccid

#       panoNumAccidents: number of accidents for which a Panoscan scanner
#                         would be used (cannot be used during the day)
        panoNumAccidents <-
              totalAccidents * p_appropriateCollision *
              p_goodWeatherAccid * p_nightAccid

# Avoided Time Costs Calculation ~~~~~~~~~~~~~~~~~~
# LiDAR - Dollar amount of saved over year
  # Homicides
  lidarSavingsPerHomicide <-
    # scanning savings
    ((lidarDiffTime_1 * p_scene1 + lidarDiffTime_2 * (1 - p_scene1)) *
      (CSI_comp + (patrol_comp * numPatrol / numCSI))
    ) +
    # Processing Savings
    ((lidarProcessTimeDiff1 * p_scene1 + lidarProcessTimeDiff2 * (1 - p_scene1)) *
      CSI_comp)

  # Per accident dollar savings for Panoscan
  lidarSavingsPerAccident <-
      (lidarDiffTime_auto + lidarProcessTimeDiffAuto) * CSI_comp

# Panoscan
  # Homicides
  panoSavingsPerHomicide <-
    # savings from scan time differences
    ((panoDiffTime_1 * p_scene1 + panoDiffTime_2 * (1 - p_scene1)) *
      (CSI_comp + (patrol_comp * numPatrol / numCSI))
```

```
    ) +
    # savings from processing time differences
    (panoProcessTimeDiff * CSI_comp)

  # Savings ($) per Accident
  panoSavingsPerAccident <- (panoDiffTime_auto + panoProcessTimeDiffAuto) * CSI_comp


# 2. Reduced traffic delay due to more rapid accident processing
#     Assumptions:
#       - We are assuming that the people on the road are commuters and not
#         business travelers.  Compensation for business travelers would be
#         counted at 100% of compensation value, whereas compensation for
#         commuters is counted as 50% of the full compensation value.
#       - For local traffic delay due to a lane closure, we assume the
#         length of delay is somewhere between 1 and 4 minutes with an average
#         of 2.5 (1+4 / 2).  The 4 comes from the average highway delay
#
# hwy_delayTime:  Multiplying factor
#                 For x min a lane is closed a total of delayTime minutes
#                 occurs - averaged of all people (convert to hours)
#                 We found a reference for 4 minutes of delay for every minute
#                 of highway lane closure.
  hwy_delayTime <- 4

# local_delayTime:  For x min a lane is closed a total of delayTime minutes
#                   occurs - averaged of all people (convert to hours)
#                   We assumed some time between 1 min and the hwy delay time (4)
  local_delayTime <- makeTriDist(min = 1, max = 4, mode = 2.5, ITER)

# avg_comp: Average compensation of a person on the road
  avg_comp <- 35.28

# Probability of accident by road type
#   p_hwyAccid: probability of a highway accident
    p_hwyAccid <- makeTriDist(min = 0.417, max = 0.466, mode = 0.444, ITER)

#   p_localAccid: probability of a local road accident
    p_localAccid <- 1 - p_hwyAccid

# Length of time spent at crash scene for diagraming
    tradAutoTimeAtScene <-
      makeTriDist(min = 0.833, max = 0.933, mode = 0.887, ITER)

# Difference in time spent at scene for the two technologies
    lidarDiffTimeOnRoad <- tradAutoTimeAtScene - lidarAuto
    panoDiffTimeOnRoad <- tradAutoTimeAtScene - panoAuto

# Dollar value of savings due to reduced traffic delay
  # Delay broken down by highway or local road
  lidarReducedDelay_hwy <-  lidarNumAccidents * p_hwyAccid * hwy_delayTime *
                            avg_comp * 0.5 * lidarDiffTimeOnRoad
  lidarReducedDelay_local <- lidarNumAccidents * p_localAccid * local_delayTime *
                             avg_comp * 0.5 * lidarDiffTimeOnRoad

  panoReducedDelay_hwy <-  panoNumAccidents * p_hwyAccid * hwy_delayTime *
                            avg_comp * 0.5 * panoDiffTimeOnRoad
  panoReducedDelay_local <- panoNumAccidents * p_localAccid * local_delayTime *
                             avg_comp * 0.5 * panoDiffTimeOnRoad

