Journal of the National Academy of Forensic Engineers®

NATIONAL ACADEMY OF FORENSIC ENGINEERS

http://www.nafe.org
ISSN: 2379-3252

Vol. 37 No. 1 December 2020

Forensic Engineering Analyses of Right-Turning Trucks Impacting Bicyclists

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Abstract

Right-turning trucks present a serious hazard to bicyclists. When a collision between a right-turning truck and a bicyclist occurs, the truck driver often does not realize an impact occurred, and the bicyclist is pushed down and dragged by the truck. Such collisions result in serious injury or death. Forensic engineers are retained to investigate and reconstruct such complex collisions. Oftentimes, there are disputes between forensic engineers as to the impact location, visibility, and reaction processes of both the driver and bicyclist. For example, physical evidence related to impact is usually faint and is a subject of debate between forensic engineers. Forensic engineers also disagree on the direct line-of-sight or line-of-sight through mirrors. Further, reactions (or lack thereof) are typically subject to debate. This paper presents the application of various techniques and methodologies to effectively reconstruct collisions between right-turning trucks and bicyclists. Such techniques and methodologies include the identification and verification of faint physical evidence regarding impact location using computer simulation and/or testing, the use of high-definition laser scans and virtual scenes to replicate mirror line-of-sight or obstruction line-of-sight, evaluation of driver and bicyclist reaction processes, and the use of scientific visualizations to effectively communicate complex issues of a case.

Keywords

Semi, truck, bicycle, pedestrian, accident reconstruction, high-definition laser scanning, mirror, side mirror, line-of-sight, perception, reaction, physical evidence, right-turning truck, multibody simulation, scientific visualization, PC-Crash, forensic engineering

Introduction

Forensic engineers are often retained to investigate and reconstruct complex incidents involving a right-turning truck impacting a bicyclist. This paper is a compilation of advanced scientific methodologies available to forensic engineers for evaluating such complex collisions. The methodologies are presented in the form of two case studies.

Case Study 1: Pillar Line-of-Sight Obstruction

A bicyclist was riding on the sidewalk under a newly constructed overpass on the sidewalk (**Figure 1**). The bicyclist approached the crosswalk shown in **Figure 1** with a pedestrian signal illuminated with a "walk" designation. As the bicyclist approached the crosswalk, a truck was turning right on a green light into the path of the bicyclist. However, the bicyclist testified he did not see the truck due to an overpass pillar obstructing his view until moments before impact. The bicyclist steered sharply to the left but was unable to avoid the collision. Similarly, the truck driver claimed he did not see the cyclist, but rather felt a minor bump at impact. As a result of the collision, the bicyclist was thrown onto the ground and dragged under the truck's front axle for 65 ft, sustaining serious injury.

The plaintiff was the seriously injured bicyclist, and

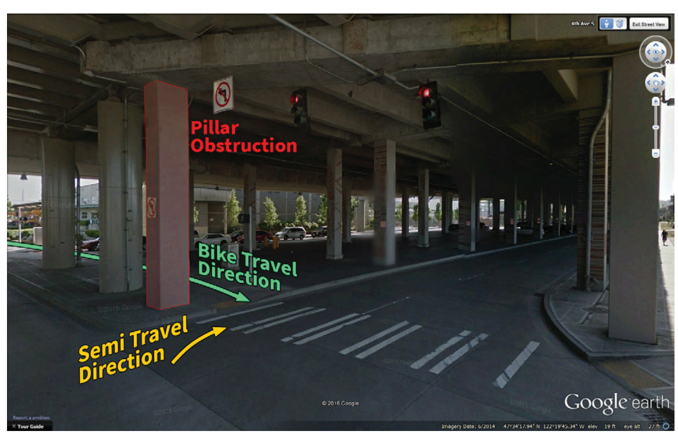

Figure 1
Path of bicyclist and semi pre-impact.

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DOI: 10.51501/jotnafe.v37i1.119

the primary defendant was the city for improperly designing the placement of the crosswalk such that there was a line-of-sight issue between pedestrians and right-turning vehicles due to the pillar obstruction. The purpose of the forensic investigation was to determine whether or not the pillar created a visual obstruction to both the bicyclist and right-turning truck driver and whether or not the bicyclist's reaction was reasonable for the conditions. Methodologies used for this forensic engineering analysis included:

1. Enhancement of photographs to identify faint physical evidence.
2. Determining the impact configuration based on physical evidence.
3. Simulating the accident.
4. Conducting a line-of-sight study to determine whether or not the pillar caused a visual obstruction.
5. Evaluating the bicyclist's reaction to determine whether or not the bicyclist reacted reasonably.

Enhancement of Photographs to Identify Faint Physical Evidence

The first step to reconstructing right-turning truck vs. pedestrian accidents is to study the police report, scene surveys, witness statements, and photographs. Witness statements and scene surveys can be used to generally identify the impact location. However, witnesses are often inconsistent in reporting the impact location, and police surveys often miss faint physical evidence that establishes the area of impact. Therefore, the investigating forensic engineer must carefully examine scene photographs for evidence that may have been overlooked during the initial scene investigation.

