Speed Analysis From Video: A Method For Determining a Range in the Calculations

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Abstract

This paper introduces a method for calculating vehicle speed and uncertainty range in speed from video footage. The method considers uncertainty in two areas; the uncertainty in locating the vehicle's position and the uncertainty in time interval between them.

An abacus style timing light was built to determine the frame time and uncertainty of time between frames of three different cameras. The first camera had a constant frame rate, the second camera had minor frame rate variability and the third had more significant frame rate variability. Video of an instrumented vehicle traveling at different, but known, speeds was recorded by all three cameras. Photogrammetry was conducted to determine a best fit for the vehicle positions. Deviation from that best fit position that still produced an acceptable range was also explored. Video metadata reported by iNPUT-ACE and Mediainfo was incorporated into the study.

When photogrammetry was used to determine a vehicle's position and speed from video recorded by a constant frame rate camera, the results closely matched the speeds reported by the instrumented vehicle being measured. This low uncertainty resulted from the constant frame rate eliminating error in time, and from low error in the vehicle's position through photogrammetry. For the variable frame rate camera, uncertainty in speed was dependent on the time between frames analyzed as well as any uncertainty in position. Quantification of this uncertainty has value for the reconstructionist. Determining speed of the vehicle in the variable frame rate video could be improved by incorporating frame timing reported by iNPUT-ACE or through other video analysis techniques and software that measure precise time differences between each frame.

Introduction

There has been a significant increase in both the private and public sectors use of recording devices, for surveillance, social media, and monitoring. As a result, more crashes are being caught on video and this evidence is more regularly available as a potential source for determining vehicle speed, or analysis of other issues needed for reconstruction. There can be considerable variability in the quality and specifications of video recorded by different cameras. This paper presents a method for determining vehicle speed from video and calculating the specific uncertainty that is present in the analysis. Calculation of the uncertainty considers potential errors in distance and time. Uncertainty in distance can arise from variability in the position of the object measured through photogrammetric analysis. Uncertainty in time may be present if the frame rate of the camera is variable. In some instances, the magnitude of variability in frame rate can be determined and incorporated into the analysis. This can be performed through analysis of the camera, analysis of the video footage using video analysis software, or through metadata of the video file itself. In this research, the uncertainty was inversely proportional to the number of frames used in the analysis. Determining the uncertainty in a video analysis allows for an understanding of the minimum number of frames needed for a specific analysis to yield useful results.

Calculation of speed from video might appear to be simple and straight forward, requiring only a measurement of distance and time which are both theoretically contained in video of moving vehicles. However, there is potential uncertainty in both distance measurements and time measurements which this paper intends to formalize.

Uncertainty Analysis

Potential Uncertainty in Distance

Vehicle positions at individual video frames can be determined using photogrammetry. The photogrammetry technique used in this study is referred to as camera-matching photogrammetry in the literature (1,2,3,4,5,6,7,8,10,11). The error rate of photogrammetry has been previously reported:

In 2006, Chou et al (2) applied photogrammetry to video frames from a rollover test to determine vehicle position, roll angle, and roll velocity. The authors reported that the camera matching results showed excellent agreement with the roll angles.

In 2008, Rose et al (7) analyzed the same dolly rollover over test as Chou and attempted to improve on the results with added camera information and a survey of the test site which included the camera locations. Over the video frames analyzed, the vehicle position obtained by two analysts was different by less than an inch, 96% of the time. The resulting roll velocities from camera matching were generally bracketed by the signals from the two roll velocity sensors on the vehicle.

Coleman et al (1) published error rates of camera matching in their 2015 paper. When lens distortion was corrected for, the maximum average error for locating evidence, including a motorcycle rest position, was 8.6 cm (0.28 feet).

In 2019, Terpstra et al built three mock accident scene diagrams using publicly available USGS LiDAR data and aerial photography (10). At each scene, mock evidence and a vehicle rest position (parked vehicle) were photographed. Five analysts then performed photogrammetry to locate the evidence and vehicle position. In the analysis that relied on a single photograph, the average error in vehicle position was 0.49 feet.

This magnitude of error was related to, among other things, the quality and resolution of the USGS LiDAR scene scan.

Potential Uncertainty in Time

For cameras with a constant frame rate, uncertainty in time, for practical purposes, can be ignored. However, uncertainty in time can arise when the frame rate is variable.

Cameras often include an embedded time stamp for each frame of the video. In some cases, the camera/software company can be contacted to verify the accuracy of the time stamp. This means that although a camera's frame rate is variable, its time stamp can be considered accurate eliminating this type of uncertainty. The accuracy of the time stamp should be verified through the camera manufacturer or some other means of video analysis.

iNPUT-ACE is a video software package designed for investigators.[1] If a video's format/file type is supported by the software, the software can extract the embedded frame timing for a variable frame rate camera. iNPUT-ACE can be used to reduce, and theoretically eliminate, the uncertainty in time between variable frames. iNPUT-ACE was used in this study.

Calculation of Uncertainty in Analysis

The average speed between two positions, *s*, can be calculated with Equation (1). The uncertainty in the speed, *δs*, is dependent on the uncertainty of each variable and can be determined using the Equation (2), as described by Taylor (9). Solving the partial equations yields Equation (3). As will be discussed, uncertainty in time is the same at each position ($\delta t_1 = \delta t_2$).

$$s = \frac{d}{t} = \frac{d_1 - d_2}{t_1 - t_2} \quad (1)$$

(2)

$$\delta s = \sqrt{\left(\left(\frac{\partial s}{\partial d_1}\delta d_1\right)^2 + \left(\frac{\partial s}{\partial d_2}\delta d_2\right)^2 + \left(\frac{\partial s}{\partial t_1}\delta t_1\right)^2 + \left(\frac{\partial s}{\partial t_2}\delta t_2\right)^2\right)} \quad (3)$$

$$\delta s = \sqrt{\left(\left(\frac{1}{t}\delta d_1\right)^2 + \left(\frac{-1}{t}\delta d_2\right)^2 + \left(\frac{-d}{t^2}\delta t\right)^2 + \left(\frac{d}{t^2}\delta t\right)^2\right)}$$

If the camera has a fixed known frame rate, then there is no uncertainty in time and Equation (3) reduces to Equation (4).

$$\delta s = \sqrt{\left(\left(\frac{1}{t}\delta d_1\right)^2 + \left(\frac{-1}{t}\delta d_2\right)^2\right)} \quad (4)$$

Timing Light

Several timing lights were built over the course of the study. The timing light is a stopwatch style clock that can be filmed so that the time of each frame, and time between frames, can be determined. For variable frame rate camera, the deviation from an average time between frames can be determined. This deviation from the average frame rate is the uncertainty, as will be discussed.

The first version of the timing light was a large five-digit digital clock, depicted in Figure 1. Some of the numbers on the clock were difficult to record in video, since the rate of display was significantly faster than the capture rate of the camera. This resulted in individual LED's from different numbers being recorded in the same frame. Figure 1 depicts this phenomenon in the last digit.

Figure 1. Timing light, Version I

An abacus style timing light was constructed to improve the results from the first version. The new timing light is composed of three major components: the microcontroller, power switching units, and the light bars.

The microcontroller is an Arduino Mega 2560 with a 16-megahertz clock speed and fifty-four output pins. It was programmed with a four-tier looping setup. The first tier displays the thousandth place of every second. The Arduino was programed with a loop that supplies power to the desired output pin, after the prescribed time the pin is turned off and power is supplied to the next pin. The next tiers follow this looping protocol. For the hundreds place, power is supplied to the desired output pin every time the previous loop cycled ten times. This pattern is continued for the tenths, and seconds places. This allows for the other lights bars to systematically increase their activation based on every ten cycles of the thousandth-place loop. The circuit that controlled the lights that displayed the hundredth, tenth, and seconds stay activated until a full 10 seconds was completed, whereas the each led in the thousandth-place lights up, then turns off as the next light is illuminated.

Each light bar has its own power switching unit that consists of ten N-channel MOSFETs (Metal Oxide Semiconductor Field Effect Transistor) (Figure 2). When power is supplied from the pins of the Arduino to the Gate pin of the MOSFET, the LED turns on. These MOSFETs were required as the Arduino is unable to regulate the current load.

[1] https://input-ace.com/

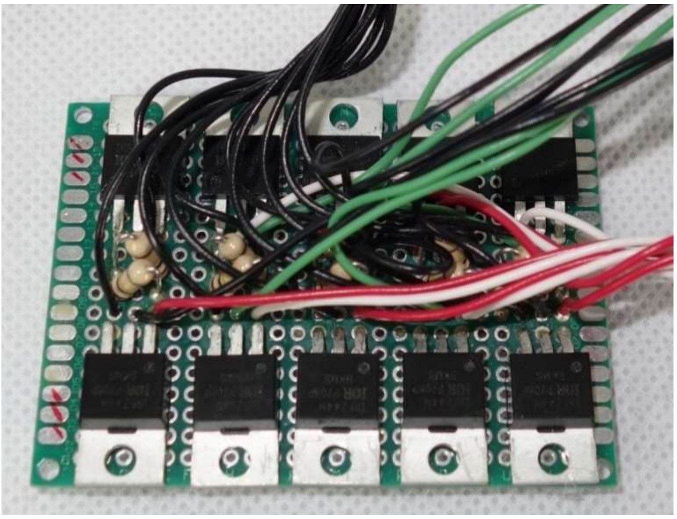

Figure 2. A Mosfet 10 channel power switching unit.

The light bars consist of aluminum C-channel with 9 LEDS in each bar. The LEDs are model number 12B-NW-B and use 12 volts at 0.07 amps. These LEDS were chosen for their 4000K white light spectrum, their 12-volt power requirements, and their machine thread style mounting. The light bars were designated to use only 9 lights because of the numeric rollover to the next decimal place. Figure 3 depicts a single light bar from the timing light.

Figure 3. One of the light bars from the timing light.

Figure 4 depicts the second iteration of the timing light. This configuration was used for part of the study. From top to bottom, the light bars display; tens, ones, tenths, hundredths, thousandths. Depending on the camera, several of the thousandth lights could be on at the same time. We adopted the methodology of always choosing the light furthest ahead in the procession. In Figure 4, the time displayed is 71.757 seconds. Due to limitations with the Arduino, the first light in the last row always remained on in this version of the light.

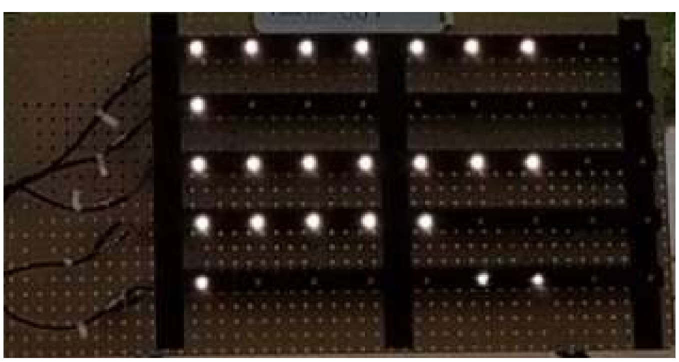

Figure 4. Timing light, Version II

The third version of the timing light, Figure 5, consists of 4 light bars that were stacked in two rows with the seconds and tenths displayed on top and hundredths and thousandths displayed on the bottom. In Figure 5, the timing light displays 4.679 seconds. Removing one row of lights eliminated the issue with a bulb remaining on. The rows were also moved closer together, which improved accuracy in the presence of rolling shutter, which will be discussed later in the paper. The final version hinges in the center to make it more portable.