# Reduced delay value per accident
# In the case of the LiDAR technology the value is negative: officers are on
# the scene longer doing LiDAR scans than they are when taking traditional
# measurements. Three people take the traditional measurements meaning that the
# traffic lane isn't closed as long even though more total person time is spent
# at the scene
```

```
  lidarReducedDelayPerAccident <- avg_comp * 0.5 * lidarDiffTimeOnRoad *
    ((p_hwyAccid * hwy_delayTime) + (p_localAccid * local_delayTime))
    # roughly -$30 to 0 per accident

  panoReducedDelayPerAccident <- avg_comp * 0.5 * panoDiffTimeOnRoad *
    ((p_hwyAccid * hwy_delayTime) + (p_localAccid * local_delayTime))
    # roughly $5 to $15 per accident

# 3. Willingness to pay for extra information
#     Value of having the additional information a scan provides for future use.
#     We are only applying this to homicides

  # Willingess to invest 10 CSI investigator hours to gather extra information
  CSIhours <- 10

  # Willingness to invest 2 patrol officers to guard scene over two day period
  # Full first day and 2 hours the next day

  patrolHours <-
    # Two patrol officers
    2 * (
      # Full days on site (10/8 = 1.25 = 1 fll day * 24 hours = 24 hours)
      ((10 %/% 8) * 24) +
      # Remaining hours (remainder of 10/8 = 2 hours)
      (10 %% 8)
    ) # Total of 52 hours (26 hours * 2 patrol officers)

  informationValuePerHomicide <- (CSIhours * CSI_comp) + (patrolHours * patrol_comp)

#~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
# COSTS
# ** Annual values are calculated later in the code **

# 1. Hardware
#   Computer, estimated lifetime 5 years - annual value is calculated later
#   Pano does not need special computer
    lidarComputerCost <- 2500

#   Scanner: cost of FARO scaner and supporting equipment (tripod, battery)
    lidarScannerCost <- 37730
    lidarScannerLifetime <- makeTriDist(min = 5, max = 10, mode = 5, ITER)

    panoScannerCost <- 4000
    panoScannerLifetime <- makeTriDist(min = 5, max = 10, mode = 5, ITER)

#   Software - Lidar: 3 yr lifetime, 2 yrs for Panoscan
    lidarSoftwareCost <- 2490
    panoSoftwareCost <- 800

# 2. Tech Infrastructure - contracting services out
#   We have two estimates for the infrastructure:
#   a low of 1050 per year and a high of 3000 per year
    techInfraCost <- runif(ITER, min = 1050, max = 3000)

# 3. Training - in USD - one time cost
    lidarSessionCost <- 2100
    panoSessionCost <- 1000
    timeAtLidarTraining <- 21 # hours
    timeAtPanoTraining <- 16 # hours

    # Travel cost LiDAR - CSI investigators have to travel for the LiDAR training
    lidarTravelTime <- 8 * 2 # hours of work missed because of travel 8hr * 2 days
    flight <- 450 # round trip flight to Texas
    hotel <- 200
    numPpl <- 2 # number of CSI investigators receiving training
```

```
    lidarTravelCost <- ((hotel * 3) + flight) * numPpl # 3 days of lodging

    # For the panoscanner, the sales representative comes to train the CSI investigators
    panoTravelCost <- hotel # session includes travel cost of training rep

    # Opportunity cost of not being at work
    lidarOpportunityCost <-
        CSI_comp * numPpl * (timeAtLidarTraining + lidarTravelTime)
    panoOpportunityCost <-
        CSI_comp * numPpl * timeAtPanoTraining

################################################################################
#
#   BENEFITS AND COSTS
#
################################################################################

