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† Paper presented at the NAFE seminar held 1/23/16 in Tampa, FL
‡ Paper presented at the NAFE seminar held 6/25/16 in Dallas, TX
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Forensic Engineering Analysis of Traffic Signal Timing and Speeds Prior to Collision by Rule-Based Triage of Indirect Video

By Daniel P. Couture, PEng (NAFE 951M)

Abstract

In most civil litigation cases pertaining to vehicle collisions, the courts attempt to assess and decide the proportion of shared liability of the drivers based on physical evidence as well as testimony of witnesses and perhaps experts. In North America's modern electronic-flooded society, an immense quantity of video coverage has become available from sources such as cell phones, security cameras, eyes-in-the sky traffic helicopters, dashboard cameras, and even personal drones. However, rarely is the camera focused directly on the area of interest. Security cameras may be pointed toward the back door of a property yet still have visual coverage of a nearby street. When faced with a case having multiple conflicting eyewitness accounts, it was pondered whether some of this indirect collateral imagery could be converted into useful knowledge — without access to expensive supercomputer-based image analysis. The author considered whether there were any rules of inclusion or exclusion that may be used in the triage of video footage to assist with determining a timeline of an event. This paper will attempt to provide some guidelines to the formation of an adaptable rule set, as a foundation for conducting the triage process, with reference to published and validated data. It will then go over a case where the methodology was applied.

Keywords

Tractor/trailer, vehicle, video, traffic signals, rule-based triage, stimulus, rural, second vehicle departure times, stopping probability

Part I — Method for Triage of Indirect Video Footage

Vehicle Actions and Site Geometry as Sources of Information

Within any typical video footage, a vehicle may be seen to start, speed up, drive by, turn, slow down, or come to a stop. That vehicle's behavior is a proxy for the driver's behavior. Although it provides useful physical information, it will never explicitly reveal the intentions of the driver — the reactions of the vehicle are a manifestation of the driver's inputs.

A video may show the first vehicle at a stop line facing a red signal. How long does it take for this vehicle to move when a new green ball lights? Certain technical studies[1] have been done on this starting activity. However, the actual position of the vehicle as first, second, or third in the queue at the stop line will change the departure interval parameter length. Some data is available from internal sensors (such as accelerometers), while other data has been developed from external factors, such as the moment a wheel of a vehicle completes a half revolution, after having been stopped. If movement can be seen, then it can both be described and compared to known landmarks in a frame. The primary and secondary categories and sources of information for the analysis are presented in **Figure 1**.

Category	Source
Primary	Security video footage encompassing the time of the incident.
	Known frame rate of the footage.
	Signal phase timing from the authority having jurisdiction (AHJ).
	Video codec needed to replay the video (sometimes proprietary).
	Local road geometry as measured by police and others.
Secondary	Time stamp in the video frame.
	Total Station survey or 3D laser scan of the site.
	Photographs of the site, the scene, and the vehicles.

Figure 1
Primary and secondary sources of information for the analysis.

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The physical characteristics of the roadway, such as the number and type of lanes, position of stop lines and crosswalks, local speed limits, and signal phases all come into play when considering the rules vehicles appear to follow. A Total Station survey or 3D laser scan from a commercial supplier can provide these coordinates to map the relative position in the frame to the absolute position on the ground.

Typical security footage is shot at 30 frames per second at low to medium resolution, and may be difficult to unlock for processing because of proprietary anti-tampering codecs. The presence of a time stamp on the videograph* is helpful. Check for metadata that may have timing information if it is not explicitly found on a screen time stamp. Without a time stamp for reference, the internal video metadata is the only timing information that would be available — and it may or may not be tied to the real world. Internal information can still be used to time activities if the frame capture rate is known. A known frame rate means that features in the viewable area can be the basis of calculated estimates of the velocities of vehicles. This is an independent source to be compared and contrasted with the physical evidence gathered post-collision.

