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Application of Matchmoving for Forensic Video Analysis with Recorded Event Data

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Abstract

A fatal collision involving a pedestrian struck by a public train at a rail station located in a major U.S. metropolitan city was investigated. The train was equipped with an event data recorder that recorded valuable empirical data related to the collision, such as the train speed, braking, and acceleration inputs. However, the original digital version of the data was not available to analyze, and only a single screenshot of the data in an analog graph format was available. The subject train was equipped with multiple video cameras at various vantage points that recorded video footage of the collision. Using the process of "matchmoving" — and with the assistance of three-dimensional LiDAR scanning of the station and train — video footage was analyzed to spatially determine the location of the train in three-dimensional space. The process of matchmoving is an established scientific process used to calibrate a virtual camera to "match" the movement and optic properties of the real-world camera that captured the video. Further analysis was performed to determine the train's kinematics (such as its speed and deceleration rates) leading up to the collision. The accuracy of the matchmoving analysis was then verified with the available event data.

Keywords

Train, pedestrian, matchmoving, LiDAR, 3D high-definition scanning, event data recorder, photogrammetry, accident reconstruction, forensic engineering

Introduction

Around midnight, a pedestrian on the passenger loading platform at a public rail station was waiting alone for a train to board. Due to medical issues, the pedestrian inadvertently fell onto the train tracks. The pedestrian laid on the tracks with minor movements from his arm for several minutes before a train arrived at the station, running over him. As a result of this collision, the pedestrian suffered fatal injuries. In deposition testimony, the train operator stated that during his arrival to the train station, he had observed a foreign object on the train track, but he was unable to tell this was a pedestrian until he got closer. He then testified that once he realized there was a pedestrian on the train tracks, he applied the emergency brakes to attempt to stop the train in an effort to avoid colliding with the pedestrian.

The train was equipped with an event data recorder (also commonly referred to as a "black box"), which recorded valuable digital data related to the incident, including the train's speed, acceleration, and brake application. However, the data in its original format was no longer available at the time of the investigation. The data was limited to a single screenshot of an analog graph. Furthermore, the screenshot of the graph had more than 10 minutes of data compressed and printed onto a single 8.5-inch (in.) by 11-in. PDF document (**Figure 1**).

The train was also equipped with several video cameras that recorded footage at the time of the incident, one of which was located at the train's front car recording a forward view from the train (approximately from the viewpoint of the train operator). The camera recorded video footage at a rate of 5 frames per second (fps) and showed the train approaching the train station. As the train entered the station, a foreign object (determined to be the pedestrian who had fallen on the train tracks) could be observed. The footage then showed the train colliding with the pedestrian before coming to a complete stop (**Figures 2, 3, 4,** and **5**).

The train operator testified that his training as well as his employer's written policy required him to avoid colliding with any foreign object on the train tracks. He further

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testified that the policy was put in place so that train operators do not assume the object could just be trash or debris — that it could actually be a dangerous object or a person instead.

The attorneys representing the estate of the pedestrian on the track theorized that the train operator should have been able to apply the emergency brakes sooner, avoiding the collision. However, the attorneys representing the