Bicycle tires will often leave some sort of scrubbing evidence on the roadway during impact. However, such evidence is often very faint and overlooked. Failure to identify such faint evidence may result in improper positioning of the area of impact, which may adversely affect the entire investigation. Therefore, digital scene photographs must be thoroughly analyzed before reaching the conclusion that there was no evidence related to impact or mistaking more pronounced evidence after the collision, such as the bicycles dragged along the roadway, as the area-of-impact.

Figure 2
Scene photograph with brightness and contrast adjusted to identify faint physical evidence related to impact.

A useful technique for identifying potential physical evidence related to impact is through the adjustment of brightness and contrast of digital scene photographs. **Figures 2** and **3** show scene photographs taken by police with the brightness and contrast adjusted to identify potential evidence related to the area-of-impact in the first case study.

The locations of the marks were established using the principles of photogrammetry[1,2,3,4,5,6,7,8]. The photogrammetry process first involved correcting the photograph for lens distortion. Next, real-world 3D coordinates were established for 2D objects seen in the photograph using the point cloud generated from high-definition laser scanning. Commercially available dedicated photogrammetry software (PhotoModeler) then solved for virtual camera positioning, orientation, and properties matching that of the real-world camera that took the photograph.

Figure 3
Scene photograph with brightness and contrast adjusted to identify faint physical evidence related to impact.

Figure 4
Viewing the high-definition point cloud through a virtual camera that matched the properties and orientation of the real-world camera that took the photograph. Faint tire marks "painted" onto the point cloud, thereby establishing the locations of the tire marks.

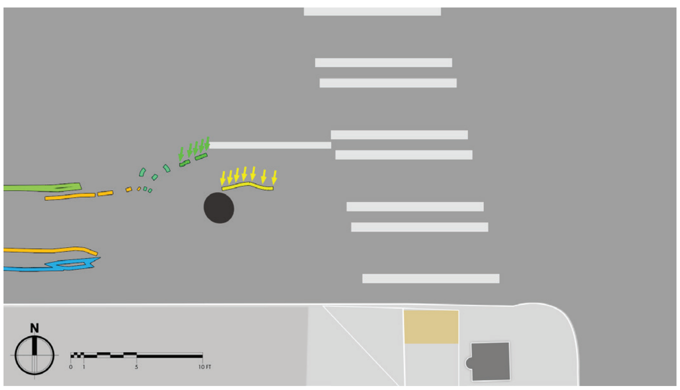

Figure 5
Locations of the faint tire marks from top view (shown with arrows).

The virtual camera was then put into the virtual point cloud scene. By viewing the point cloud through the virtual camera, the marks were "painted" onto the point cloud, thereby establishing the positions of the marks (**Figures 4** and **5**).

Impact Configuration Based on Physical Evidence

The impact configuration between the right-turning truck and bicycle was established using physical evidence on the truck's front bumper and bicycle. Scratches were observed on the truck's front bumper consistent with an impact with a bicycle (**Figure 6**).

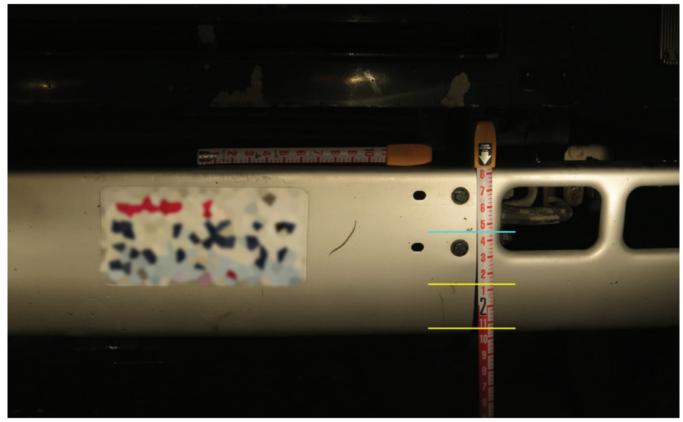

Figure 6
Evidence on truck bumper. Horizontal lines added to show scrape heights.

The locations of the bumper scrapes were added to a virtual truck model to-scale. A scaled virtual bicycle was aligned with the truck's bumper so that the bicycle was properly aligned with the bumper scrapes. The bicycle's rear bike rack aligned with the contact marks on the bumper (**Figure 7**).

The bicycle's rear rack was deformed, consistent with impact between the semi's front bumper and the right side of the bicycle's rear rack. **Figure 8** shows the rack damage and approximate principal direction of force (PDOF), a term defined to simplify collision analysis. The PDOF is the direction of the summation of all collision forces required to deform the vehicle. The PDOF was consistent with an angled impact between the truck bumper and bicycle (**Figure 9**).