Keep in mind that the distortion characteristics of the optical hardware must be considered, since the central field may have much less distortion than the edges of frame due to lens characteristics.

Steps to Follow for the Videograph Analysis

The key activity will be to patiently observe and document the video-recorded actions of the vehicles and determine if they are patterned in a way that would fit the signal phases of the lights that cannot be directly seen. It may be possible to track a vehicle that appears in one part of the frame, disappears momentarily, and then reappears in another portion of the view.

The larger the set of observations of these individual vehicle actions, the more confidence in the match between the overall action patterns and the phase sequence that will be obtained when an arbitrary degree of fit is apparent. The suggested steps are shown in **Figure 2**.

It can be cumbersome to quickly add, subtract, and calculate time intervals in the hour:minute:second (“h:mm:ss”) format — for ease of reference, a “tick” system was developed in which one unit is equivalent to one second on the videograph, where the original tick was at the beginning of the recording. To determine the number of seconds between two events, the smaller tick is subtracted from the larger. An arbitrary frame starting point can be chosen to simplify or shorten a period of interest into manageable size.

Each observation can be assessed with a validity criteria — that is whether it was reasonable or typical behavior, given the assumed signal phase for the direction the vehicle was traveling. A weighting rule will give more to observations in the direct foreground and in the camera field of view when compared to distant background vehicle actions. Certain angles may provide only enough information to check overall validity — in other words, a vehicle should not be in a place that would be contrary to typical rules of the road, except in special circumstances. An example would be a first-responder vehicle on its way to a fire. It is just as important to consider what a vehicle is not doing as it is to consider its actions. The investigator may ask whether there are patterns that fit the signal phases that cannot be directly seen.

The full set of observations is compiled into a spreadsheet set with the signal phases on the left-side columns and the sets of observations to the right. The rules and exclusions are applied to the observations. By iterating forward or backward, the phases are shifted until the best fit criteria are met to the satisfaction of the investigator. This

Step One	Create a spreadsheet with signal color by road, validity, time, observations by road with position in frame.
Step Two	Set one interval per row, matching seconds (or ticks).
Step Three	Observe the video, and note the number of vehicles, actions, and positions for each interval.
Step Four	Code the range of interest, then add the signal phase timing to the spreadsheet.
Step Five	Compare the activities and observations to the phase, and rank according to rules.
Step Six	Iterate the placement of phases until a validity acceptance criteria is met.
Step Seven	Verify the timing assumptions by validating the actions with an external source (SAE papers, data from third parties).
Step Eight	Set the signal phase sequence, and tie it to the observations.

Figure 2
Steps to follow for the videograph analysis of a collision.

* A videograph is the physical record made by a video device that describes movement captured in a scene over time. It is derived from Latin videre “to see” and Greek grapho “to describe.”

Advantages	Limitations
Provides an independent means of collecting data about the vehicle motion prior to, during, and after an event.	The assumptions about the vehicle actions can be scrutinized and disputed, if not carefully explained in the documentation.
It can allow development of a more precise timeline for the sequence of events.	The results are sensitive to the accuracy of the signal phase description obtained from the AHJ and to the quality of the ground survey.
It can be used to develop velocity information that can then be compared to the physical evidence and reconstruction calculations.	The clarity of the image may affect the frame analysis, since many security video cameras employ low resolution hardware or low frame rates.
It may reveal other helpful collateral data to create clearer context of the event.	The area of interest may be offset in a corner of the frame, or obscured by time stamp numbers.
It can be used along with video footage as a convincing display in testimony.	

Figure 3
Summary of advantages and limitations of the method.

could be a threshold level, in which 95% of the observations are not in conflict with the setting of the phases, for example.

Figure 3 presents some advantages and limitations for the method under discussion. This method provides independent data about vehicle motion prior to, during, and after an event, and this may lead to a better resolution of the timeline. Velocity information derived from the comparison of features and positions can be compared and contrasted with that developed by regular collision reconstruction techniques. The method may reveal collateral data about the context and allow further insights into the collision event. Finally, indirect video footage may be a convincing tool for the litigation proceedings.