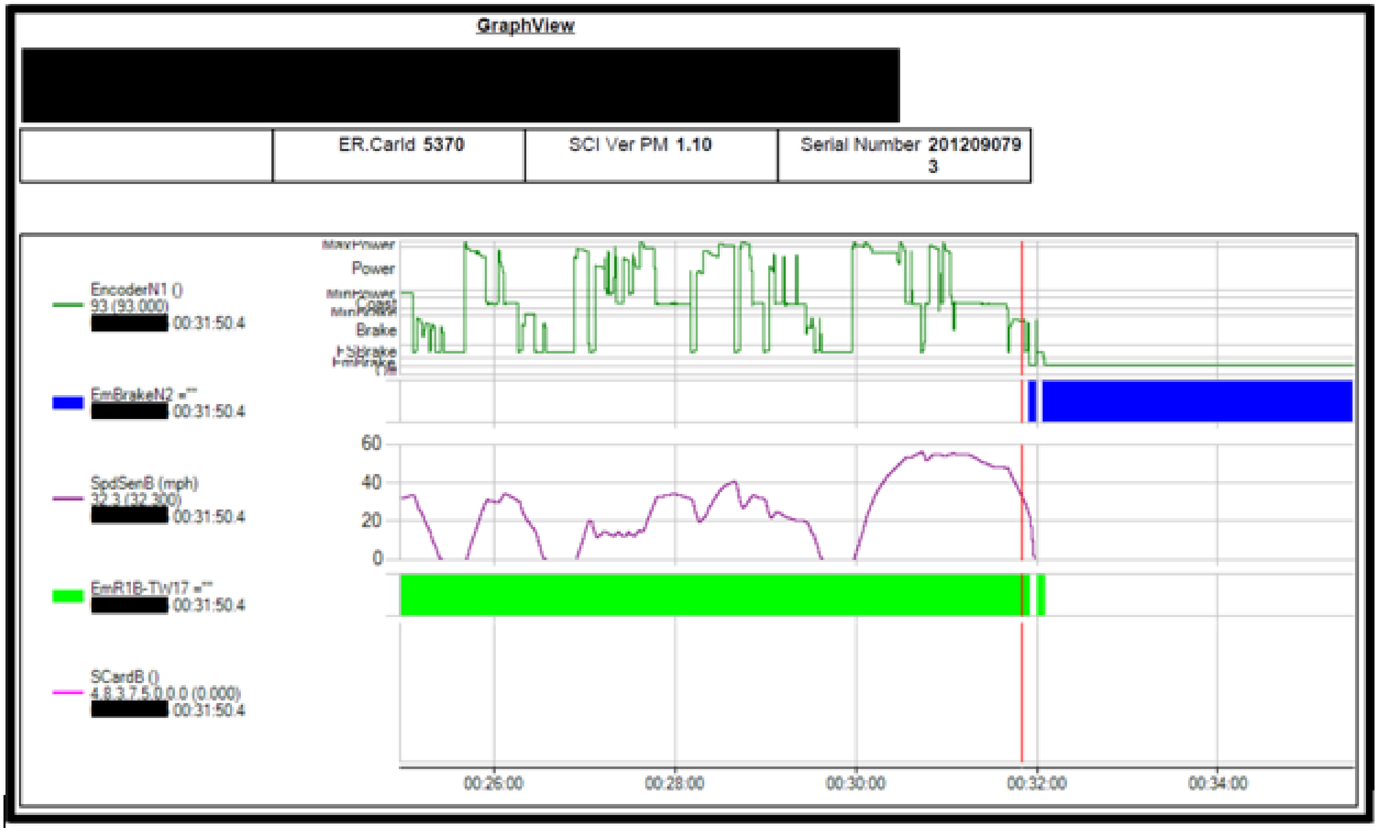

Figure 1

The original screenshot of the graphs that were generated from data recorded by the train's event data recorder at the time of the incident. The graph data traces include the train's speed profile (purple curve), the train's acceleration/service brake input position (dark green curve and light green bar) and the application of the train's emergency brakes (blue bar) as a function of time in minutes.

Figure 2

A screenshot from the footage recorded from the front camera of the train at the time of the incident, showing the train approaching the station.

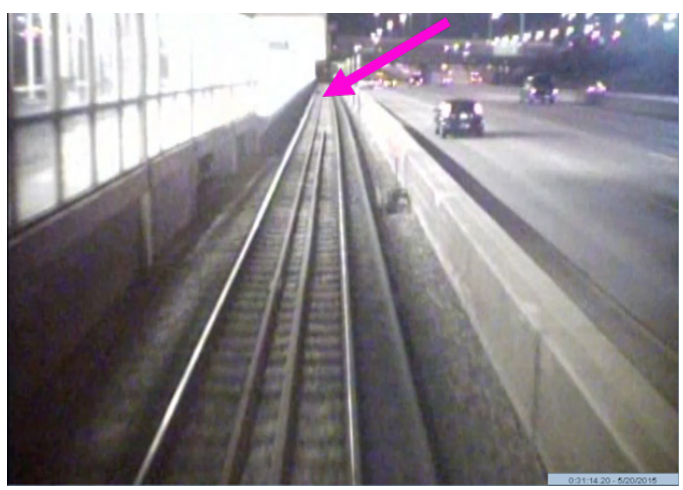

Figure 3

Another screenshot from the footage recorded from the front camera of the train at the time of the incident, showing the train approaching the station's passenger loading platform. The magenta arrow was added to show the position of the pedestrian lying on the train tracks.

Figure 4
Another screenshot from the footage recorded from the front camera of the train at the time of the incident, showing the pedestrian lying on the train tracks. This was the last frame in which the pedestrian was visible before the train collided with him. The magenta arrow was added to show the position of the pedestrian lying on the train tracks.