Figure 5. Timing light, Version III.

Camera Calibration

At the beginning of this research, it was proposed that the timing light be calibrated against a very high accuracy nuclear clock located at The National Standards and Technology (NIST) in Boulder Colorado. Due to the current work/travel restrictions related to COVID-19, the technology within NIST was not available for public access.

An alternate method was devised that utilized a high-speed camera and its frame rate. The timing light was calibrated using Casio EX-F1 capable of recording video up to 1200 fps. The timing light was positioned such that it would fill the extents of the recorded frame and approximately 90 seconds of video was captured using the 1200 fps setting. Individual frames were exported so that they could be counted compared to the nominal 1200 fps to establish an elapsed time independent of the time displayed by the timing light.

The timing of the light bar system was adjusted to more closely match the Casio. The Arduino was programmed with a loop that supplies power to the desired output pin for 941 microseconds for each thousands LED before shutting off. The 941 microseconds delay is an adjustment unique to this system to account for several design factors such as the refresh rate of the code programed into the Arduino, the computer chip cycle speed and the physical construction of the electrical components. The final settings resulted in 104,641 frames from the Casio being equivalent to 87.150 seconds on the clock. Because this video was recorded at 1200 fps, 104,641 frames amounts to 87.201 seconds of video. The difference from the timing light and the Casio video was -0.051 seconds over 87.201 seconds, or -0.058%. This difference is low enough as to be negligible for most reconstruction purposes, and hence the timing light calibration gave adequate results for the purposes of this research.

Uncertainty in the Camera Frame Times

Cameras Used in the Study

Cameras were chosen from three tiers; a cellular phone camera (Google Pixel II smartphone), a portable hobbyist camera (Sony RX100 II), and a wifi based security system (Vivint).

The Google Pixel II is equipped with a 12.2 megapixel, approximately 0.385 inch, CMOS sensor[2]. The Pixel 2 records using an aperture of f/1.8 and a focal length equivalent to a 27mm lens in a full frame camera with a mp4 video format, H.264 compression. For this research video was recorded at 1920x1080 resolution, and a published record rate from Pixel II of 30 frames per second.

Figure 6. The Google Pixel II.

The Sony RX100 II is equipped with a 20.2 Megapixel Exmor R 1 inch CMOS sensor. The Sony has a Zeiss Vario-Sonnar T lens. The Sony records with a mp4 video format, H.264 compression. For the purposes of this research video was recorded at 1920 x 1080 resolution, and a published frame rate from Sony of 30 frames per second.

Figure 7. The Sony RX100 II.

The Vivint outdoor security camera was a HD300 model number V-HD300W wifi camera. The Vivint recorded with 3GP video format with H.264 compression at 1280x 720 resolution and a variable frame rate recording speed.

Figure 8. The Vivint outdoor building security camera.

Determining Uncertainty in Frame Time

The timing light was filmed several times with all three cameras. All the video frames were extracted and metadata from each video file was obtained. To analyze the metadata and extract information about the timing information between video frames, the program iNPUT-ACE was used, though other techniques exist for extracting frame timing. Based on the timing light reading, a time was assigned to each frame. An average frame rate was then determined from total frames over the time duration of interest. This calculated average frame was in agreement with the metadata average frame rate in all cases. Next, the average frame rate was used to calculate an ideal frame time at each frame assuming that the camera frame rate was constant. At each frame, the difference between the actual time and the ideal constant time was calculated. These differences represent the error in time at each frame had a constant frame rate assumption been made. The first and second standard deviations of frame time error were calculated. Appendix A depicts a screengrab from the spreadsheet used to calculate uncertainty in one of the Vivint videos, which records at a variable frame rate.

Camera Frame Time Uncertainty Results

Google Pixel II

The Google Pixel II has nearly a constant frame rate camera capturing 29.89 to 30.12 frames per second, according to the metadata. This is confirmed by the iNPUT-ACE data, which indicated times between frames varying between .0332 and .0335 seconds. According to the timing light analysis, the difference in time between frames was typically 0.032 to 0.034 seconds, nearly constant. Occasionally, one frame was shorter (.024 seconds), and the next longer (.042 seconds), then the frames resumed a constant frame timing. The frame rate from the video analysis was 0.6% greater than the frame rate recorded in metadata. Table 1 was created from a 9.932 second video captured by the Pixel II.

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[2] https://www.phonearena.com/phones/Google-Pixel-2_id10584

Google Pixel II	
Avg Frame Rate - Meta Data [fps]	30.03
Frame Rate - Video Analysis [fps]	30.21
Diff - Video Analysis and Meta %	0.60%
Avg Time Between Frames - video [s]	0.033
δt (1 Std Dev) [s]	0.004
δt (2 Std Dev) [s]	0.008
Analysis Duration [s]	9.932

Table 1. Summary of frame time uncertainties of the Google Pixel II.

The Sony RX 100 II is a constant frame rate camera capturing 29.97 frames per second. Similar to the Pixel II, the difference in time between frames was nearly constant, between 0.032 and 0.034 seconds, except occasionally when one frame was shorter (.023 seconds), and the next longer (.044 seconds). The frames then resumed a constant frame timing. This camera is constant frame rate, and this variance is likely due to limitations in the timing light system in the presence of rolling shutter effect. This will be discussed in greater detail later in the paper. For the speed analysis to come, the uncertainty in frame time of the Sony was included in the results. The frame rate from the video analysis was again 0.6% greater than the frame rate recorded in metadata. Table 2 was created from a 13.267 second video captured by the Sony.

Sony RX 100 II	
Avg Frame Rate - Meta Data [fps]	29.97
Frame Rate - Video Analysis [fps]	30.15
Diff - Video Analysis and Meta %	0.60%
Avg Time Between Frames - video [s]	0.033
δt (1 Std Dev) [s]	0.004
δt (2 Std Dev) [s]	0.007
Analysis Duration [s]	13.267

Table 2. Summary of frame time uncertainties of the Sony RX 100 II.

The Vivint camera records with a variable frame rate. The camera is motion trigger activated, and the video is uploaded to Vivint servers as it's being captured. The average frame rate, and amount of variability from video to video was also variable between runs. Table 3 depicts information from seven videos taken on various days. According to the metadata, the average frame rate varied between 1.81 and 5.53. The frame rate from the video analysis was sometimes more or less than the frame rate recorded in metadata. The frame rate variability was related to the average frame rate (Figure 9), a third order polynomial resulted in the best fit to the data. In short time periods on the same day (the videos on August 20th were recorded in a 43-minute window), the average frame rate varied suggesting that the variability was automated. Vivint was contacted to inquire about the variability. The company informed us that they had manual control over the frame rate as well. Apparently, this camera's frame rate can be adjusted manually, but also automatically adjusts.

Vivint Office Building Security Camera								
Date	Test number	Frame Rate - Meta	Frame Rate - Vid Analysis	Diff - vid analysis and meta	1st std dev uncertainty	2nd std dev uncertainty	Analysis Duration [s]
8/20/2020	0	3.47	3.49	0.8%	0.028	0.094	19.743
	1	4.49	4.52	0.7%	0.028	0.094	19.676
	2	5.40	5.35	-0.9%	0.023	0.046	19.810
	3	5.53	5.52	-0.3%	0.017	0.034	19.576
	4	3.92	3.94	0.5%	0.046	0.092	18.525
	5	3.83	3.80	-0.7%	0.048	0.097	19.477
	6	3.79	3.81	0.5%	0.048	0.095	18.615
10/6/2020	1	4.54	4.54	-0.1%	0.038	0.077	18.522
10/23/2020	1	2.12	2.09	-1.4%	0.187	0.373	19.612
	2	2.54	2.56	0.9%	0.081	0.162	19.118
	3	1.81	1.81	0.0%	0.236	0.472	18.777
12/17/2020	1	4.55	4.55	0.0%	0.042	0.085	18.453
	2	4.21	4.25	1.1%	0.075	0.151	19.284
	3	4.37	4.39	0.5%	0.076	0.152	18.909

Table 3. Summary of frame time uncertainties of the Vivint Camera.

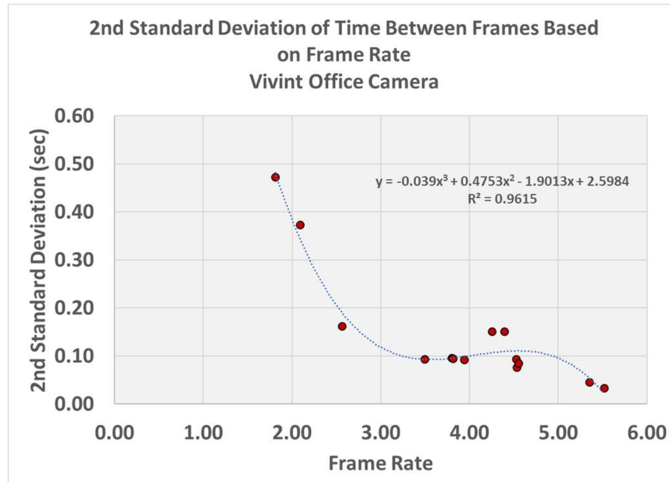

Figure 9. Second standard deviation of uncertainty of frame time versus average frame rate.

Testing

The two portable cameras were positioned next to the stationary security camera via a tripod and angled such that they would capture the same general view of the parking lot and adjacent roadway. The location of the cameras relative to each other and the surrounding structures were documented using a total station and Faro three-dimensional scanner.

The timing light was placed in the view of all three cameras and ran for the duration of the testing. A 2003 Honda S2000 instrumented with a VBOX GPS 20 hertz data logger was used as the test vehicle. Three test speeds were chosen based on available operating space. The achieved average test speeds in each run were 11, 21, and 26 mph. For each run, a high and low speed was extracted from the VBOX as the vehicle traveled across the field of view.

All cameras were activated, the test vehicle was accelerated up to one of the test speeds and then the vehicle was placed in neutral to negate engine drag effects. The vehicle coasted through the cameras' field of view.

Testing Data

When the test vehicle entered the view of the cameras, the vehicle was shifted into neutral and allowed to coast. The speed of the vehicle varied slightly while the vehicle was in view of the cameras. Figure 10 depicts the speed history from the three tests as the vehicle traveled through the camera's view. The min and max speeds are indicated in the legend.