The limitations of the method include disputes about vehicle assumptions, if such assumptions are not properly set down. The results are sensitive to both the accuracy of the signal phase information from the AHJ and to the quality of the ground survey used to do position and motion analysis of vehicle actions. Resolution of video camera equipment is often low, and this may affect clarity and the frame analysis. Considerations should be made regarding the value of having the video enhanced by software techniques, and whether this would be appropriate. The area of interest may be at a frame edge (where the hardware may create distortion) or obscured by image features like a time stamp.

The reader may consider that for any given set of actions, certain conditions of the signal are impossible, which allows the triage to be performed while narrowing in on the actual possibility of signal color at a given instant.

Figure 4 provides some examples of descriptions for analysis of vehicle behavior in a situation where there are

Position in the Frame	Observed Vehicle Activity
Foreground Traffic	Going through to edge of frame, to a known position
	Stopping in the through lane
	Stopping in the left turn lane
	Accelerating from a stopped position in the through lane
	Accelerating from a stopped position in the left turn lane, then being seen in another frame portion
Approaching Background Traffic	Being seen approaching on the screen
	Going out of the videograph frame close to a stop line, with variable lane positions
	Being seen going through at pace; going through slowly; slowing to a stop; or stopped on the roadway
	Making a right turn into the foreground, then disappearing and then reappearing in another part of the frame
	Reacting to signals by slowing down, by going through, or by starting to accelerate

Figure 4
Example of description sets for two partial views of perpendicular roadways.

Figure 5
View looking north to the intersection of
Mayfield Road and Airport Road.

two partial views of perpendicular roadways.

Part II — Case Study Employing the Analysis of Indirect Video

A Southbound tractor and dump trailer combination collided with a West-turning car in daylight at a major rural intersection. The collision was observed either directly or indirectly by 16 nearby persons. These witnesses stated that the tractor/trailer was traveling at high speed at the moment it engaged the left-turning passenger vehicle, but offered conflicting accounts about the signal color facing the tractor/trailer driver. The collision resulted in fatal injuries to both the driver of the car and her passenger.

The Collision Site

Airport Road is a major arterial road with multiple asphalt-paved lanes, with an approximately north-south axis in the Peel Region. Mayfield Road is a designated regional road with dual lanes lying on an east-west axis. The posted speed for both was 60 km/h (37 mph).

Southbound Airport Road, just north of the intersection, consisted of a left turn bay, two through lanes (Lanes 1 & 2), and a right turn bay. South of the intersection, this became two through lanes (Lanes 1 & 2), adjacent to a filling station located on the southwest corner lot.

Northbound Airport Road was similarly configured, that is with a left turn bay, two through lanes, a right turn bay, and two through lanes north of the intersection. North- and south-bound portions of the highway were separated by a concrete median in the approaches to the intersection. This northward view is shown in **Figure 5**.

For eastbound traffic, Mayfield Road just west of the intersection comprised a left turn bay, a through lane (Lane 1), and a through/right turn option lane (Lane 2). East of the intersection, the eastbound lanes merged to form one through lane. Westbound traffic east of the intersection with Airport Road could employ a left turn bay, a through lane, and a through/right turn option lane. West of the intersection were two through lanes for westbound vehicles, separated from eastbound vehicles by a concrete median.

On the day of the collision, the northwest corner of the intersection was a construction site, which included a construction trailer and construction equipment. The northeast corner was vacant, with a barn building set some distance away from the roadway. Several tall electric concrete poles were set back from the east shoulder of northbound Airport Road, lying along a line parallel to the road's north-south axis.

Signal-Phase Information

The sequence of the two-phase signal phases at 2:30 p.m. on the date of the incident was gathered directly from the public works department:

a. For Mayfield Rd – Green Ball 35 seconds, amber 4 seconds, all-red 2.9 seconds;

b. For Airport Rd – Green Ball 35 seconds, amber 4 seconds, all-red 2.9 seconds.