Figure 5
Another screenshot from the footage recorded from the front camera of the train at the time of the incident, showing when the train came to a stop after colliding with the pedestrian.

train company and the train operator asserted the video and event data clearly showed that the operator did apply the emergency brakes in a timely manner to try and avoid the pedestrian — and that there was simply not enough time and distance to react and avoid an impact.

The authors were tasked with an engineering investigation and analysis of the incident to determine the kinematics of the train during the incident, including how fast the train was traveling when it entered the station, when the train's service brakes and emergency brakes were applied, and when the emergency brakes would need to be engaged to avoid the impact.

The attorneys requested engineering assistance because the point of impact was not clearly known in the event data. In addition, the portion of the data that was of interest, which was approximately a 20-second window leading up to the collision, made up a very small portion of the available graph. Furthermore, the video footage that showed the collision between the train and pedestrian did not include relevant information, such as the train's speed or when its various braking systems were applied. In addition, the timestamp in the event data was offset and out of sync from the timestamp in the video.

Methodology and Analysis

Inspection of the incident site and exemplar train

In conducting the forensic investigation and analysis, the authors inspected an exemplar train car and the subject train station where the collision occurred (**Figure 6** and **Figure 7**). The inspection consisted of taking photographs and performing a high-definition three-dimensional laser scan of the train and the crash site with a high-definition 3D light detection and ranging (LiDAR) scanner. More than 300 million data points were scanned/collected for the exemplar train, and more than 2 billion data points were scanned/collected for the crash site.

Matchmoving Analysis of Video Footage

The photogrammetric process of matchmoving was performed to analyze the recorded footage from the forward-facing camera mounted on the front of the train which documented the subject incident. The process of

Figure 6
Photograph of the train station where the subject incident occurred. The station was inspected and 3D laser scanned. The laser scanner is shown in the foreground.

Figure 7
A photograph of the exemplar train car
that was inspected and 3D laser scanned.

matchmoving is an established scientific process used to calibrate a virtual camera to "match" the movement and optic properties of the real-world camera that captured the video. In conjunction with the established technology of high-definition 3D laser scanning[10,12,13], the process can be used to virtually analyze the movement of objects (e.g., vehicles, pedestrians, etc.) visible in the video captured by moving cameras with high precision. The above process has been peer reviewed and accepted in the forensic engineering industry[1,2,3]. In summary, using principles and techniques based upon photogrammetry[4,5,6,7,8,9,11], each frame of the video can be analyzed to determine the object's position, path, average speed, and average acceleration between video frames.

For this investigation, a 3D point cloud model of the train station, passenger platform, and pedestrian bridge was generated based on 3D high-definition scan data collected during the inspection of the train station. The point cloud model was used to track the train's forward-facing camera through its approach to the train passenger platform and impact with the pedestrian.

The author's firm used widely and publicly available software (Syntheyes) to perform the matchmoving process. First, two-dimensional points (or features) were identified and tracked through multiple frames of the video. Each feature represents a specific point on the surface of some fixed objects of the train station (i.e., structural columns, signs, passenger platform corners, etc.). Each tracked feature was then assigned and constrained to the feature's corresponding three-dimensional coordinates (x, y, z) as defined by the train platform point cloud (**Figure 8**).

Figure 8
Screenshot showing a sample of the three-dimensional (x, y, z) coordinate data from the train station
point cloud model used to constrain the corresponding two-dimensional trackers.

Using the two-dimensional trackers and their given three-dimensional x, y, z coordinate constraints, the software mathematically solved for (or "calibrated") a virtual camera (relative to the train platform point cloud) that emulates the lens characteristics and movement of the real-world camera used to record the footage.

With the virtually calibrated camera and the train station point cloud model imported into the 3ds Max software by Autodesk, the authors were able to view the original footage through the virtual camera and track the position of the pedestrian on the tracks. This position, along with the movement of the camera, allowed the authors to determine the train's movement and distance over time, as it approached the passenger platform to the point of impact and to the train's resting position (**Figure 9** and **Figure 10**).

Since the framerate of the video was known to be 5 fps, the train's average speed between each video frame was then determined based on the matched positions of the train at each frame and the frame rate of the video with the below calculation:

$$S = \frac{\sqrt{(\Delta X)^2+(\Delta Y)^2+(\Delta Z)^2}}{\Delta t}$$

Where:

S = Speed of the train for that video frame

ΔX, ΔY, ΔZ = The train's change in distance between the current frame and the previous frame in the three-dimensional space (X, Y, Z).

Δt = the elapsed time between video frames or the inverse of the video's framerate.

The speed profile of the train at the time of the incident was then graphed as a function of time (**Figure 11**).