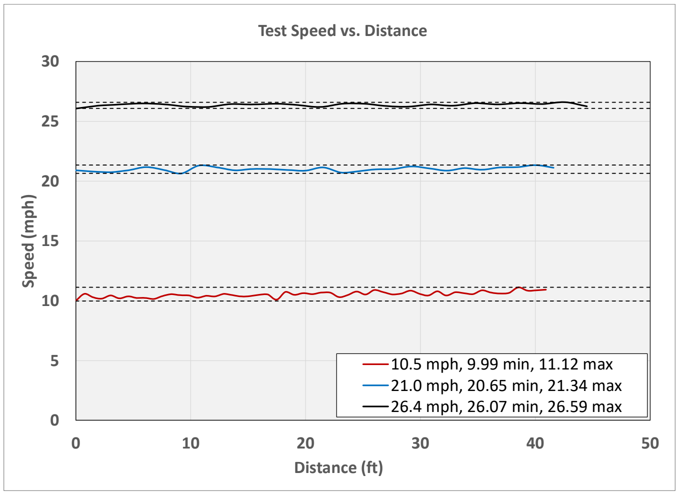

Figure 10. Vehicle speed during the 26 mph test.

A scene diagram was created with the scan and survey data. The test vehicle was three dimensionally scanned. The video from all three cameras was downloaded and individual frames were exported. Metadata was retrieved for each video file. The videos were imported into iNPUT-ACE and frame timing was acquired. Four frames from each video (four different vehicle positions, approximately equidistant across the view of the camera) were identified to be matched and used in the speed analysis. Figure 11 is an example of four frames from a test to be analyzed.

Figure 11. An example of four frames analyzed from one of the tests

Photogrammetry Analysis

The Pixel Farm PFTrack was used to solve for the lens distortion parameters of each camera used in the study (6,11). The process involved taking photographs of a checkerboard pattern while covering the full frame of the photo. Due to optical design of lenses, straight lines in the checkerboard pattern appear bent inward or outward from the image center depending on the distortion type (Barrel-Pincushion). PFTrack is capable of correcting lens distortion by automatically detecting the checkerboard pattern and obtaining the parameters that are needed to undistort the image.

In order to locate vehicle positions in the video, independent camera-matching photogrammetry was performed by two analysts so the results could be compared. Each analyst performed the following steps:

(1) The computer model of the scene was imported into 3ds Max, modeling software package, and a number of computer-generated cameras were set up in the documented camera locations to view the scene from perspectives similar to the perspectives characterized in the video camera views.

(2) The corrected image was then imported into the modeling software and was designated as a background image for the corresponding computer-generated camera with the same perspective.

(3) Adjustments were made to the position, orientation and focal length of the computer-generated camera until there was an overlay between the computer-generated scene model and the video frame from each camera.

(4) Once the camera location and parameters were determined and the overlay between the environment model and the video frame was obtained, the vehicle position in that frame could be located. For each match, the analyst adjusted the vehicle position until a best fit was found.

Figure 12 depicts a sampling of the photogrammetric analysis. The first image is a video frame that was camera matched. In the second image, the Faro 3D scan of the scene is overlaid and aligned to the video frame. In the third image, the vehicle position is located by overlaying the vehicle scan with the vehicle in the video. The still frame is removed in the fourth image leaving the scene model and positioned vehicle. Figure 13 depicts the photogrammetry results from the analysis of one of the tests. This same analysis was performed with all three cameras for all three tests. For each test, frames with similar vehicles positions were chosen from each video.

Figure 12. An example of the photogrammetry analysis.

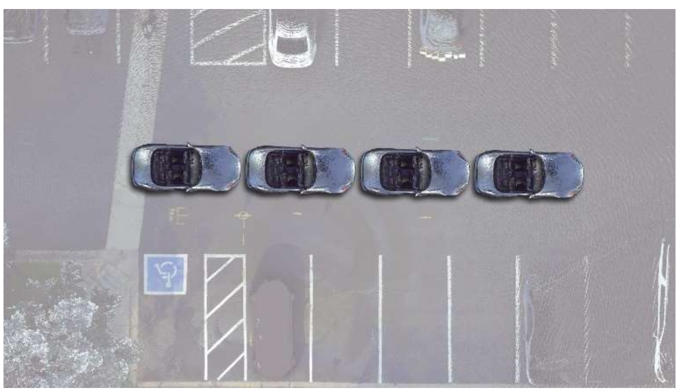

Figure 13. Four positions camera matched from one of the videos.

Determining Uncertainty in Vehicle Position

For each camera, the analyst first found the best fit vehicle position as described above. Next, the 11 mph test was used to determine uncertainty in vehicle positions. The vehicle position of the computer model was adjusted forward (relative to the vehicle) as far as possible while maintaining an acceptable match with the video frame. A match was deemed unacceptable when geometry of the computer model being matched was obviously too far away from its corresponding image in the video. Freedom was given to move the vehicle along its lateral axis also during the process. This process was repeated, moving the vehicle backward as far as possible while still achieving an acceptable match. This was repeated for all four positions for each of the three cameras in all tests. The acceptable variance in the vehicle position from the photogrammetry analysis was used as the uncertainty for the speed calculations discussed in the next section. The uncertainties in each position are summarized in Table 4 and Table 5. Since similar vehicle positions were selected in all tests, the uncertainties in Table 4 and Table 5 were used in the speed analysis of all three tests. When the test vehicle first came into the view of the camera, the vehicle movement was perpendicular to the camera perspective which gave the camera matches the smallest uncertainty. As the vehicle progressed through the field of view, the vehicle's position relative to the camera transitioned from a more perpendicular perspective to a more parallel perspective which generally increased the uncertainty in vehicle position.

Position Uncertainty (ft) Analyst #1			
	Sony	Pixel II	Vivint
Position-1	0.08	0.09	0.01
Position-2	0.19	0.22	0.16
Position-3	0.30	0.31	0.18
Position-4	0.43	0.41	0.29
Average	0.25	0.26	0.16

Table 4. Uncertainty in vehicle positions for each camera from Photogrammetry – Analyst #1.

Position Uncertainty (ft) Analyst #2			
	Sony	Pixel II	Vivint
Position-1	0.02	0.07	0.03
Position-2	0.17	0.16	0.14
Position-3	0.15	0.28	0.09
Position-4	0.18	0.16	0.15
Average	0.13	0.16	0.10

Table 5. Uncertainty in vehicle positions for each camera from Photogrammetry – Analyst #2.

Speed Analysis

The average speed of the vehicle between positions was calculated with Equation 1 using the distance between best fit positions from photogrammetry and the average frame rate. The speed was calculated in three segments; A, B, and C, as described in Figure 14. For each test, this was repeated for all three cameras. The uncertainty in speed was calculated in each case using the second standard deviation error in frame time from the camera frame analysis and the position uncertainty above. The uncertainty in time for the Pixel II and Sony cameras was included in the analysis. However, the Sony camera has a constant frame rate, and the Pixel II is nearly constant according to the meta data. The speeds were reanalyzed with the uncertainty in time for the Sony set to zero (constant frame rate assumption) and the uncertainty Pixel II set to .0003 seconds which is the variability noted in the metadata. The variability in the Pixel II is insignificant to the speed results. Those revised plots are included in Appendix B. An example of the speed analysis workbook is included in Appendix C. Tabular results of the analysis are included in Appendix D.

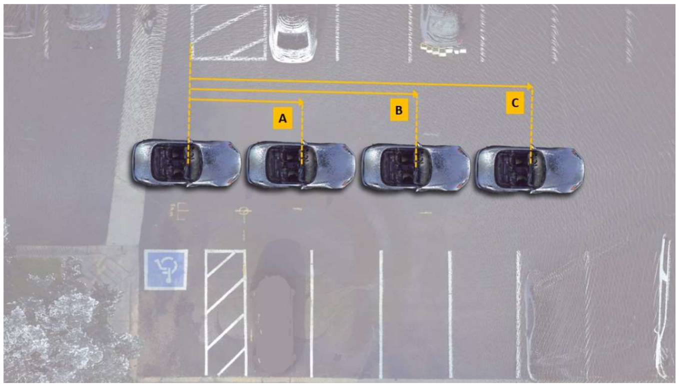

Figure 14. The three speed analyzed segments.

Figure 15 and Figure 16 depict the results of the analysis of the lowest speed test, 11 mph. The average speeds (the blue, green, yellow and orange bars) were calculated using the best fit photogrammetry positions from each analyst independently. The difference in vehicle positions from each analyst had a negligible effect on the results – Figure 15 and Figure 16 are nearly identical. The actual speed of the vehicle, measured with a VBOX, varied slightly as the vehicle traveled through the video area. The grey bars on the left are the high and low VBOX recorded speed of the vehicle as it coasted through the area. The colored bars correspond to the different cameras and are the average calculated speed of the vehicle of each segment (A, B and C in Figure 14). The error bars represent the range of speeds considering the uncertainty in time and distance. Both the analyzed speed of the Pixel (blue) and the Sony (green) agreed well with the VBOX speed in all segments.

For the first analysis with the Vivint camera (yellow), the average frame rate from the metadata was used. The average frame rate of the camera was also variable between runs. For Segments A and B, the average calculated speed fell inside the actual range. The calculated average speed for Segment C was higher than the measured range of speeds. The error bars represent the range of speeds considering the uncertainty in time from the camera study and uncertainty in distance. For the uncertainty in time, the equation in Figure 9 was used which relates the uncertainty in time to the average frame rate. The speed analysis is more sensitive to the uncertainties in time and distance when fewer frames (less time) lie between positions. As segment distance is increased (Segment B), the range of calculated speeds decreases. However, this effect is offset by the uncertainty in distance. The uncertainty in vehicle position increased as the vehicle traveled through the field of view, as discussed previously. Due to the offsetting effects, the range of speeds was similar in Segment B and C.

The timing for each frame can be found in the excel file export from iNPUT-ACE. In the orange columns, this timing data was used to supplement the analysis. The specific time between the analyzed frames exported via iNPUT-ACE was used, and the uncertainty in that time was assumed to be zero. As can be seen, the results are improved dramatically by incorporating the frame timing from iINPUT-ACE. In Appendix A, the frames used in the analysis are highlighted in yellow. The times from iNPUT ACE are aligned in time and used in the analysis.

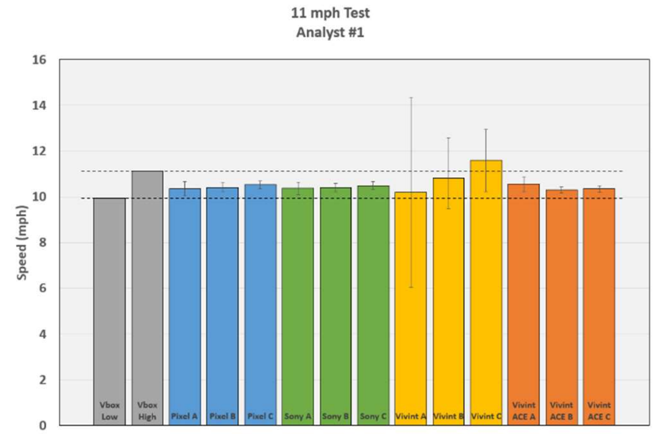

Figure 15. Results – Lowest speed, 11 mph, Analyst #1.