The signals had been functioning correctly when checked during maintenance activities. The author observed that these phases were symmetrical — and that a full cycle comprised a total time of 83.8 seconds.

Collision Reconstruction Analysis

1) The Collision Scene

Photographs of the scene taken by police indicated that the tractor/trailer combination had come to rest in a jack-knifed position on the lawn area of the filling station. The passenger vehicle had been pushed in front of the tractor/trailer and came to rest in the driveway of the filling station (**Figure 6**). A short gouge in the asphalt was noted along the southward extension of the demarcation line of Lanes 1 and 2 traveled by southbound traffic at about 20 meters (66 feet) south of the southbound stop line. This gouge and the surrounding debris field indicated the probable area of impact (AOI), and their positions were specified by police data points. No tire marks were seen north of the gouge during the site inspection by

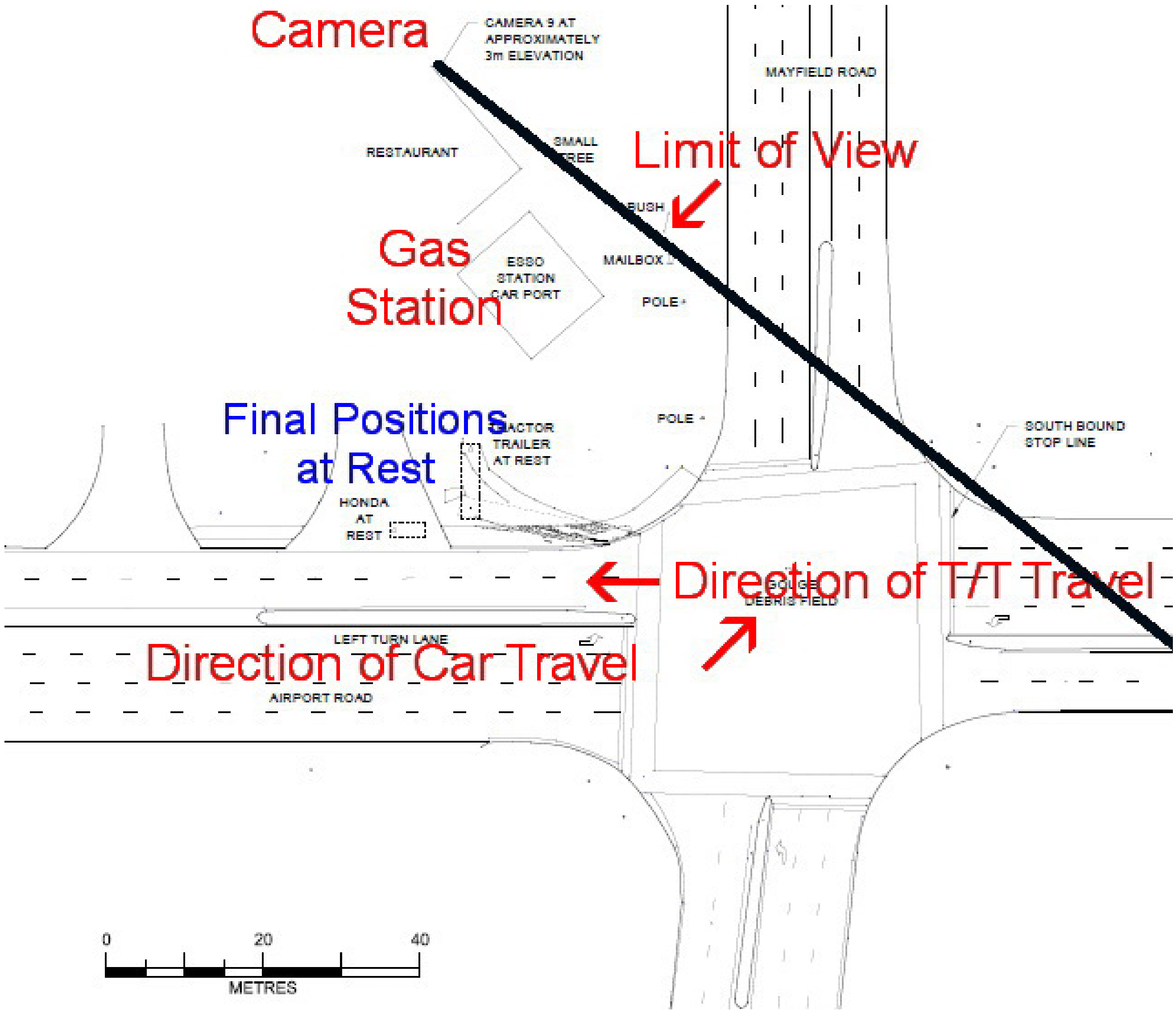


Figure 6

The scale diagram incorporates Arcon's Total Station measurements and information from of the Ontario Provincial Police (O.P.P.) collision reconstruction team's site drawings. It provides an excerpt that zooms in on the area of interest, showing the directions of vehicle travel, the final positions at rest, and the camera with the limit of view.

police officers. Tire marks extended from 6 meters (20 feet) beyond the gouge to the positions at rest. Tire impressions were seen in the soft ground on the lawn of the station, as shown in **Figure 7**.

2) The Passenger Vehicle (Honda)