To verify the train's speed profile that the authors determined through the matchmoving process, the speed profile graph from the train's event data recorder was transformed by scaling and zooming in so that the time and speed scales were the same (**Figure 12**). The two independent speed profiles were then overlaid onto each other so that the profiles could be compared (**Figure 13**). The comparison of the speed profiles showed the train's speed (determined through matchmoving) closely matched the speed recorded by its event data recorder. The above analysis and verification with event data determines that the matchmoving process when used with recorded video footage can analyze the movement of the train with accuracy, resulting in a reliable method to determine the train's

Figure 9
The video footage (center and red box) overlaid onto the 3D point cloud model of the train station, showing how the footage matches up with reference features, such as the station's structural columns, signs, passenger platform corners, and the barrier separating the train from the road highway.

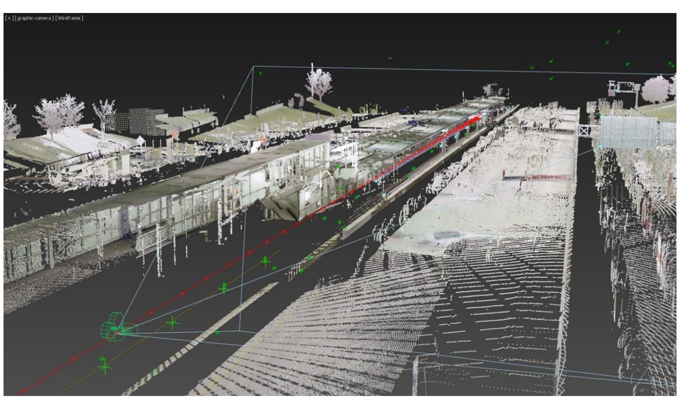

Figure 10
Screenshot from the computer software showing the path (red line) of the camera (green camera icon) mounted on the train in the 3D point cloud model of the train station, determined through the process of matchmoving.

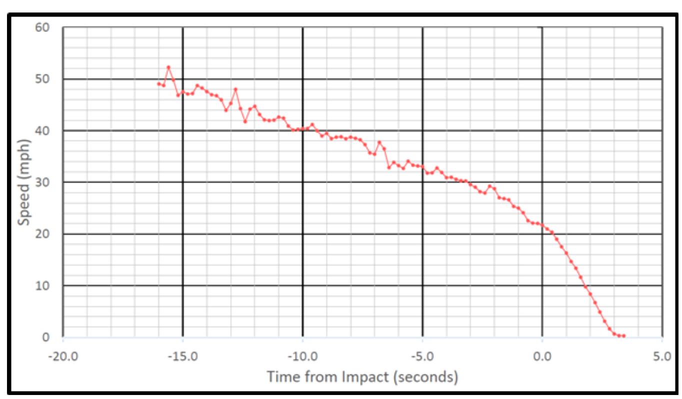

Figure 11
The train's speed profile determined through matchmoving analysis. Impact with the pedestrian occurred at "time from impact" = 0 seconds.

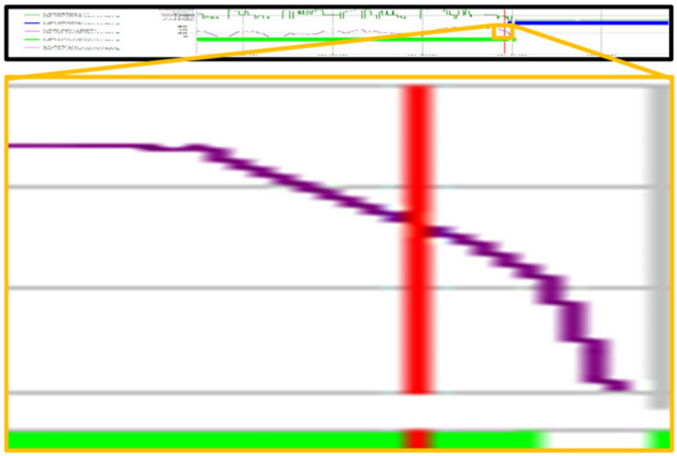

Figure 12
The graph generated by data recorded from the train's event data recorder scaled to match the speed and time scale of **Figure 11** (black boxed). The speed profile graph zoomed in to the portion of interest and to compare with **Figure 11** (orange box). It should be noted that the speed profile appears distorted/blurry because the graph was zoomed into and scaled so that the time and speed scales of the speed profiles could be matched up.