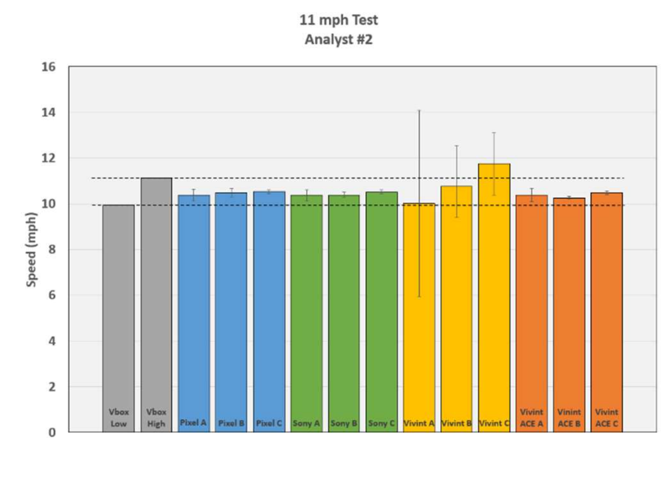

Figure 16. Results – Lowest speed, 11 mph, Analyst #2.

The results of the middle speed tests, an average of 21 mph, are shown in Figure 17 and Figure 18. Again, the difference between the two photogrammetry analysts had a negligible effect on speed. Since the time between positions (number of frames) was less at this higher speed, the range of uncertainty increased, as expected. The Pixel and Sony (blue and green) results compared well to the measured speed, even with the uncertainty in time included (These cameras have constant and near constant frame rates). Using the iNPUT-ACE frame times once again improved results (orange compared to yellow). Even with the times known from iNPUT-ACE, the speed range for Segment B fell entirely outside the actual speed range. In segment A, the calculated range narrowly overlapped the actual speed.

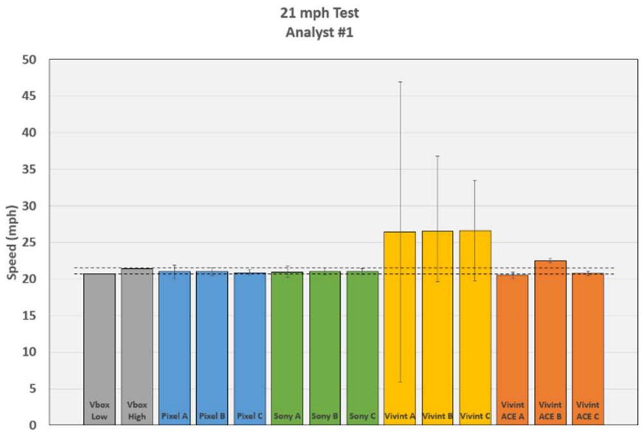

Figure 17. Results – Middle speed, 21 mph, Analyst #1.

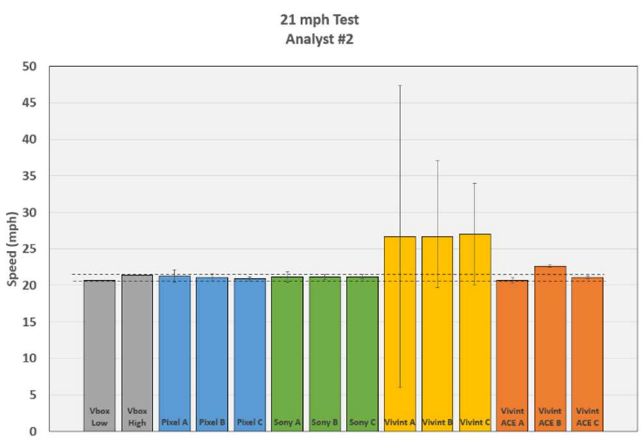

Figure 18. Results – Middle speed, 21 mph, Analyst #2.

The results of the highest speed tests, an average of 26 mph, are shown in Figure 19 and Figure 20. Again, the difference between the two photogrammetry analysts had a negligible effect on speed. The Pixel and Sony (blue and green) results compared well to the measured speed, even with the uncertainty in time included (These cameras have constant and near constant frame rates). However, due to the inclusion of the uncertainty in time, the range of speeds exceeded the actual speed range by a more significant amount in Segment A, the shortest time. Using the iNPUT-ACE frame times once again dramatically improved results (orange compared to yellow). Even with the times known, the speed range for Segment A, for the Vivint Camera, fell entirely outside the actual speed range.

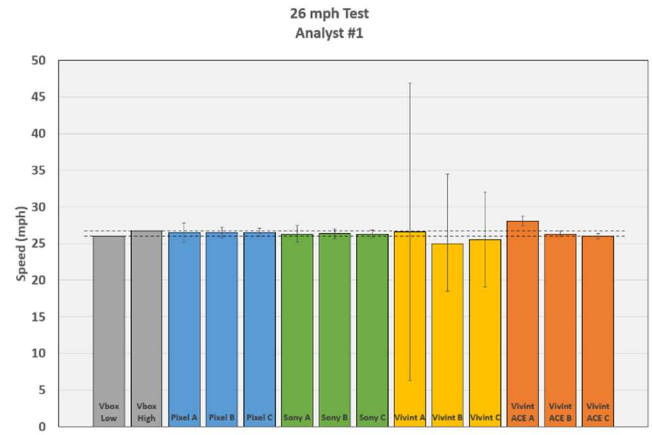

Figure 19. Results – Highest speed, 26 mph, Analyst #1.

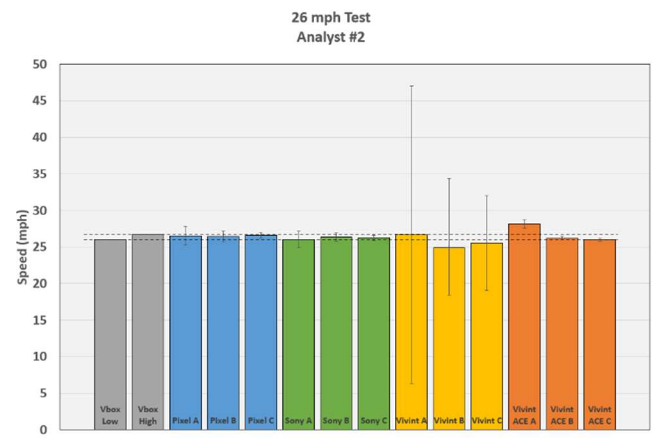

Figure 20. Results – Highest speed, 26 mph, Analyst #2.

Additional tests were performed with the Vivint office camera to explore how accuracy can be improved with more frames between positions. The same test vehicle was driven on the road beyond the parking lot. A single test with a near constant speed was selected for analysis. The vehicle was traveling approximately 32 mph. Photogrammetry was used to position the vehicle model in two frames. The photogrammetry was conducted by a single analyst. In the first position, the vehicle was further from the camera and the uncertainty in photogrammetry was greater than in previous testing, +/- 2.7 feet. The vehicle traveled approximately 145 feet in 3.1 seconds (14 frames) between these two positions. The equation in Figure 9 was used to calculate the uncertainty in time. Despite the larger uncertainty in vehicle position, the accuracy of the uncertainty in the speed calculations was improved, as shown in Table 6.

Vivint Road Test	
Distance [ft]	145.5
+/- Position 1 [ft]	2.7
+/- Position 1 [ft]	0.7
Frames	14
Time [sec]	3
+/- Time [sec]	0.11
Speed [mph]	32.0
+/- Speed [mph]	2.6
+/- Speed [%]	8.1%
Measured Speed [mph]	31.6 +/- 0.9

Table 6. Results of analysis of the Road Test.

Discussion

Analysis – Uncertainty in Time

The uncertainties in time of the Vivint created far larger ranges in speed than the other cameras, if analysis of the frame timing was not performed, such as using iNPUT-ACE. However, this larger uncertainty does mean this camera footage could not be useful in practice.

Figure 21 plots the speed uncertainty, as a percentage of calculated speed, plotted against the number of frames between positions. In Figure 21, the frame rate from the 26 mph Vivint test was used - 3.79 fps. The uncertainty in time from that video was also used - .0963 seconds. This uncertainty assumes the average frame rate was known but the camera recorded the video at a variable frame rate. The plot assumes no uncertainty in distance. The uncertainty in calculated speed decreases as the number of frames between positions increases.

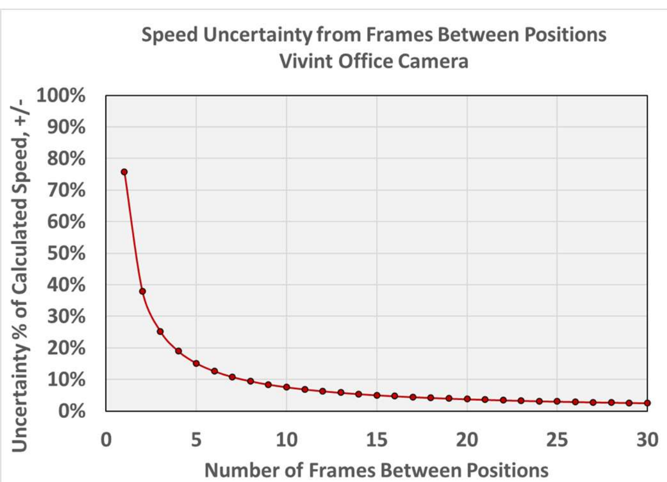

Figure 21. The uncertainty in speed calculations for the Vivint camera as a percentage of average speed.

The following example highlights the implications of this trend in uncertainty. Assume that a vehicle traveled through the field of view of this variable frame rate camera, on a road that has a posted speed limit of 30-mph. A reconstructionist is asked to analyze the video and determine the vehicle speed. The analysis is conducted, and an average speed of 50 mph is calculated, well over the speed limit. However, if there was only one frame between positions (a separation of 19.4 feet and 0.26 seconds), the speed analysis would result in a high level of uncertainty; a range of speeds of approximately 12 to 88 mph (+/- 76%). It is clearly not possible to determine whether the vehicle was traveling over the 30-mph speed limit with this range. On the other hand, if 10 frames were available between positions (193.5 feet, 2.64 seconds) the range is much tighter; 46 mph to 55 mph (+/- 7%). For this hypothetical, it can be said with confidence that the vehicle was traveling over the speed limit.

It should be noted that the frame rate and variability is different from camera to camera. The uncertainties in time are camera specific, and the uncertainty in position will depend on other circumstances of the recorded video, such as distance away from the camera and quality of the photogrammetry match. Although the plot and example above are specific to this camera, the trend that more frames will reduce uncertainty from frame variability is universal. Understanding the magnitude of this uncertainty gives the analyst confidence that a question can or cannot be answered.