# Benefits ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
# 1. Avoided Time Cost Savings

  # LiDAR
  lidarHomicideTimeSavings <- numHomicides * lidarSavingsPerHomicide
  lidarAccidentTimeSavings <- lidarNumAccidents * lidarSavingsPerAccident
  lidarTimeSavings <- lidarHomicideTimeSavings + lidarAccidentTimeSavings

  # Panoscan
  panoHomicideTimeSavings <- numHomicides * panoSavingsPerHomicide
  panoAccidentTimeSavings <- panoNumAccidents * panoSavingsPerAccident
  panoTimeSavings <- panoHomicideTimeSavings + panoAccidentTimeSavings

# 2. Reduced Delay Savings
  lidarReducedDelay <- lidarNumAccidents * lidarReducedDelayPerAccident
  panoReducedDelay <- panoNumAccidents * panoReducedDelayPerAccident

# 3. Information Value Benefits - applies to LiDAR and Panoscan
  infoValue <- numHomicides * informationValuePerHomicide

# Costs ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

intRate <- 0.035  # interest rate of 3.5%

# 1. Hardware/Software
  # Computer - only applies to LiDAR scans which need more computing power
  lidarAnnualCompCost <-
      calcAnnualValue(totalValue = lidarComputerCost,
                      lifetime = 5, interestRate = intRate )

  # Scanner
  lidarAnnualScannerCost <-
      calcAnnualValue(totalValue = lidarScannerCost,
                      lifetime = lidarScannerLifetime, interestRate = intRate)

  panoAnnualScannerCost <-
      calcAnnualValue(totalValue = panoScannerCost,
                      lifetime = panoScannerLifetime, interestRate = intRate)

  # Software
  lidarAnnualSoftwareCost <-
      calcAnnualValue(totalValue = lidarSoftwareCost,
                      lifetime = 3, interestRate = intRate)

  panoAnnualSoftwareCost <-
      calcAnnualValue(totalValue = panoSoftwareCost,
                      lifetime = 2, interestRate = intRate)

  # Total Equipment Costs
```

```
  lidarEquipment <-
    lidarAnnualCompCost + lidarAnnualScannerCost + lidarAnnualSoftwareCost

  panoEquipment <- panoAnnualScannerCost + panoAnnualSoftwareCost

# 2. Technology Infrastructure Costs
  # techInfraCost - calculated above

# 3. Training Costs
  lidarTotalTrainingCost <- lidarSessionCost + lidarTravelCost + lidarOpportunityCost
  # Annual Cost
  lidarTrainingCost <- calcAnnualValue(totalValue = lidarTotalTrainingCost,
                                       lifetime = lidarScannerLifetime,
                                       interestRate = intRate)

  panoTotalTrainingCost <- panoSessionCost + panoTravelCost + panoOpportunityCost
  # Annual Cost
  panoTrainingCost <- calcAnnualValue(totalValue = panoTotalTrainingCost,
                                      lifetime = panoScannerLifetime,
                                      interestRate = intRate)

################################################################################
#
#     TOTAL BENEFITS AND COSTS
#
################################################################################

# LiDAR
  lidarBenefits <- lidarTimeSavings + infoValue + lidarReducedDelay
                                                # lidarReducedDelay is negative

    # CI: Range of values that capture 95% of the data points
    lidarBenefits_CI <- quantile(lidarBenefits, c(0.025, 0.975))
    lidarTimeSavings_CI <- quantile(lidarTimeSavings, c(0.025, 0.975))
    infoValue_CI <- quantile(infoValue, c(0.025, 0.975))
    lidarReducedDelay_CI <- quantile(lidarReducedDelay, c(0.025, 0.975))

  lidarCosts <- lidarEquipment + techInfraCost + lidarTrainingCost
    lidarCosts_CI <- quantile(lidarCosts, c(0.025, 0.975))
    lidarEquipment_CI <- quantile(lidarEquipment, c(0.025, 0.975))
    techInfraCost_CI <- quantile(techInfraCost, c(0.025, 0.975))
    lidarTrainingCost_CI <- quantile(lidarTrainingCost, c(0.025, 0.975))