PC-Crash Simulation Turning Dynamics

PC-Crash was used to simulate the dynamics of the truck's turn[9,10,11]. First, the PC-Crash scene and tractor-trailer were developed. The point cloud from the high-definition laser scan of the accident site was used to generate a terrain mesh of the accident site. The terrain mesh and physical evidence locations were imported into the PC-Crash scene. A scaled truck model was also imported into the scene.

Figure 7
Virtual model of bicycle aligned with bumper scrapes. The bicycle's rear rack aligned with the bumper scrapes.

Timing of similar-sized exemplar right-turning trucks at the intersection were provided. The timing values were used to establish acceleration and velocity profile for the truck that were input into the PC-Crash simulation. The path of the model truck was adjusted until the simulation of the truck's path matched the physical evidence and rest position of the truck (**Figure 10**).

PC-Crash Multibody Impact Simulation

After the truck's turning dynamics and path were established in PC-Crash. A multibody impact simulation was used to simulate the collision between the truck and the bicycle. The purpose of the multibody impact simulation was to:

1. Verify impact speed estimate based on exemplar turning truck dynamics.

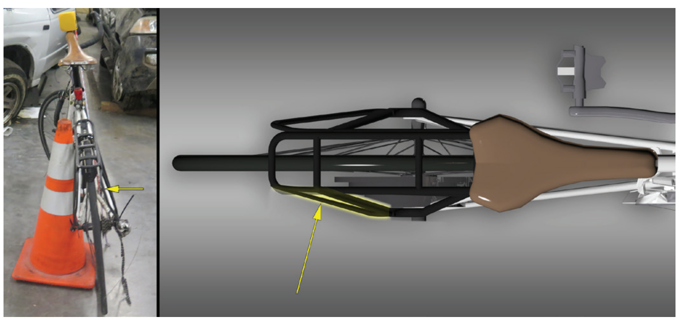

Figure 8
Inspection photograph of subject bicycle. Yellow arrow showing deformation to the right side of the bicycle's rear rack.

Figure 9
Bicycle rear-rack damage consistent with angle between truck bumper and bicycle at impact. The bicyclist is shown diagrammatically. In actuality, the front wheel of the bicyclist was leaning in a turn in response to the pending impact.

2. Validate whether or not faint physical evidence was related to the incident.

3. Refine area of impact.

4. Provide scientific imagery of the impact phase of the collision.

The bicycle multibody simulation involved first modeling the bicycle multibody and rider. A pre-packaged bicycle and rider multibody model was used as a template. The bicycle and rider multibody geometry, size, and weight were adjusted to closely match those of the subject bicycle and rider (**Figure 11**).

Further, using the PC-Crash simulation software's multibody model of bicycle and rider, the joint properties of the bicycle were adjusted by the authors to allow articulation of the front wheel and handlebars that were not included in the template multibody model. The articulation of the front wheel and handlebars allows from more realistic post impact movement of the bicycle.

The multibody bicycle was placed in the established

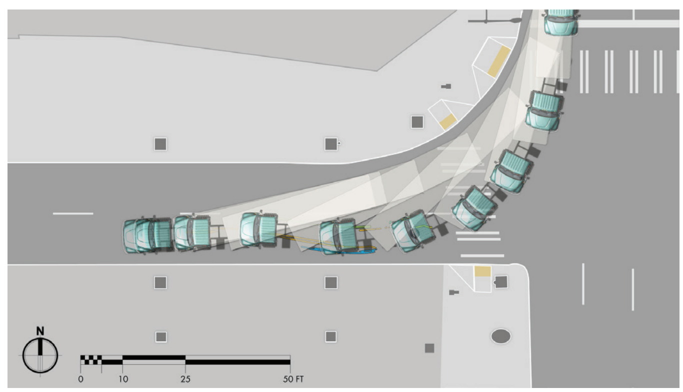

Figure 10
Turning dynamics of the truck based on the physical evidence and rest position of truck simulated using PC-Crash. The location of physical evidence is depicted in Figures 2, 3, 4, and 5.

Figure 11
Bicycle and rider multibody model (left) closely matching the geometry, size, and weight of the subject bicycle and rider (right).

Figure 12
Impact progression of bicycle and rider based on PC-Crash simulation.

impact configuration relative to the truck based on analysis of the physical evidence. Simulations were conducted at various impact locations along the turn path of the truck until the impact dynamics of the bicycle best matched the physical evidence. **Figure 12** shows the progression of impact matching the physical evidence based on the PC-Crash simulation.

The bicycle movement after impact shown in **Figure 12** shows the that faint physical evidence identified in scene photographs is consistent with the bicycle's tires scrubbing against the ground as the bicycle was pushed down. After the bicycle was pushed down, the semi-tractor's right front wheel ran over the bicycle's front wheel creating an imprint in the pavement.

Bicycle Pre-Impact Motion

After the and impact configuration were established based on physical evidence and multibody simulation, pre-impact motion of the bicycle was simulated using PC-Crash using a kinematic simulation model. The pre-impact trajectory of the bicycle was based on the deposition testimony of the bicyclist. The bicyclist testified that he was riding on the right side of the sidewalk and swerved when he first observed the truck beyond the pillar. **Figure 13** shows the trajectory of the bicycle leading to impact and the throw distance of the bicycle.