In the analysis of the Vivint camera, the metadata was used for the average frame rate. In practice, this would represent a case where metadata was available, but complete frame by frame timing from software such as iNPUT-ACE was unavailable. iNPUT-ACE is capable of reading the duration between the frames in a variable frame-rate video thanks to mpeg compression. If the video is not in mpeg compression, it is usually not possible to get individual frame timing using iNPUT-ACE or FFmpeg (another software package). A Digital video file typically contains four major parts: Video stream, Audio Stream, Metadata and a container. Frame rate of a video is typically stored in the Metadata of the file. In case of variable frame rate video, usually an averaged frame rate is reported. MPEG-4 Part 14 (MP4) is a type of container that supports variable frame rate video and sets an individual timecode for each frame of a video stream. The frame timing can be extracted from metadata of the file using software like FFMpeg or iNPUT-ACE.

If frame timing was not available for the Vivint camera, it may have been difficult to determine the average frame rate since it was different among the videos recorded. In that case, the uncertainties would have been larger.

There may be other information in the video to assist in the determining frame time, and time uncertainty. Vehicles known to be moving at a constant speed can bracket the time. Time stamps on the video can offer information. On occasion, frame timing information can be acquired by the online video platform or camera manufacturer. Further, if other video exists from a different perspective, this may provide additional data to perform an accurate vehicle speed calculation.

iNPUT-ACE offered a dramatic improvement in the speed calculation range. However, the calculated speeds did fall slightly outside the measured speed range on a few occasions. iNPUT-ACE relies on the accuracy of the camera's internal clock, which varies from camera to camera. More research could be done here. In any case, the speed calculated with the iNPUT-ACE timing offers a significant improvement and gave acceptable results.

Rolling Shutter

Some digital cameras do not record the entirety of the frame at the same time. Rather, the frame images are recorded in a similar manner to how English is read, starting at the top left and reading line by line until finishing at the lower right (relative to the camera). This recording process is known as rolling shutter. Since different portions of the image are recorded at slightly different times, different portions of the timing light are recorded at different times, potentially affecting the accuracy of the timing light. Evidence of rolling shutter can be seen in Figure 22, a frame recorded by a Sony a7S camera. When the camera recorded the bottom light bar (thousands place), the fourth light from the left was off. Then, when the camera recorded the table surface below the light, the reflection of the now on light is visible (yellow arrow).

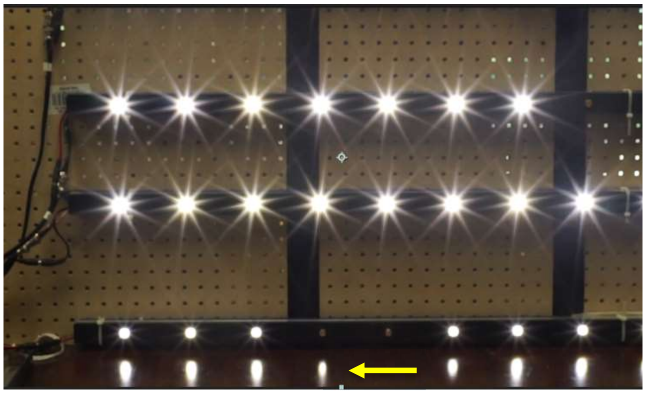

Figure 22. An example of rolling shutter effect.

Analysis of frames from the Pixel II and Sony indicated that the cameras had a nearly constant time of .032 to .034 seconds between frames for the majority of the time. Occasionally, the timing light indicated one shorter frame (~30% shorter), and one longer frame (~30% longer). The iNPUT-ACE data indicated the frame rate was constant for both cameras. Review of the timing light with high speed video revealed no discrepancies in time with the timing light.

The shorter and longer frames occurred at predictable timing light illumination configurations, consistent with being a rolling shutter effect. Consider Figure 23, which represents four consecutive frames displaying simplified clock times that occurred during analysis of the Google Pixel II. Each 'o' indicates an illuminated light. The first two frames read correct times, and the resulted in a timing between frames of 0.033 seconds, as expected. The next frame, in red, occurred sooner, resulting in a shorter frame (0.024 seconds) followed by a longer frame (0.042 seconds). This same error occurred occasionally and is the result of rolling shutter.

	1	2	3	4	5	6	7	8	9		
80.564	o	o	o	o	o	o	o	o			
	o	o	o	o	o						
	o	o	o	o	o	o					
				o							
										0.033	Seconds
80.597	o	o	o	o	o	o	o	o			
	o	o	o	o	o						
	o	o	o	o	o	o	o	o	o		
							o				
										0.024	Seconds
80.621	o	o	o	o	o	o	o	o			
	o	o	o	o	o	o					
	o	o									
	o										
										0.042	Seconds
80.663	o	o	o	o	o	o	o	o			
	o	o	o	o	o	o					
	o	o	o	o	o	o					
			o								

Figure 23. Four consecutive times from the Pixel II camera, which produced uncertainty in the frame timing. The third frame shows an error in the thousandths place (red).

The frame image of the timing clock was recorded from left to right and top to bottom as a result of rolling shutter. In the third frame (highlighted in red), the camera recorded the fourth row of lights, a '2'. When the 5th row of lights was recorded a little later, the '1' light was illuminated, but a moment earlier, when the fourth row was being recorded, instead the '9' was illuminated. Due to rolling shutter, the '1' was recorded instead of the '9' in the fifth row. The light sequence in the third frame was corrected to account for rolling shutter in Figure 24. As can be seen, the timing between frames is between 0.032 and 0.034 seconds with the correction made.

	1	2	3	4	5	6	7	8	9		
80.564	o	o	o	o	o	o	o	o			
	o	o	o	o	o						
	o	o	o	o	o	o					
				o						0.033	Seconds
80.597	o	o	o	o	o	o	o	o			
	o	o	o	o	o						
	o	o	0	o	o	o	o	o	o		
							o				
										0.032	Seconds
80.629	o	o	o	o	o	o	o	o			
	o	o	o	o	o	o					
	o	o									
									o		
										0.034	Seconds
80.663	o	o	o	o	o	o	o	o			
	o	o	o	o	o	o					
	o	o	o	o	o	o					
			o								

Figure 24. The same four consecutive frames from the Pixel II, with a correction for rolling shutter error.

The rolling shutter effect was always present, but the effect was systematic and negligible most of the time. Typically, the thousands light shifted to a slightly higher digit while being recorded, the same shift occurred in most frames, so the timing between frames didn't change substantially. However, if during the recording of one frame, the hundredths place recorded, then the thousands place reached full cycle and went back to zero before it was recorded, the error showed up. Due to rolling shutter effects, the uncertainties determined with the timing light were larger than the uncertainties due to the variability of the frames alone.

In the case of the Sony, the data from iNPUT ACE confirmed that the camera had a constant frame rate. If a constant frame rate can be confirmed, uncertainty in time, for practical purposes, can be ignored.

Exposure Time Error

There was another error that potentially occurred that was related to the time it took to record the still frame image. This phenomenon appears to be an effect from exposure time. The exposure effect was infrequent with the Pixel II (darker video, less exposed) and occurred more often with the Sony (lighter video, more exposed). Consider Figure 25, three consecutive frames from the Sony. The correct time digits have been added to the images. The top image reads 81.668, no issue there. In the next frame, the lights are in the process of changing. In the tenth place, the '7' is beginning to turn on. However, the hundredths place still shows a '9'. The clock has rolled over to 81.702, but the hundredths place lights took time to turn off and were captured as on. In other instances, the hundredths place is captured in the process of turning off. If the timing light is read as 81.792, an obvious error shows up. The next frame reads 81.735, giving a negative time between frames, which is impossible unless the frames are recorded out of sequence. In order to adjust for this affect, if a tenth-place light had begun to turn on and all the lights were on in the hundredths place, the hundredths place was marked '0'.

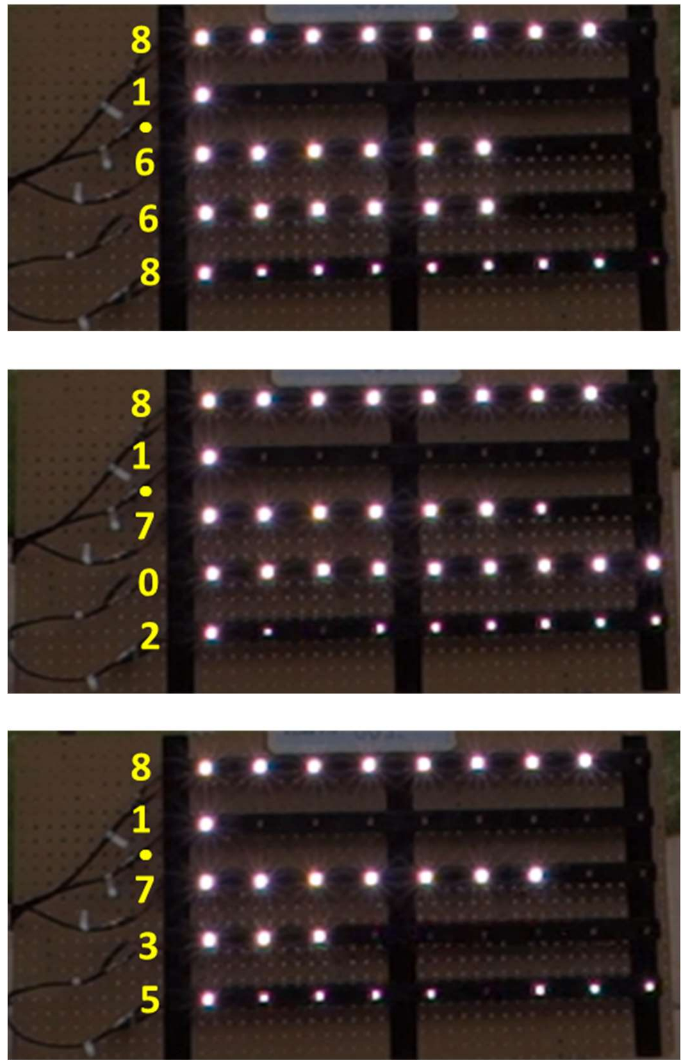

Figure 25. Three consecutive frames from a Sony recording showing the exposure effect.

The timing light orientation was modified to better handle rolling shutter effects (Version III). The light bars were arranged so the timing light was wider, and the bars were closer together vertically. The change reduced the time it would take to record the timing light in the video frame, theoretically reducing the effect of rolling shutter. Video was recorded of the Version III timing light with the Google Pixel 2 and the Sony RX 100 II. The rolling shutter error still occurred, but much less frequently. With the new light configuration, the uncertainty was reduced by 89% and 76% for the Pixel II and Sony, respectively. Moving the clock farther away from the camera helps as well, so long as the individual lights are still visible. Changing the light configuration did not affect the exposure effect, as expected.