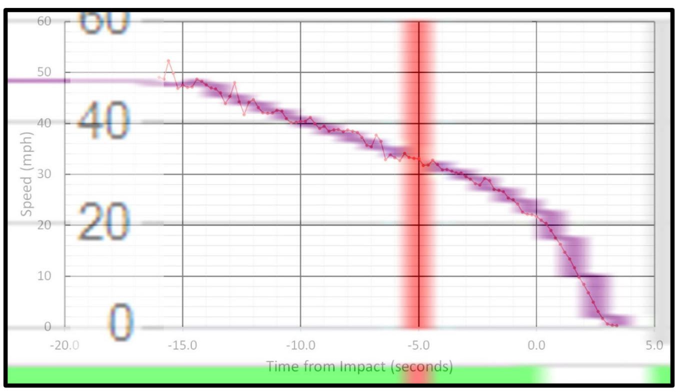

Figure 13
The train's speed profile determined through the matchmoving analysis (**Figure 11**) overlaid onto the speed profile generated by the train's event data recorder (**Figure 12**).

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Train Braking Analysis

The train was equipped with three independent braking systems. Based on the train's specifications provided by the train operating company, the following is a description of each of the braking systems and their maximum specified deceleration rates:

1. *Electric brake* — The train is equipped with electric motors. Depending on the position of the throttle control, the polarity to the motors can provide acceleration or deceleration to the train. The electric brake acts as the train's service brakes during normal operation and has a specified maximum deceleration rate of 2.8 miles per hour per second (or 0.13 g).

2. *Friction brake* — Similar to disc brakes seen on automobiles, the friction brake has a specified maximum deceleration rate of 2.5 miles per hour per second (or 0.11 g).

3. *Track brake* — Magnetically decelerating the train with an electromagnet that acts on the train's rails, the track brake has a specified maximum deceleration rate of 1.0 miles per hour per second (or 0.046 g).

The train operator can also activate the train's emergency braking system, which simply applies all three of the train's braking system simultaneously. The train operating company specified the train's maximum theoretical deceleration rate was the summation of the deceleration rates for each individual braking system. Therefore, during emergency braking, the train's effective specified maximum theoretical deceleration rate was 6.3 miles per hour per second (or 0.29 g).

From the train's speed profile determined through the matchmoving process, the train's deceleration rate during the incident was determined with the following calculation:

$$a = \frac{\Delta S}{\Delta t}$$

Where:

a = acceleration of the train in a specific time frame (negative value is deceleration)

ΔS = the change in the train's speed in a specific time frame

Δt = the elapsed time between a specific time frame

From the above analysis, the authors determined that as the train approached the passenger platform, the train decelerated at an average rate of approximately 1.81 miles per hour per second (or 0.082 g). Since the deceleration rate was about 64 percent of the specified maximum deceleration rate of 2.8 miles per hour per second (or 0.13 g) for the service brakes, the train was decelerating at a rate below the maximum rate that the service brakes could provide. This was consistent with the train gradually slowing down to a planned stop at the station.

At approximately 0.8 seconds before the train collided with the pedestrian, the train decelerated at a much higher rate until it was brought to a complete stop at approximately 3.4 seconds (or 53 feet) after impact. The deceleration rate in the above time frame was approximately 5.7 miles per hour per second (or 0.26 g), which is well above the maximum rate the service brakes could provide and just below the emergency brake's specified maximum theoretical deceleration rate of 6.3 miles per hour per second (or 0.29 g). Therefore, the above analysis showed the emergency brakes were not engaged until approximately 0.8 seconds before the train collided with the pedestrian — or when the train was approximately 26 ft from the pedestrian (see **Figure 14**).

As previously discussed, the train's event data recorder recorded the train's service brake and emergency brake application at the time of the incident. Like the speed profile recorded by the event data recorder, the brake input data was used to verify the deceleration calculations above. The braking input graphs had line and bar traces that showed when each of the braking systems were applied as a function of time. Also like the speed profile, the braking input traces were overlaid onto the train's speed profile determined through the matchmoving process, and the graphs were scaled until the time scales were the same (**Figure 15** and **Figure 16**). The event data recorder