This vehicle was a silver-colored early '90s model year, four-door Honda Civic. There was a major crush laterally from the trailing edge of the right rear door forward to the front bumper, inboard past the centerline, from 85 cm (33.5 in.) to a maximum of 130 cm (51.2 in.) at a fold in the roof panel. The vehicle had characteristics of being rolled as if overridden in the engagement. There were tire marks on the central portion of the right rear door, and

Figure 7

View to the northeast along the path of post-impact vehicle movement.

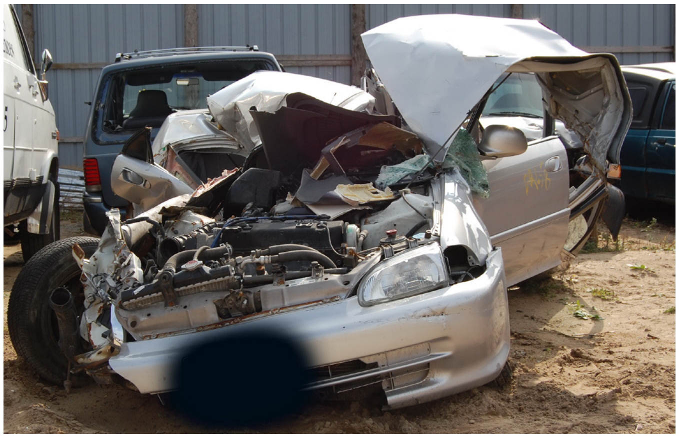


Figure 8
Front view of the Honda, showing depth of lateral crush.

similar marks on the bumper fascia just forward of the right front wheel, as seen in **Figure 8** and **Figure 9**.

3) The Tractor/Trailer Combination

The Western Star tractor was a blue mid-'90s conventional. The trailer was a Cobra dump body fully loaded with gravel. The calculated length of the combination was 20.1 to 20.3 meters (65.9 to 66.6 feet). The right front tractor bumper had been deformed upward and aft (**Figure 10**), with the lower portion pushed back. Bumper deformation extended across to the left side, which was folded back and under the driver's side headlight assembly (**Figure 11**). The right front wheel suspension components had deformed to splay the wheel outboard at the front with respect to its typical position. Contact was noted on the suspension components. There was silver paint transfer on the forward portion of the bumper.

4) The Impact Engagement

The Honda was engaged from the right side rear passenger door to the right front bumper by the left, center,

Figure 9
Right side view of the Honda.