Due to differences between cameras, different lighting conditions between locations, exposure effects, rolling shutter effects, and general circumstances of the video, we expect some time discrepancies may arise when using the timing light in practice. Some of these discrepancies may be obvious and could be corrected for, like the exposure effect with the Sony. In video from the Sony and Pixel II, the rolling shutter effect artificially added uncertainty, which added uncertainty in speed calculation making the results more conservative. It could be that rolling shutter and exposure effects also added to the uncertainty in the analysis of the variable frame rate Vivint camera. With a variable frame rate, it was more difficult to detect these errors due to the lack of pattern in the signal. Again, this would increase uncertainty and make the analysis more conservative. Whenever possible, it is recommended that average frame rate be acquired with Mediainfo and frame timing be acquired through video analysis techniques or with video analyzing software such as iNPUT-ACE.

Conclusions

1. Uncertainties in time and vehicle positions contribute to uncertainty in calculated speed.
2. The uncertainties in distance, from photogrammetry, had a minor influence on calculated speed in this study.
3. For the variable frame rate camera, the uncertainty in time was more influential than the uncertainty in distance. The uncertainties in time in this study were specific to the camera and to the number of frames analyzed.
4. All other things being equal, the uncertainty in speed decreases as the number of frames between positions increases.
5. Specific frame timing, from a program like iNPUT-ACE, improved the speed analysis results for the variable frame rate camera.

Practical Use of This Research

The results of this paper can guide the analysis of vehicle speed from video. Here are a few steps that can be followed in practice:

1. Create a three-dimensional diagram of the area captured on video. It is helpful to include the camera position in this diagram.

2. Extract all relevant frames from the video.

3. Select specific frames to be analyzed. Perform photogrammetry to determine the best fit vehicle position in each frame.

4. Determine the amount the vehicle can be moved from the best fit position in order for the match to remain acceptable. This will establish the range of error in each vehicle position.

5. Export metadata from the video to acquire the average frame rate. If possible, acquire frame timing of the video using a program such as iNPUT ACE.

<u>If the frame rate is constant:</u>

6A. The time between each frame can be calculated, the inverse of the frame rate.

7A. Determine the time between vehicle positions, based on the number of frames between positions.

8A. Measure the distance between positions.

9A. The average speed between positions can be calculated with Equation 1.

10A. The uncertainty in speed is only dependent on the uncertainty in each vehicle position from photogrammetry and can be calculated using Equation 4.

<u>If the frame rate is variable, but the individual frame timing is known:</u>

6B. Assign the actual frame time to each frame from which vehicle position was determined.

7B. Determine the time between vehicle positions, based on the actual frame timing.

8B. Measure the distance between best fit positions.

9B. The average speed between positions can be calculated with Equation 1.

10B. The uncertainty in speed is only dependent on the uncertainty in each vehicle position from photogrammetry and can be calculated using Equation 4.

<u>If the frame rate is variable, but the individual frame timing is NOT known:</u>

6C. Using the same camera that recorded the vehicle in question, take several recordings of a timing light similar to the one used in this study. In this study, 10 to 20 second videos were adequate.

7C. Export metadata and frame timing from the timing light videos.

8C. Export each frame from each timing light video.

9C. Create a spreadsheet to document the time at each frame from the timing light, then calculate the times between consecutive frames. Using the average frame rate, calculate the ideal time between frames assuming that the frame rate was constant. Calculate the difference between actual time between frames and ideal time between frames at each segment. Calculate the standard deviation of the difference of actual time between frames and ideal time between frames. Also calculate two standard deviations. An example of these calculations is shown in Appendix A.

10C. Determine the ideal time between vehicle positions, based on the average frame timing (assume a constant frame rate).

11C. Measure the distance between best fit positions.

12C. The average speed between positions can be calculated with Equation 1, assuming the ideal time between positions.

13C. The uncertainty in speed is dependent on the uncertainty in each vehicle position from photogrammetry and the uncertainty in time. In this study, using two standard deviations in time error (from step 9C) captured the actual speeds well. Use Equation 3 to calculate the uncertainty in speed.

14C. There may be other information available to retrieve actual frame timing. Is there anything else in camera view that speaks to timing? Was the vehicle captured from any other cameras? Data can sometimes be acquired from the camera/data logging company. Is there anything to be learned from the company about the frame rate variability? Is there a time stamp? What is the accuracy of the time stamp? This list is not inclusive, other data about frame timing may be available.

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Appendix A

Example of calculation of camera uncertainty and aligning iNPUT-ACE data from one of the Vivint videos. Positioned analyzed are highlighted in yellow.

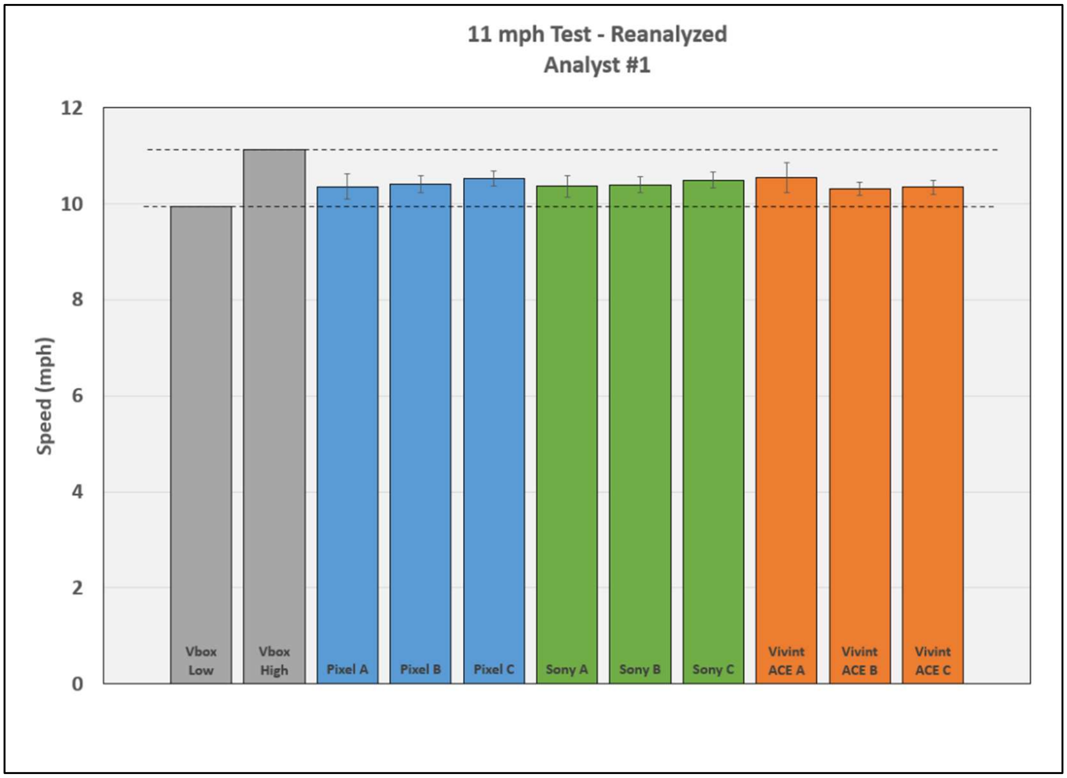
	meta data	frame analysis	difference
AVG Frame Rate	3.92	3.94	0.5%
ertainty, Standard Deviation (sec)	0.046		
nty, 2nd Standard Deviation (sec)	0.092		

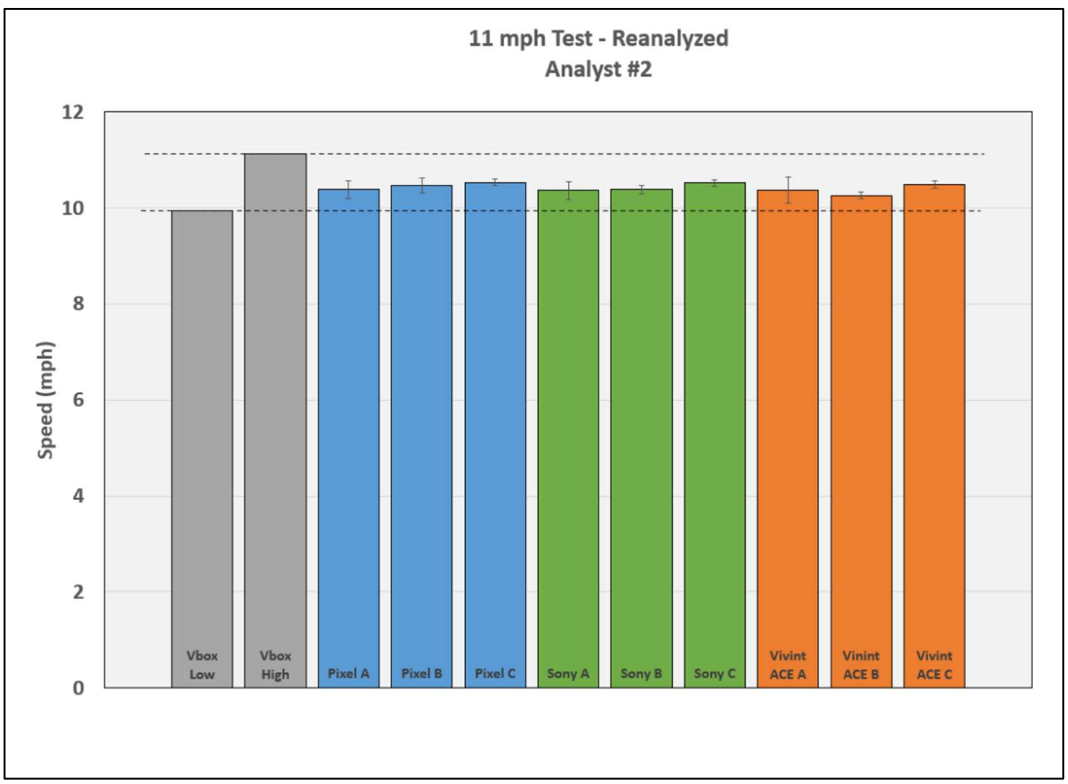
Frame	Running Time from Timing	Time Between Frames (sec)	Frame Rate (fps)	Time Between Frames -	Difference (Uncertainty) (sec)	INPUT ACE running	INPUT ACE adj
37	70.173					8.550	70.201
		0.232	4.310	0.254	-0.022		
38	70.405					8.797	70.448
		0.331	3.021	0.254	0.077		
39	70.736					9.130	70.781
		0.331	3.021	0.254	0.077		
40	71.067					9.463	71.114
		0.331	3.021	0.254	0.077		
41	71.398					9.760	71.411
		0.265	3.774	0.254	0.011		
42	71.663					10.057	71.708
		0.232	4.310	0.254	-0.022		
43	71.895					10.303	71.954
		0.256	3.906	0.254	0.002		
44	72.151					10.550	72.201
		0.241	4.149	0.254	-0.013		
45	72.392					10.797	72.448
		0.265	3.774	0.254	0.011		
46	72.657					11.097	72.748
		0.331	3.021	0.254	0.077		
47	72.988					11.397	73.048
		0.331	3.021	0.254	0.077		
48	73.319					11.727	73.378
		0.332	3.012	0.254	0.078		
49	73.651					12.057	73.708
		0.232	4.310	0.254	-0.022		
50	73.883					12.303	73.954
		0.265	3.774	0.254	0.011		
51	74.148					12.550	74.201
		0.231	4.329	0.254	-0.023		
52	74.379					12.797	74.448
		0.266	3.759	0.254	0.012		
53	74.645					13.097	74.748
		0.331	3.021	0.254	0.077		
54	74.976					13.397	75.048
		0.331	3.021	0.254	0.077		
55	75.307					13.727	75.378
		0.331	3.021	0.254	0.077		
56	75.638					14.057	75.708
		0.223	4.484	0.254	-0.031		
57	75.861					14.300	75.951
		0.274	3.650	0.254	0.020		
58	76.135					14.543	76.194