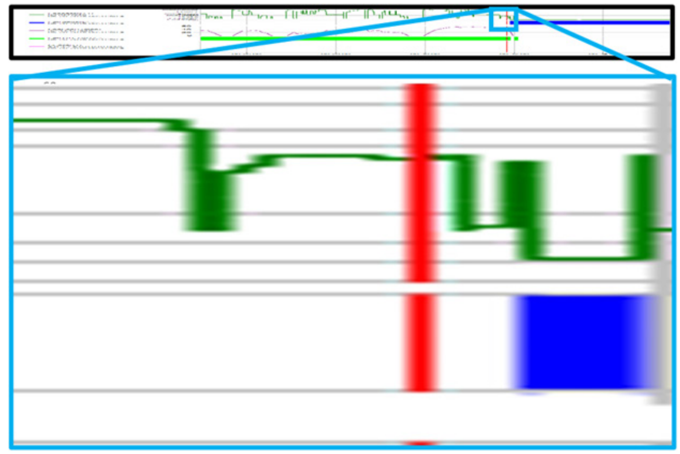

Figure 15
The graph generated by data recorded from the train's event data recorder scaled to match the time scale of **Figure 11** (black box). The service and emergency braking graph zoomed in to the portion of interest and to compare with **Figure 11** (blue box). The braking input traces appears distorted/blurry because the original graph was low resolution, and the graph was zoomed into and scaled so the time and speed scales of the speed profiles could be matched up.

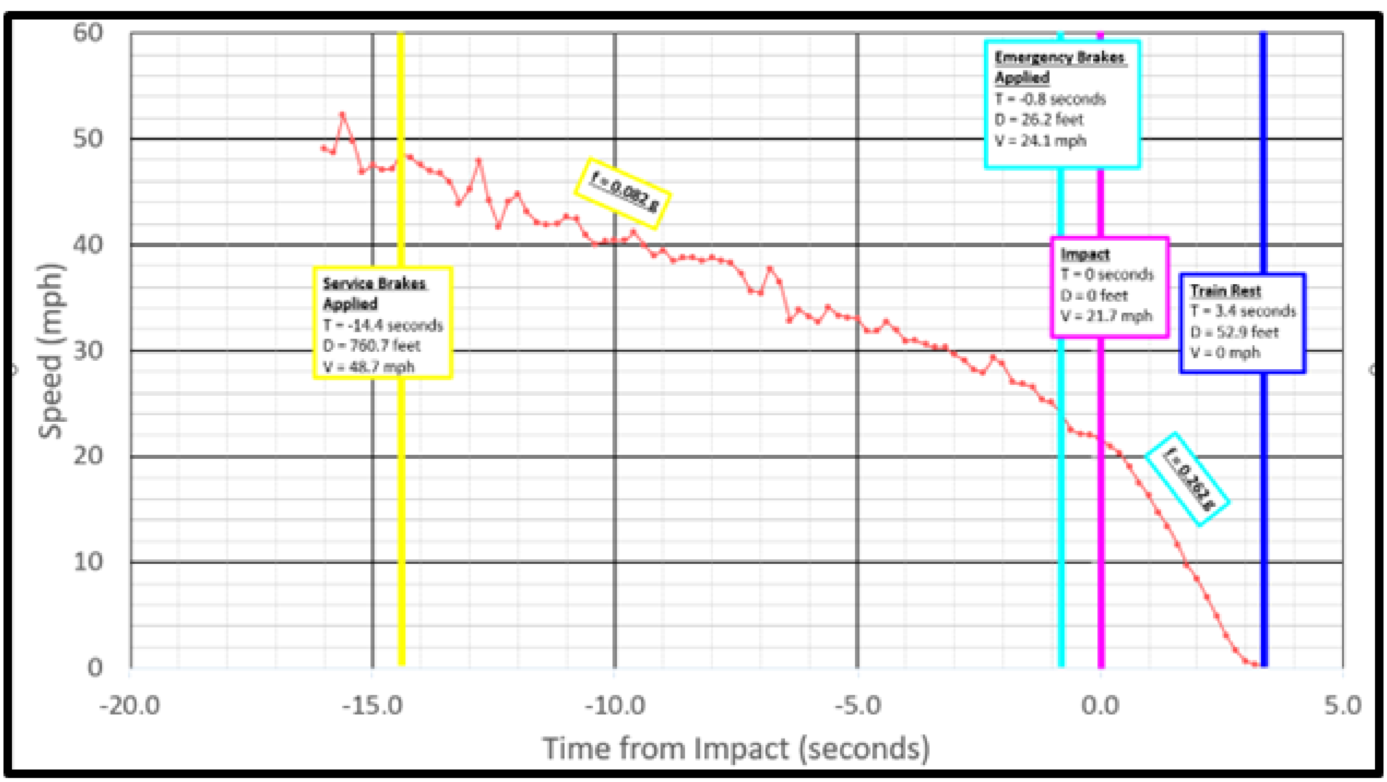

Figure 14
The train's speed profile determined through the matchmoving analysis with callouts showing when the train's service and emergency brakes were engaged in relation to the point of impact with the pedestrian.