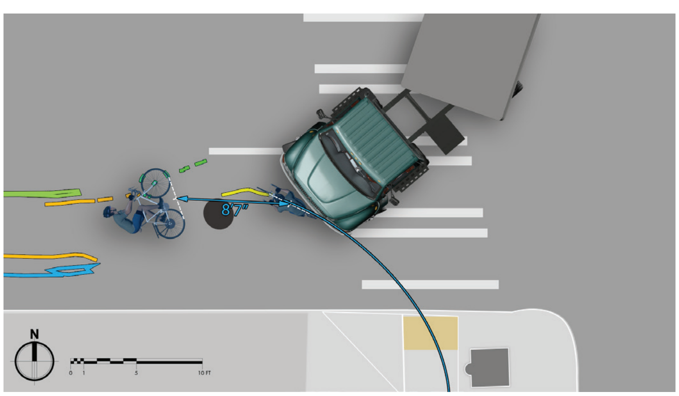

Figure 13
Simulated trajectory of bicycle pre-impact and throw distance of bicycle.

Line-of-Sight Evaluation (Obstruction)

After simulating the motion of the truck and bicycle pre-impact, line-of-sights can be evaluated if needed. The process of evaluating line-of-sight can be done in either 2-D and 3-D space. PC-Crash's "sight-lines" feature was used to draw a sight line between the bicyclist and the corner of the truck. **Figure 14** shows the sight-line in 2D and the sight-line in 3D within PC-Crash.

Case Study 1: Conclusions

The sight-line analysis showed the bicyclist first saw the truck turning approximately 2.25 seconds before

Figure 14
2D line-of-sight (left) and 3D line-of-sight in PC-Crash.

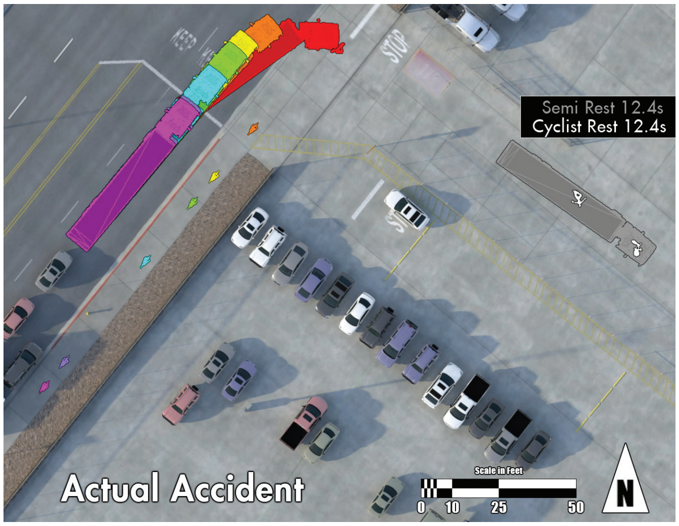

Figure 15
Bicyclist was riding on sidewalk and was struck by right-turning semi. Bicyclist was dragged 95 ft after impact.

impact. Pre-impact simulation showed that the bicyclist reacted for approximately 1 second and then made a swerve maneuver to the left to avoid the semi. However, the bicyclist was unable to avoid impact and was struck by the semi. Therefore, the line-of-sight obstruction contributed to the bicyclist's inability to react in time to avoid being impacted by the semi.

Case Study 2: Truck Turning into Warehouse Driveway

A bicyclist was riding on the sidewalk during rush hour traffic. The bicyclist approached the driveway to a warehouse facility. According to witnesses, a semi-tractor was stopped and was preparing to make a right turn into the driveway. As the bicyclist approached the driveway, the semi-truck driver turned in front of the bicyclist The bicyclist was struck by the semi and dragged under the semi-tractor approximately 95 ft before the truck stopped. As a result of the collision, the bicyclist sustained serious injuries. A general graphic showing the movement of the truck and bicycle is shown in **Figure 15**.

Figure 16
Plotted scene survey data.

The purpose of the investigation was to determine whether or not the bicyclist reacted reasonably to the truck and to determine whether or not the truck driver could have seen the bicyclist had the driver used his side-mirrors. Methodologies used for this forensic engineering analysis included:

1. Identification of faint physical evidence related to the area-of-impact.
2. Determining the impact configuration based on physical evidence.
3. Using video footage and videogrammetry to test exemplar truck motion.
4. Simulating the accident and evaluation of the bicyclist's reaction.
5. Testing to validate faint physical evidence related to the area-of-impact.

Figure 17
Cropped scene photograph analyzed for faint physical evidence related to impact.