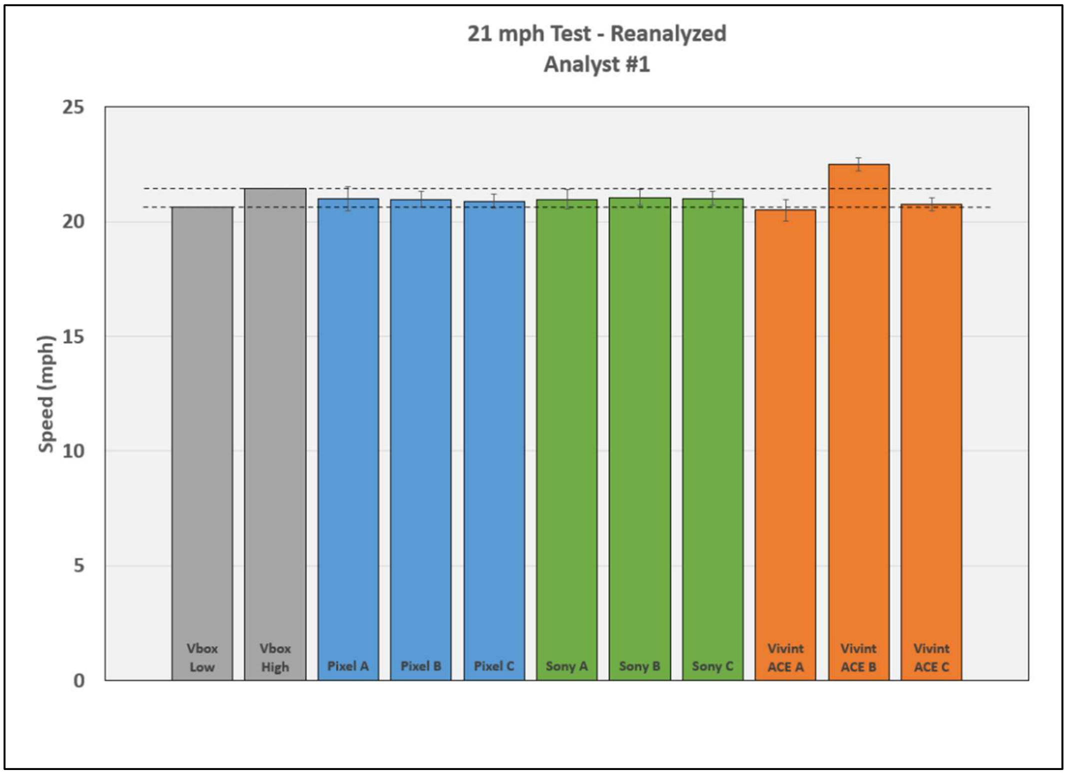
Input Ace Summary	
pos 1 to 2	0.488
pos 1 to 3	1.325
pos 1 to 4	1.988

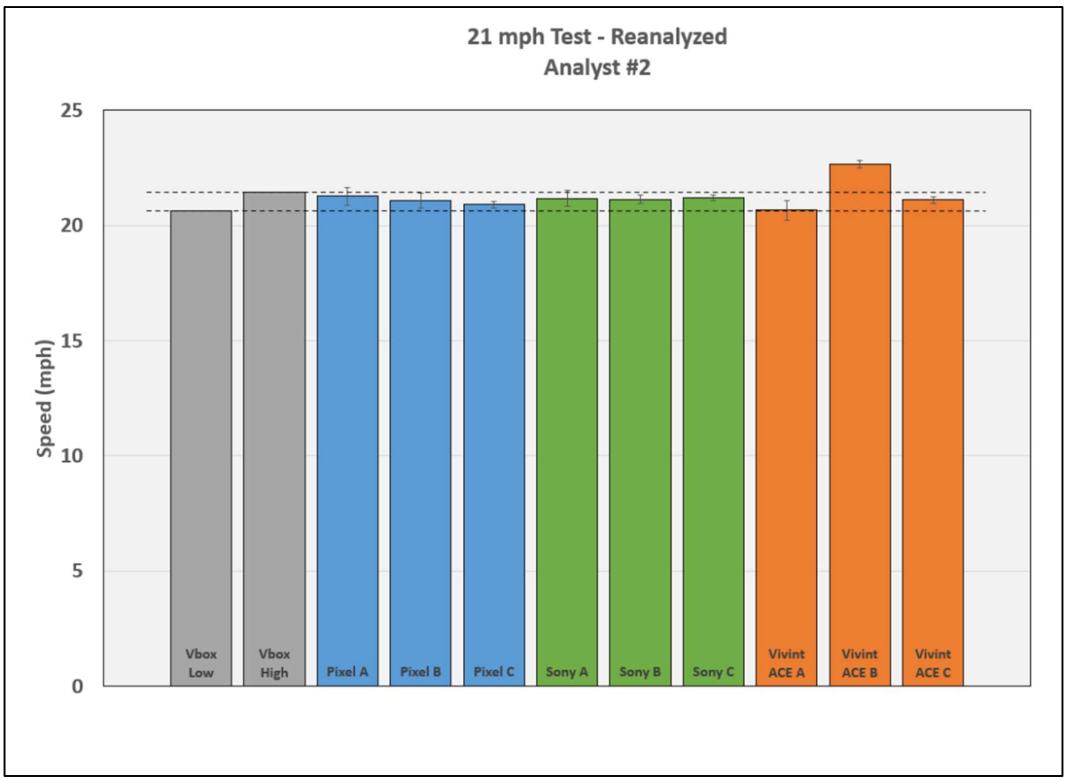
Appendix B

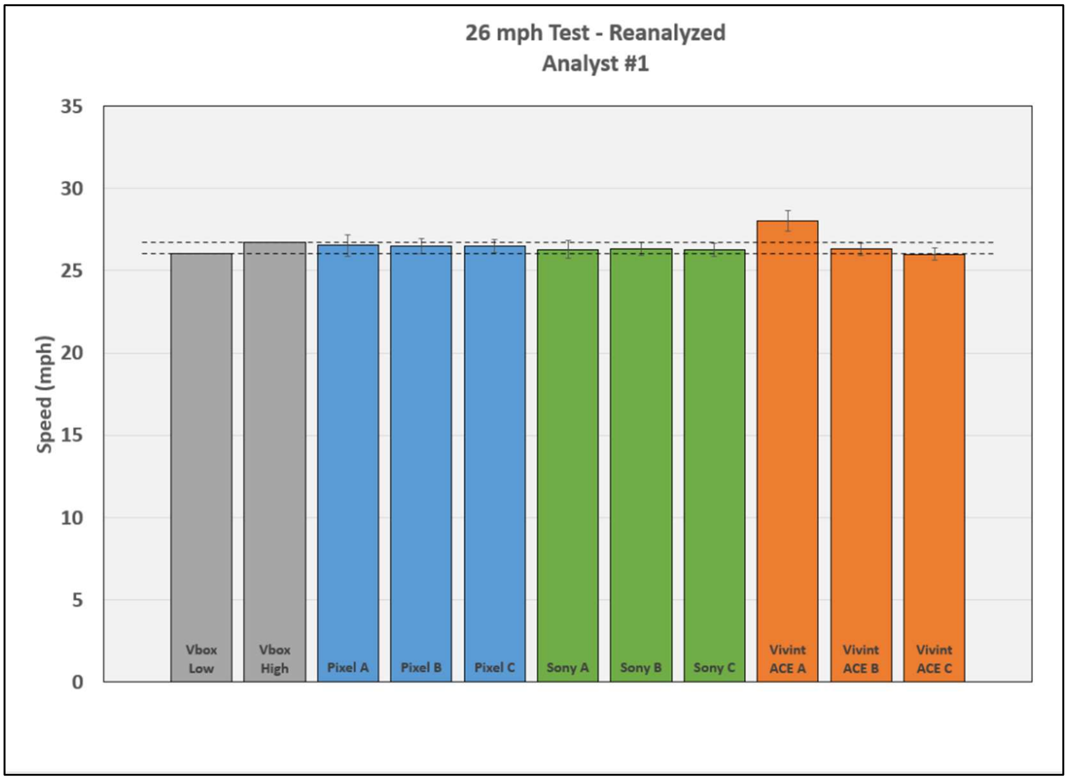
The videos from all three cameras included metadata with frame timing information. The Sony has a constant frame rate. The Pixel II has a nearly constant frame rate, .0003 seconds of variability. The Vivint office camera had a variable frame rate, but individual frame timing was available with iNPUT ACE. In practice, if footage from these cameras were analyzed, this metadata would have been used. The Sony would be considered constant frame rate, .0003 seconds of variability would have been used for the Pixel II and iNPUT ACE frame times would have been used for the Vivint camera. The plots below show the results of such an analysis.