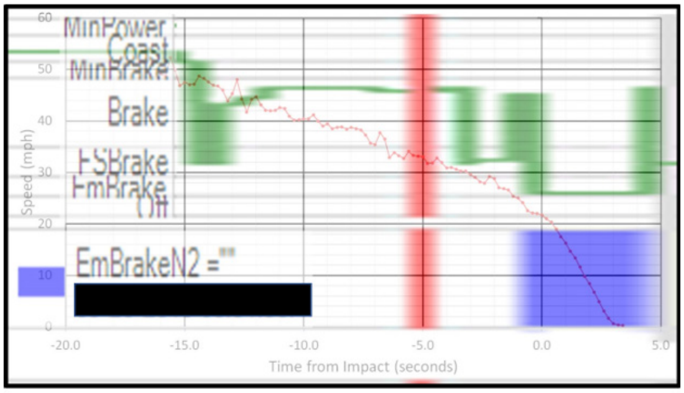

Figure 16
The speed profile determined through the matchmoving analysis (**Figure 11**) overlaid onto the service and emergency braking input traces generated by the train's event data recorder (**Figure 15**). The train's service brake input indicated with the dark green line and the application of the train's emergency brakes indicated with the blue bar.

verified and confirmed the authors' analysis, which showed the train's service brakes were applied as the train approached the station, but the emergency brakes did not engage until approximately 0.8 seconds before the train collided with the pedestrian.

Further analysis was performed to determine the points in time that the emergency brakes could be engaged to bring the train to a complete stop and avoid colliding with the pedestrian. Absent of perception-reaction time, the following formula was used to determine the distance the train would need to stop with the emergency brakes engaged based on a given speed:

$$d_{brake} = \frac{S^2}{(2*f*g)}$$

Where:

d_{brake} = the distance it takes for the train to come to a complete stop

S = Speed of the train at the given time

f = the train's emergency braking deceleration rate, 0.26

g = gravitational constant

The calculation was performed at every video frame to determine the distance the train would need to decelerate to a stop and to avoid impacting the pedestrian. Based on the above calculations, the authors determined the emergency brakes would need to engage when the train was at least 3.0 seconds from impact (or at least 114 ft from the pedestrian) to avoid the impact. The train was traveling approximately 30 mph at this time (**Figure 17**).