  # Annual net benefits for the LiDAR scanner
  NB_lidar <- lidarBenefits - lidarCosts
    NB_lidar_CI <- quantile(NB_lidar, c(0.025, 0.975))

  # Percent of trials below 0
  lidarTrialsBelow0 <- length(NB_lidar[NB_lidar < 0]) # Number of Trials below 0
  (lidarTrialsBelow0 / ITER) * 100  # Percent of trials below 0, 1.255%

# Panoscan
  panoBenefits <- panoTimeSavings + panoReducedDelay + infoValue
    panoBenefits_CI <- quantile(panoBenefits, c(0.025, 0.975))
    panoReducedDelay_CI <- quantile(panoReducedDelay, c(0.025, 0.975))
    panoTimeSavings_CI <- quantile(panoTimeSavings, c(0.025, 0.975))

  panoCosts <- panoEquipment + techInfraCost + panoTrainingCost
    panoCosts_CI <- quantile(panoCosts, c(0.025, 0.975))
    panoEquipment_CI <- quantile(panoEquipment, c(0.025, 0.975))
    panoTrainingCost_CI <- quantile(panoTrainingCost, c(0.025, 0.975))

  # Annual net benefits for the Panoscan scanner
  NB_pano <- panoBenefits - panoCosts
    NB_pano_CI <- quantile(NB_pano, c(0.025, 0.975))
```

```
################################################################################
#
#     SENSITIVITY ANALYSIS
#     Break-even values for homicides and accidents
#
################################################################################

# What is the fewest number of hommicides or accidents the DCSO would need to
# handle per year to break even with the costs?

avgLidarCost <- mean(lidarCosts)  # $ 11572.07
avgPanoCost <- mean(panoCosts)  # $ 3678.452

# Homicides ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
#
# Analysis 1:     Break even annual number of homicides if no accidents were
#                 processed with a scanner
#
#   Sub-analysis: With and without the information value benefit
# ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

# LiDAR ~~~~~~~~~~~~~~~~~~~~~~~
  # With information value
    lidarAvgBenefitPerHomicide <-
      mean(lidarSavingsPerHomicide + informationValuePerHomicide)

    L_h1 <- ceiling(avgLidarCost / lidarAvgBenefitPerHomicide)

  # WITHOUT information value
    lidarAvgBenefitPerHomicide_noInfoValue <- mean(lidarSavingsPerHomicide)

    L_h2 <- ceiling(avgLidarCost / lidarAvgBenefitPerHomicide_noInfoValue)

# Panoscan ~~~~~~~~~~~~~~~~~~~~~~~~~~~~
  # with information value
    panoAvgBenefitPerHomicide <-
      mean(panoSavingsPerHomicide + informationValuePerHomicide)

    P_h1 <- ceiling(avgPanoCost / panoAvgBenefitPerHomicide)

  # WITHOUT information value)
    panoAvgBenefitPerHomicide_noInfoValue <- mean(panoSavingsPerHomicide)

    P_h2 <- ceiling(avgPanoCost / panoAvgBenefitPerHomicide_noInfoValue)

# Accidents ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
#
# Analysis 2:       Break even annual number of accidents
#
#   Sub-analysis 1: With and without the information value benefit
#   Sub-analysis 2: With the DSCO number of annual homicides and without any
#                   homicides
#   Sub-analysis 3: With and without the reduced traffic delay benefit
# ~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~

# LiDAR ~~~~~~~~~~~~~~~~~~~~~~~~~

  # with DSCO homicides, with information value, with reduced delay
  lidarAvgBenPerAccid_withHom <- mean(
    (numHomicides * (lidarSavingsPerHomicide + informationValuePerHomicide)) +
    (lidarSavingsPerAccident + lidarReducedDelayPerAccident)
  )