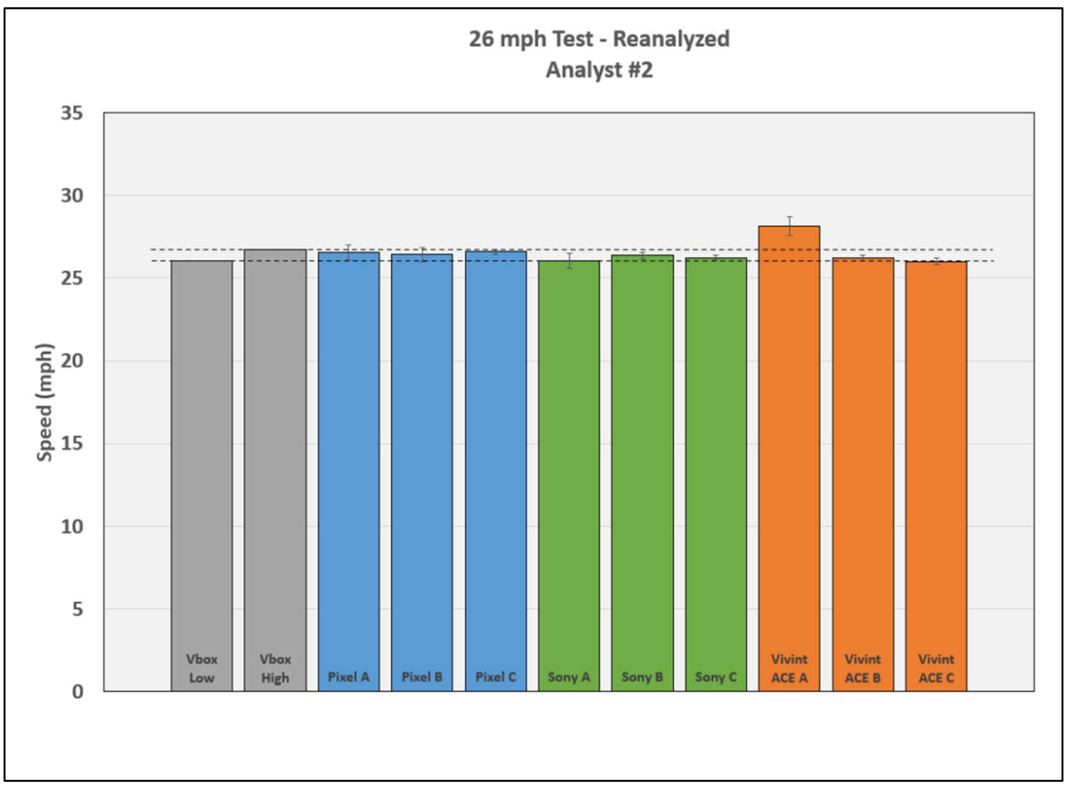





21 mph Test - Reanalyzed
Analyst #1
Speed (mph)
25
20
15
10
5
0
Vbox Low
Vbox High
Pixel A
Pixel B
Pixel C
Sony A
Sony B
Sony C
Vivint ACE A
Vivint ACE B
Vivint ACE C


21 mph Test - Reanalyzed
Analyst #2
Speed (mph)
25
20
15
10
5
0
Vbox Low
Vbox High
Pixel A
Pixel B
Pixel C
Sony A
Sony B
Sony C
Vivint ACE A
Vivint ACE B
Vivint ACE C


26 mph Test - Reanalyzed
Analyst #1
Speed (mph)
35
30
25
20
15
10
5
0
Vbox Low
Vbox High
Pixel A
Pixel B
Pixel C
Sony A
Sony B
Sony C
Vivint ACE A
Vivint ACE B
Vivint ACE C


26 mph Test - Reanalyzed
Analyst #2
Speed (mph)
35
30
25
20
15
10
5
0
Vbox Low
Vbox High
Pixel A
Pixel B
Pixel C
Sony A
Sony B
Sony C
Vivint ACE A
Vivint ACE B
Vivint ACE C

Appendix C

Sample speed analysis.

Pixel - (11 mph)

Position 1 to 2				
Distance [ft]	13.66		Uncertainty in position 1 [ft]	0.09
Constant Frame Rate	30.0253		Uncertainty in position 2 [ft]	0.22
Frame position 1	3132		Uncertainty in time at each Frame [sec]	0.0076
Frame Position 2	3159		Uncertainty in Speed [mph]	0.32
Time [sec]	0.90			
Speed [mph]	10.4			
Speed - high [mph]	10.7			
Speed - low [mph]	10.0			

Position 1 to 3				
Distance [ft]	27.47		Uncertainty in position 1 [ft]	0.09
Constant Frame Rate	30.0253		Uncertainty in position 3 [ft]	0.31
Frame position 1	3132		Uncertainty in time at each Frame [sec]	0.0076
Frame Position 3	3186		Uncertainty in Speed [mph]	0.20
Time [sec]	1.80			
Speed [mph]	10.4			
Speed - high [mph]	10.6			
Speed - low [mph]	10.2			

Position 1 to 4				
Distance [ft]	41.13		Uncertainty in position 1 [ft]	0.09
Constant Frame Rate	30.0253		Uncertainty in position 4 [ft]	0.41
Frame position 1	3132		Uncertainty in time at each Frame [sec]	0.0076
Frame Position 4	3212		Uncertainty in Speed [mph]	0.17
Time [sec]	2.66			
Speed [mph]	10.5			
Speed - high [mph]	10.7			
Speed - low [mph]	10.4			

Appendix D

Tabular analysis results.

Sony - Analyst #1									
	Distance [ft]	+/- Position 1 [ft]	+/- Position 2 [ft]	Number of Frames	Time [sec]	+/- Time [sec]	Speed [mph]	+/- Speed [mph]	+/- Speed [%]
11 mph, Segment A	13.70	0.08	0.19	27	0.90	0.007	10.37	0.28	2.7%
Segment B	27.99	0.08	0.30	55	1.84	0.007	10.40	0.19	1.8%
Segment C	42.12	0.08	0.43	82	2.74	0.007	10.49	0.17	1.6%
21 mph, Segment A	14.37	0.08	0.19	14	0.47	0.007	20.97	0.79	3.8%
Segment B	27.82	0.08	0.30	27	0.90	0.007	21.05	0.48	2.3%
Segment C	42.17	0.08	0.43	41	1.37	0.007	21.01	0.39	1.9%
26 mph, Segment A	14.16	0.08	0.19	11	0.37	0.007	26.30	1.19	4.5%
Segment B	28.36	0.08	0.30	22	0.73	0.007	26.34	0.67	2.6%
Segment C	42.46	0.08	0.43	33	1.10	0.007	26.29	0.53	2.0%

Pixel II - Analyst #1									
	Distance [ft]	+/- Position 1 [ft]	+/- Position 2 [ft]	Number of Frames	Time [sec]	+/- Time [sec]	Speed [mph]	+/- Speed [mph]	+/- Speed [%]
11 mph, Segment A	13.66	0.09	0.22	27	0.90	0.008	10.35	0.32	3.1%
Segment B	27.47	0.09	0.31	54	1.80	0.008	10.41	0.20	1.9%
Segment C	41.13	0.09	0.41	80	2.66	0.008	10.52	0.17	1.6%
21 mph, Segment A	14.37	0.09	0.22	13	0.43	0.008	21.00	0.94	4.5%
Segment B	27.67	0.09	0.31	27	0.90	0.008	20.97	0.51	2.5%
Segment C	40.82	0.09	0.41	40	1.33	0.008	20.89	0.40	1.9%
26 mph, Segment A	14.26	0.09	0.22	11	0.37	0.008	26.53	1.31	4.9%
Segment B	27.20	0.09	0.31	21	0.70	0.008	26.51	0.76	2.8%
Segment C	41.45	0.09	0.41	32	1.07	0.008	26.51	0.56	2.1%

Vivint - Analyst #1									
	Distance [ft]	+/- Position 1 [ft]	+/- Position 2 [ft]	Number of Frames	Time [sec]	+/- Time [sec]	Speed [mph]	+/- Speed [mph]	+/- Speed [%]
11 mph, Segment A	7.63	0.01	0.16	2	0.51	0.100	10.19	4.14	40.6%
Segment B	20.27	0.01	0.18	5	1.28	0.100	10.83	1.76	16.3%
Segment C	30.36	0.01	0.29	7	1.79	0.100	11.59	1.35	11.7%
21 mph, Segment A	14.37	0.01	0.16	1	0.26	0.097	26.45	20.49	77.5%
Segment B	20.32	0.01	0.18	2	0.52	0.097	26.53	10.28	38.7%
Segment C	30.55	0.01	0.29	3	0.78	0.097	26.59	6.87	25.9%
26 mph, Segment A	10.29	0.01	0.16	1	0.26	0.097	26.61	20.26	76.1%
Segment B	19.30	0.01	0.18	2	0.53	0.097	24.96	9.50	38.1%
Segment C	29.65	0.01	0.29	3	0.79	0.097	25.56	6.49	25.4%

Sony - Analyst #2									
	Distance [ft]	+/- Position 1 [ft]	+/- Position 2 [ft]	Number of Frames	Time [sec]	+/- Time [sec]	Speed [mph]	+/- Speed [mph]	+/- Speed [%]
11 mph, Segment A	13.70	0.02	0.17	27	0.90	0.007	10.37	0.25	2.4%
Segment B	27.95	0.02	0.15	55	1.84	0.007	10.38	0.12	1.1%
Segment C	42.21	0.02	0.18	82	2.74	0.007	10.52	0.09	0.8%
21 mph, Segment A	14.51	0.02	0.17	14	0.47	0.007	21.17	0.76	3.6%
Segment B	27.93	0.02	0.15	27	0.90	0.007	21.13	0.38	1.8%
Segment C	42.54	0.02	0.18	41	1.37	0.007	21.20	0.26	1.2%
26 mph, Segment A	14.02	0.02	0.17	11	0.37	0.007	26.03	1.14	4.4%
Segment B	28.39	0.02	0.15	22	0.73	0.007	26.36	0.57	2.2%
Segment C	42.38	0.02	0.18	33	1.10	0.007	26.24	0.39	1.5%

Pixel II - Analyst #2									
	Distance [ft]	+/- Position 1 [ft]	+/- Position 2 [ft]	Number of Frames	Time [sec]	+/- Time [sec]	Speed [mph]	+/- Speed [mph]	+/- Speed [%]
11 mph, Segment A	13.70	0.07	0.16	27	0.90	0.008	10.39	0.26	2.5%
Segment B	27.63	0.07	0.28	54	1.80	0.008	10.47	0.18	1.7%
Segment C	41.16	0.07	0.16	80	2.66	0.008	10.53	0.09	0.9%
21 mph, Segment A	14.51	0.07	0.16	13	0.43	0.008	21.27	0.87	4.1%
Segment B	27.81	0.07	0.28	27	0.90	0.008	21.08	0.49	2.3%
Segment C	40.84	0.07	0.16	40	1.33	0.008	20.90	0.28	1.3%
26 mph, Segment A	14.27	0.07	0.16	11	0.37	0.008	26.55	1.23	4.6%
Segment B	27.11	0.07	0.28	21	0.70	0.008	26.42	0.72	2.7%
Segment C	41.57	0.07	0.16	32	1.07	0.008	26.59	0.43	1.6%

Vivint - Analyst #2									
	Distance [ft]	+/- Position 1 [ft]	+/- Position 2 [ft]	Number of Frames	Time [sec]	+/- Time [sec]	Speed [mph]	+/- Speed [mph]	+/- Speed [%]
11 mph, Segment A	7.50	0.03	0.14	2	0.51	0.100	10.02	4.07	40.6%
Segment B	20.16	0.03	0.09	5	1.28	0.100	10.77	1.75	16.2%
Segment C	30.76	0.03	0.15	7	1.79	0.100	11.74	1.36	11.6%
21 mph, Segment A	14.51	0.03	0.14	1	0.26	0.097	26.66	20.65	77.5%
Segment B	20.47	0.03	0.09	2	0.52	0.097	26.72	10.35	38.7%
Segment C	31.05	0.03	0.15	3	0.78	0.097	27.02	6.98	25.8%
26 mph, Segment A	10.32	0.03	0.14	1	0.26	0.097	26.69	20.31	76.1%
Segment B	19.24	0.03	0.09	2	0.53	0.097	24.88	9.47	38.0%
Segment C	29.63	0.03	0.15	3	0.79	0.097	25.54	6.48	25.4%