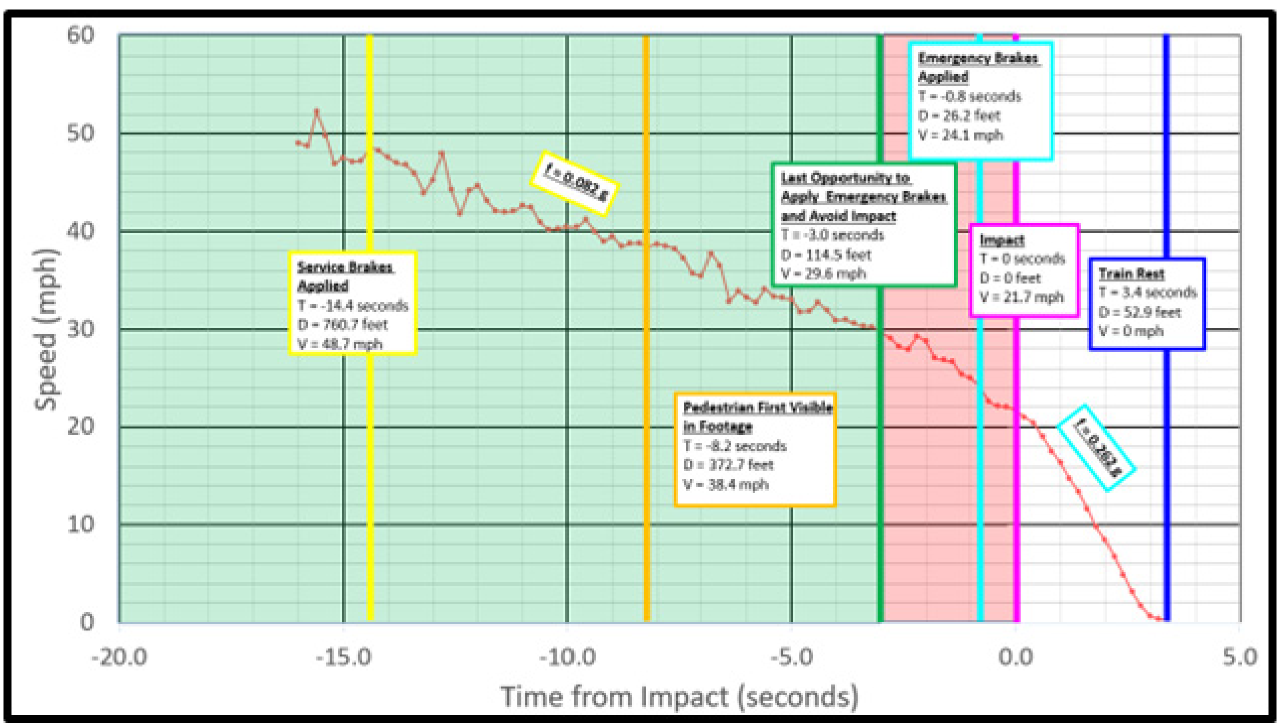

Figure 17
The train's speed profile determined through the matchmoving analysis with callouts showing when the pedestrian was first visible in the footage and the points in time the impact was avoidable (green) and unavoidable (red) had the emergency brakes been engaged at that time.

The authors then overlaid the train's speed, time to impact, distance to impact, type of braking system applied, and whether the collision would have been avoidable had the emergency brakes been engaged sooner at each frame in the video. Below are screenshots showing when the emergency brakes were applied and what points in the footage the collision was avoidable had the emergency brakes been engaged sooner (**Figure 18**).

Discussion and Conclusions

This paper demonstrates that using video footage from moving objects with sufficient visual detail for identifying reference points/features, allows for the determination of positions, speeds, and acceleration rates of the moving object and stationary objects using the photogrammetric method of matchmoving. In addition, through verification and confirmation with data by the train's event data recorder, the paper further validates that the process of matchmoving is a highly accurate and reliable methodology in the field of accident reconstruction and forensic engineering.

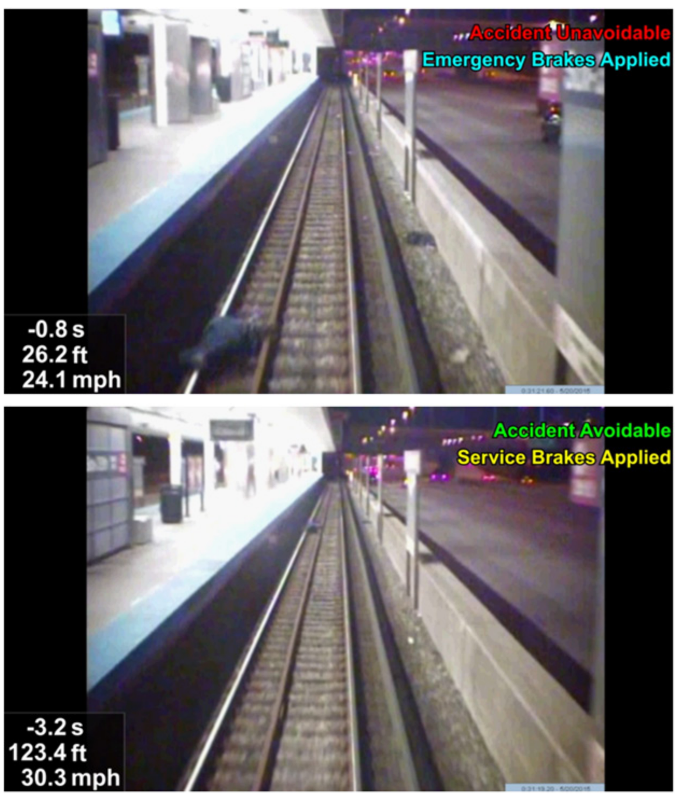

Figure 18
Screenshots of footage recorded from the front of the train at the time of the incident with the train's speed, time to impact, distance to impact, which braking system was applied, and whether the collision would have been avoidable at that moment in time. These screenshots show the moment that the operator applied the emergency brakes during the incident (top) and when the collision was avoidable — had the emergency brakes engaged sooner (bottom).

The above methodology is not limited to analyzing the kinematics of trains and pedestrians; it can be applied to other moving objects, such as automobiles, motorcycles, bicycles, aircrafts, and marine vehicles. Providing valuable data and information for triers of fact, this process can be especially useful in reconstructing accidents when a video of the incident is available but there is a lack of physical evidence or when recorded event data is limited or no longer available/accessible.

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