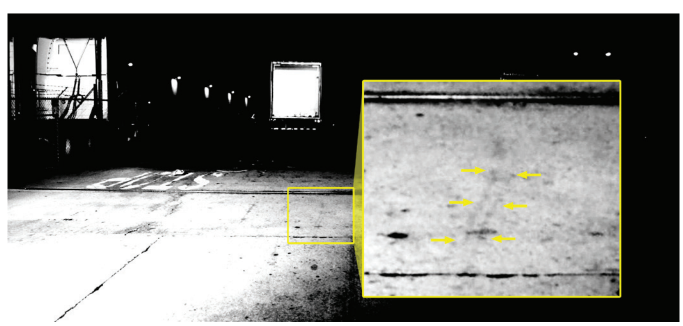

Figure 18
Scene photograph in black-and-white with adjusted brightness and contrast. Arrows pointing to suspected tire scrub marks related to impact.

6. Using high-definition scans to create virtual mirror models to test mirror line-of-sight.

Identifying Area of Impact

The police photographed and surveyed the accident scene. **Figure 16** shows a scene diagram depicting physical evidence surveyed by scene investigators. While the survey was very thorough, there was no evidence identified in the survey that was clearly related to impact.

Figure 19
Subject bicycle (left) and exemplar bicycle (right). Subject bicycle and exemplar bicycle had the same brand and model tires.

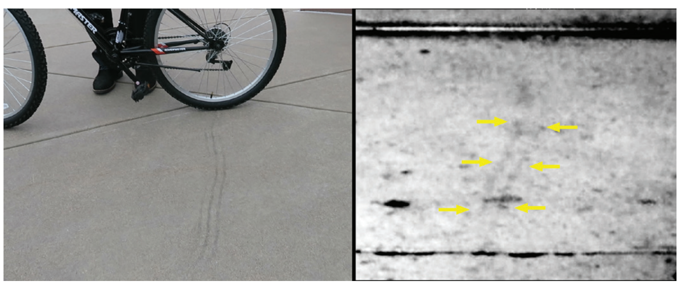

Figure 20
Tire scrub marks generated through testing (left) consistent with scrub marks identified in scene photograph (right).

Figure 21
Scrapes on right corner of truck's front bumper consistent with the bumper impacting the bicycle's frame.

Therefore, the scene photographs were evaluated to identify faint physical evidence consistent with impact, such as bicycle tire scrubbing against the pavement.

Similar to the first case study, the contrast and brightness of scene photographs in the second case study were adjusted to identify potential evidence related to the area-of-impact. **Figure 17** shows an original scene photograph, and **Figure 18** shows the same scene photograph in black-and-white with contrast and brightness adjusted. **Figure 18** also shows faint physical evidence suspected as a bicycle tire scrubbing mark during impact.

Testing to Confirm Tire Mark Pattern

After identifying suspected scrub marks related to impact, testing was conducted to establish whether or not the marks were consistent with tire scrub marks during impact. An exemplar bicycle with the same make of tires as the subject bicycle was tested (**Figure 19**).

The exemplar's bicycle tires were inflated to the manufacturer's recommended operating pressure. The bicycle was then pushed down and dragged, closely replicating the motion of the bicycle pushed down by a semi's bumper. **Figure 20** shows the bicycle tire formed parallel scrub marks similar to the faint marks identified in the scene photographs. Therefore, the parallel scrub marks identified in the scene photograph is consistent with scrub marks left by the subject bicycle's rear tire as it is pushed down by the truck.

Impact Configuration Based on Physical Evidence

The truck was inspected for physical evidence related to impact. There were scrape marks surrounding the corner of the right front bumper consistent with the bumper impacting the bicycle's frame (**Figure 21**). There were also scrub marks on the front bumper consistent with the front bumper impacting the front tire of the bicycle (**Figure 22**).

Truck Turning Dynamics and Simulation

Several exemplar trucks were video recorded making right turns into the facility. One of the trucks had very similar geometry as the subject truck and made a wide turn into the driveway very similar to the turn made by the driver during the incident.

The video footage of the truck was processed using the principles of videogrammetry (or the application of photogrammetry to multiple frames of a video) to identify the acceleration profile of the exemplar truck. The

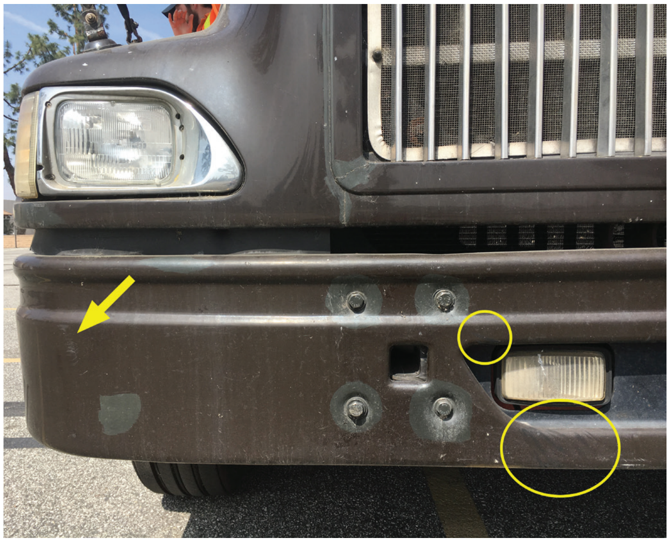

Figure 22
Scrapes on front corner (arrow) and front bicycle tire scrub marks (circles) on truck's front bumper.