  L_a1 <- ceiling(avgLidarCost / lidarAvgBenPerAccid_withHom)
```

```
  # With DCSO homicide numbers, without information value, with reduced delay
  lidarAvgBenPerAccid_withHom_noInfoVal <- mean(
      (numHomicides * (lidarSavingsPerHomicide)) +
      (lidarSavingsPerAccident + lidarReducedDelayPerAccident)
    )

  L_a2 <- ceiling(avgLidarCost / lidarAvgBenPerAccid_withHom_noInfoVal)

  # No homicides, by default no information value, with reduced delay
  lidarAvgBenPerAccid_NOHomicide <-
      mean(lidarSavingsPerAccident + lidarReducedDelayPerAccident)

  L_a3 <- ceiling(avgLidarCost / lidarAvgBenPerAccid_NOHomicide)
  ##### 195 Accidents

  # with DCSO homicides, with information value, without reduced delay
  lidarAvgBenPerAccid_withHom_noDelay <- mean(
    (numHomicides * (lidarSavingsPerHomicide + informationValuePerHomicide)) +
    (lidarSavingsPerAccident)
  )

  L_a4 <- ceiling(avgLidarCost / lidarAvgBenPerAccid_withHom_noDelay)
  ##### 3 Accidents # reduced delay per accident is -$30 to $0

  # With DCSO homicide numbers, without information value, without reduced delay
  lidarAvgBenPerAccid_withHom_noDelay_noInfoVal <- mean(
    (numHomicides * (lidarSavingsPerHomicide)) +
    (lidarSavingsPerAccident)
  )

  L_a5 <- ceiling(avgLidarCost / lidarAvgBenPerAccid_withHom_noDelay_noInfoVal)

  # No homicides, by default no information value, no reduced delay
  lidarAvgBenPerAccid_NOHomicide_noDelay <- mean(lidarSavingsPerAccident)

  L_a6 <- ceiling(avgLidarCost / lidarAvgBenPerAccid_NOHomicide_noDelay)

# Panoscan PointGun ~~~~~~~~~~~~~~~~~

  # With DCSO homicides, with information value, with reduced delay
  panoAvgBenPerAccid_withHom <- mean(
    (numHomicides * (panoSavingsPerHomicide + informationValuePerHomicide)) +
    (panoSavingsPerAccident + panoReducedDelayPerAccident)
  )

  P_a1 <- ceiling(avgPanoCost / panoAvgBenPerAccid_withHom)

  # With DCSO homicides, without information value, with reduced delay
  panoAvgBenPerAccid_withHom_noInfoVal <- mean(
    (numHomicides * (panoSavingsPerHomicide)) +
    (panoSavingsPerAccident + panoReducedDelayPerAccident)
  )

  P_a2 <- ceiling(avgPanoCost / panoAvgBenPerAccid_withHom_noInfoVal)

  # No homicides, by default no info value, with reduced delay
  panoAvgBenPerAccid_NOHomicide <-
    mean(panoSavingsPerAccident + panoReducedDelayPerAccident)

  P_a3 <- ceiling(avgPanoCost / panoAvgBenPerAccid_NOHomicide)

  # With DCSO homicides, with info value, without reduced delay
  panoAvgBenPerAccid_withHom_noDelay <- mean(
    (numHomicides * (panoSavingsPerHomicide + informationValuePerHomicide)) +
    (panoSavingsPerAccident)
```

```
)

P_a4 <- ceiling(avgPanoCost / panoAvgBenPerAccid_withHom_noDelay)

# With DCSO homicides, without info value, without reduced delay
panoAvgBenPerAccid_withHom_no_Delay_noInfoVal <- mean(
  (numHomicides * (panoSavingsPerHomicide)) +
  (panoSavingsPerAccident)
)

P_a5 <- ceiling(avgPanoCost / panoAvgBenPerAccid_withHom_no_Delay_noInfoVal)

# No homicides, by default no info value, without reduced delay
panoAvgBenPerAccid_NOHomicide_noDelay <- mean(panoSavingsPerAccident)

P_a6 <- ceiling(avgPanoCost / panoAvgBenPerAccid_NOHomicide_noDelay)
```