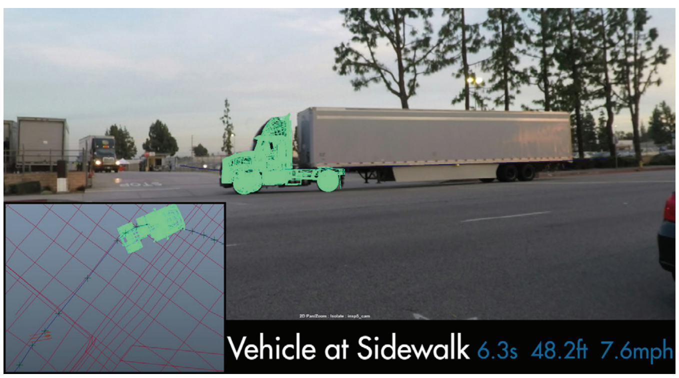

Figure 23
Example of camera matched virtual truck model position overlaid on video footage.

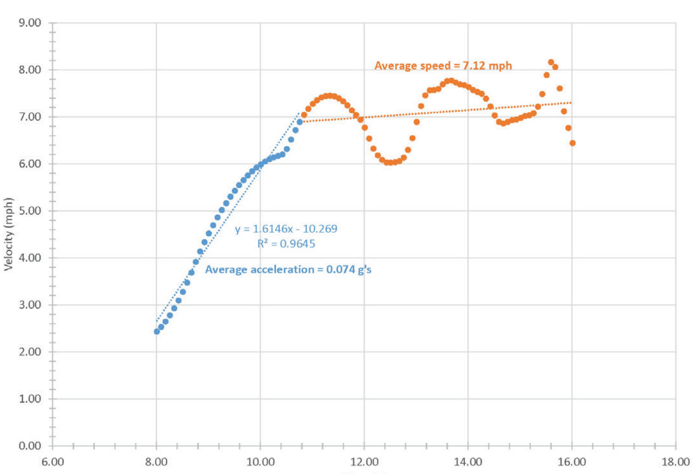

Figure 24
Velocity and acceleration of exemplar making wide right turn.

videogrammetry process involved first calibrating the camera used to capture the video to correct for lens distortion.

High-definition laser scan data was then used to identify real-world coordinates of fixed objects seen in the video footage. The real-world coordinates were then input into the photogrammetry software to solve for the video-camera's properties, position, and orientation. After solving for the video-camera's properties, position, and orientation, a virtual camera was placed into a virtual scene with the point cloud generated from the high definition scanning. Captured video frames were placed in the virtual scene. The 3D model of the truck was placed into the scene to match the position and orientation of the truck seen in the video footage over multiple frames (**Figure 23**).

After matching the position and orientation of the truck over multiple frames, the velocity and acceleration of the truck were determined throughout the video sequence. **Figure 24** shows the velocity profile of the exemplar truck making a right turn. The exemplar truck accelerated at approximately 0.074 g's and reached a peak speed of approximately 7 mph during the turn.

After establishing the acceleration rate and peak speed of an exemplar truck turning into the facility, PC-Crash was used to simulate the dynamics of the truck's turn. The acceleration and peak speed values were input into the PC-Crash simulation. The path of the model truck was adjusted until the simulation of the truck's path matched the physical evidence and rest position of the truck (**Figure 25**).

The truck driver testified that he did not make a buttonhook turn, but rather proceeded to go forward and then made a 90 degree turn. The turning path in **Figure 25** and **Figure 15** is consistent with the driver's deposition testimony/physical evidence and shows that the truck turned

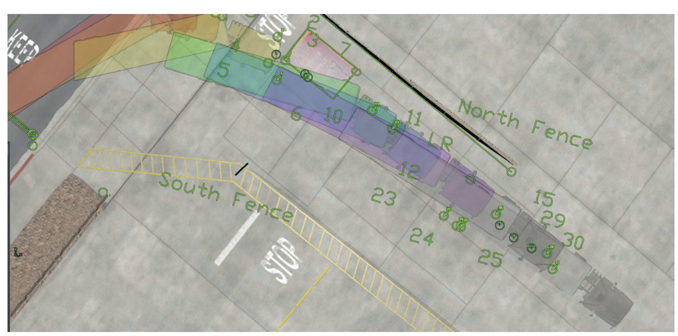

Figure 25
Turning dynamics of the truck simulated using PC-Crash.

into the driveway's opposing lane of travel. Therefore, when the truck reached the driveway, the truck would have appeared to have been going straight rather than turning into the driveway from the perspective of the bicyclist. However, when the truck reached the middle of the driveway, it made a sharp right turn in front of the bicyclist, creating an emergency situation.

Impact Simulation

After establishing the area of impact, impact orientation, and the dynamics and path of the truck turn, the impact with the bicycle was simulated using the multibody simulation model in PC-Crash. Similar to case study 1, the purpose of the multibody impact simulation was to:

1. Verify impact speed estimate based on exemplar turning truck dynamics.
2. Validate whether or not faint physical evidence was related to the incident.
3. Refine area of impact.
4. Provide scientific imagery of the impact phase of the collision.

The geometries, sizes and weights of the bicycle and rider multibody models were adjusted to closely match those of the subject bicycle and rider. Further, the joint properties of the bicycle were adjusted to allow articulation of the front wheel and handlebars that were not included in the template multibody model.

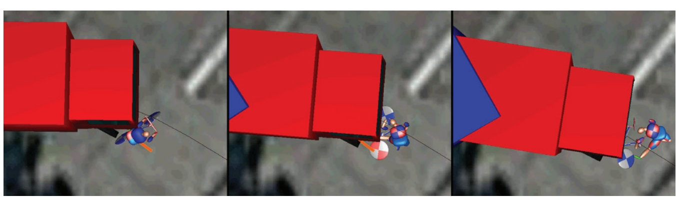

Figure 26
Impact progression of bicycle and rider based on PC-Crash simulation. Orange line shows location of tire scrub mark identified in scene photograph.

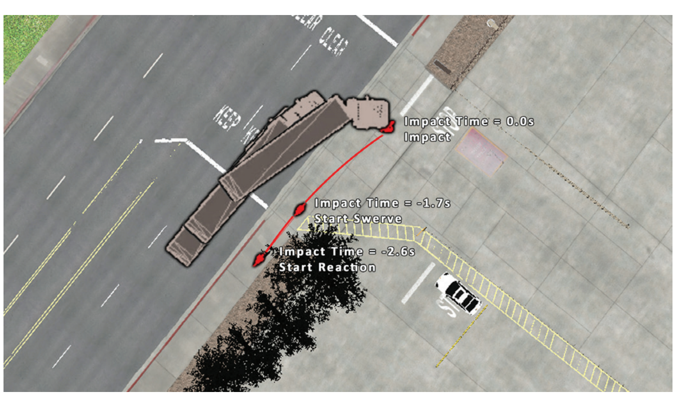

Figure 27
Bicyclist pre-impact motion start of reaction to impact.

The multibody bicycle was placed in the established impact configuration relative to the truck based on analysis of the physical evidence. For the analysis purposes, the speed of the bicycle was set at 15 mph consistent with multiple witness statement and the speed of the truck was estimated at 7 mph, based on turning dynamics of the exemplar truck. Simulations were conducted at various impact locations along the turn path of the truck until the impact dynamics of the bicycle best matched the physical evidence. **Figure 26** shows the progression of impact matching the physical evidence based on the PC-Crash simulation.

The bicycle movement after impact shown in **Figure 26** shows the that faint physical evidence identified in scene photographs is consistent with the bicycle's tires scrubbing against the ground as the bicycle was pushed down. Further, the bicycle and rider ended up under the center of the truck and dragged consistent with the physical evidence. Therefore, the multibody simulation provided additional basis for impact speeds, identification of physical evidence related to impact, and area of impact. In addition, the multibody simulation was used as basis for the motion of the bicycle and rider after impact in scientific visualizations.

Bicycle Pre-Impact Motion

Pre-impact motion of the bicycle was simulated using PC-Crash's kinematic simulation model. The pre-impact motion of the bicycle was based on:

1. Area of impact.
2. Impact configuration.
3. Impact speed.
4. Deposition testimony that the bicyclist was initially riding on sidewalk and swerved immediately prior to impact.
5. Assumption that the bicycle made an emergency swerve maneuver at 0.3 g's lateral acceleration prior to impact.

Figure 27 shows the bicyclist started reacting at approximately the same time that the truck began turning near the middle of the driveway, 2.6 seconds before impact. After a reaction time of approximately one second, the bicyclist began swerving, but was unable to avoid striking the semi.

Mirror Analysis

Truck driver line-of-sight through truck mirrors was also conducted in virtual space[12]. The geometry of the truck's interior, exterior and side-mirrors was documented using high-definition laser scanning. These scans don't register points on highly reflective materials, such as mirrors. Therefore, blue painter's tape was applied to the mirrors to mask the reflective material.

Detailed virtual models of the bicycle and truck were created from the point cloud generated from the high definition laser scans. Meshes of the mirrors were created from the high-definition laser scans, detailing the curvature of the mirrors. (**Figure 28**).

Motion of the bicycle and truck were exported from PC-Crash to the virtual bicycle and truck objects in visualization software. Within the visualization software, reflective material properties were assigned to the mirror meshes. The lighting within the scene was adjusted to account for the sun position and brightness at the time of the incident. A virtual camera was added to replicate the driver's perspective looking at the mirrors while making the turn.

Once simulation motion, material properties, lighting, and virtual cameras were added to the scene, the visualization was rendered. **Figure 29** shows an example of a still frame showing the driver's view out of each of the mirrors eight seconds before impact. The figure clearly shows that the bicyclist was visible in two mirrors eight seconds before impact. Further, the bicyclists speed, 8 seconds before impact, is approximately 7 mph. It is consistent with witnesses statements and time-space of semi and bicyclist approaching the point of impact. After traveling at the speed of 7 mph, the bicyclist sped up to 15 mph, attempting to avoid right turning semi.

Further, mirror visibility cones were created using the rendered visualization of the mirrors. The visibility cone for each mirror was calibrated by plotting the extent of the visibility in a 2D top view. **Figure 30** shows an example of the visibility cones 8 seconds before impact.

Case Study 2: Conclusions

There were some major conclusions made in the second case study:

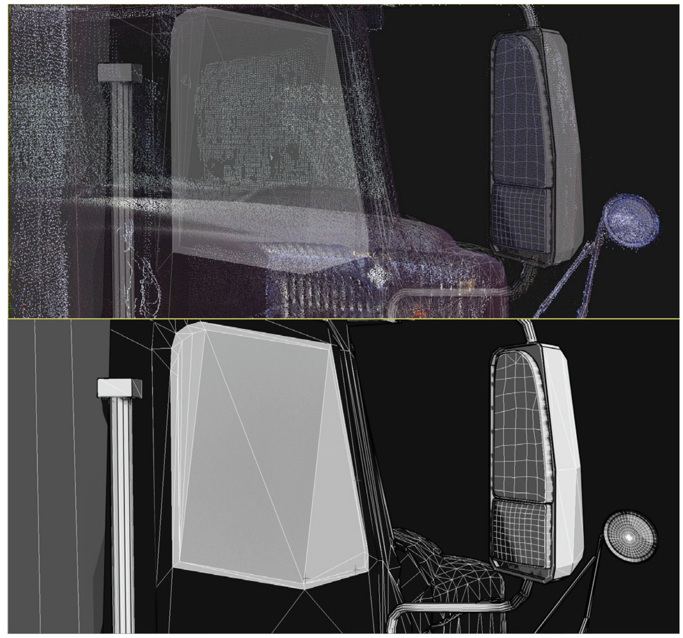

Figure 28
Mesh of mirror created from point cloud (top) and resulting mesh (bottom).

Figure 29
View out of each of the right hand side mirrors 8 seconds before impact from the driver's perspective.

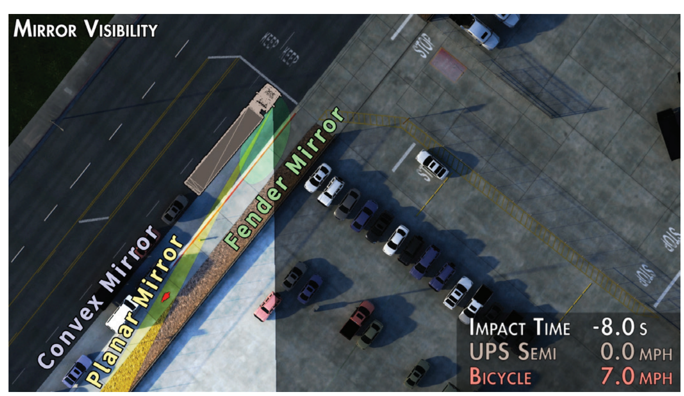

Figure 30
Visibility cones created for the three mirrors 8 seconds before impact.

1. The analysis showed the bicyclist first saw the truck turning approximately 2.6 seconds before impact.

2. Pre-impact simulation showed that the bicyclist, for a 1 second reaction time, made a swerve maneuver to the right to avoid the semi at 1.7 second prior to impact; however, the bicyclist was unable to avoid impact

3. The truck driver could have seen the bicyclist in one or more of the mirrors for more than 12 seconds before impact.

Conclusion

Two case studies were presented regarding right-turning trucks impacting bicyclists. They show that faint physical evidence related to impact is often overlooked by investigators. However, adjusting the brightness and contrast of scene photographs is helpful to locate overlooked physical evidence. Photogrammetry can be used to identify the locations of identified physical evidence. Testing and PC-Crash multibody simulations can be used to validate whether or not suspected physical evidence is consistent with impact.

Truck impact speeds can be estimated by video recording exemplar trucks making similar right turns and evaluating speeds and accelerations by timing or videogrammetry techniques. The truck turning path can be established through PC-Crash simulation by following the trail of physical evidence and matching the truck's rest position.

Once the impact speeds are established, PC-Crash multibody simulations can be used to validate estimated impact speeds, impact location, and/or identified impact scuffing. The multibody simulations are also useful in providing a visualization of the severity of the accident.

In both case studies, major debate revolved around the visibility that the bicyclists and the trucks had of one another. The line-of-sight tool in PC-Crash is useful in establishing whether or not an obstruction limited driver and rider visibility leading up impact. Further, truck mirror visibility cones can be created by capturing high-definition scans of the truck's mirrors, creating virtual mirror geometry, applying reflective material properties to the virtual mirrors, and rendering the truck driver's view looking at the virtual mirrors.

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