Figure 10
Front view of the tractor
with post-impact bumper deformation.

Figure 11
Driver's side oblique view of the tractor.

and right sides of the tractor bumper, over the bumper's full width of 2.4 meters (7.9 feet). The depth of the crush at 100 cm (39.4 in.) height was greater than 85 cm (33.5 in.), which indicated that the passenger compartment was deformed to a depth of more than halfway, while other characteristics of the crush pattern demonstrated override of the tractor bumper over the Honda had occurred.

5) Eyewitness Commentary and Distribution

The eyewitnesses were distributed all around the AOI from 20 to 150 meters (66 to 492 feet) away. Their comments are summarized in **Figures 12a** and **12b**, with a cluster of reported speeds ranging from 90 to 100 km/h (56 to 62 mph). The author compiled the geographic distribution information of the eyewitnesses, as shown in **Figure 13**.

Few eyewitnesses recalled directly observing the signal status during the moments leading up to the collision,

No.	Position with Respect to Area of Impact	Comment on Tractor/ Trailer Speed	Comment on Signal Color for Tractor/Trailer
1	60 m west/northwest on the construction site, standing	Well over 90 km/h	Color unknown
2	70 m south/southwest, parked by coffee shop	90 to 100 km/h	Amber at truck entry
3	Accompanied #2 but did not recall the event.		
4	25 m south/southeast, stopped at northbound Lane 1 stop line	Not going 80 km/h	Amber northbound
5	150 m north/northeast in northbound Lane 1, driving	60 to 70 km/h	Amber northbound
6	60 m west/northwest on the construction site, standing	Well over 80 km/h	Red for southbound
7	45 m east in Lane 1 of Mayfield Westbound, stopped	Going really fast	Red for north/south
8	30 m northwest, at the construction site behind the fence	80 km/h, Maybe over 100 km/h	
9	30 m east, stopped in a westbound car on Mayfield	At least 100 km/h	Green for Mayfield
10	30 m east, stopped in a westbound car on Mayfield	100 km/h	Green for Mayfield
11	60 m west/northwest on the construction site, standing		
12	80 m south in the northbound left turn lane, to coffee shop	Over the limit of 60 km/h	
13	150 to 200 m north/northwest of the intersection, standing	Looked overspeeding	
14	15 m west, stopped in the eastbound left turn lane		Green for Mayfield after impact
15	40 m northwest, on an excavator at the corner	80 to 100 km/h	
16	50 m southwest pumping gas at the Esso, standing	90 to 110 km/h	

Figure 12a

Synopsis of eyewitness geographic distribution at the scene (in metric units).

No.	Position with Respect to Area of Impact	Comment on Tractor/Trailer Speed	Comment on Signal Color for Tractor/Trailer
1	197 feet west/northwest on the construction site, standing	Well over 56 mph	Color unknown
2	230 feet south/southwest, parked by coffee shop	56 to 62 mph	Amber at truck entry
3	Accompanied #2 but did not recall the event.		
4	82 feet south/southeast, stopped at northbound Lane 1 stop line	Not going 50 mph	Amber northbound
5	492 feet north/northeast in northbound Lane 1, driving	37 to 44 mph	Amber northbound
6	197 feet west/northwest on the construction site, standing	Well over 50 mph	Red for southbound
7	148 feet east in Lane 1 of Mayfield westbound, stopped	Going really fast	Red for north/south
8	98 feet northwest, at the construction site behind the fence	50 mph, Maybe over 62 mph	
9	98 feet east, stopped in a westbound car on Mayfield	At least 62 mph	Green for Mayfield
10	98 feet east, stopped in a westbound car on Mayfield	62 mph	Green for Mayfield
11	197 feet west/northwest on the construction site, standing		
12	262 feet south in the northbound left turn lane, to coffee shop	Over the limit of 37 mph	
13	492 to 656 feet north/northwest of the intersection, standing	Looked overspeeding	
14	49 feet west, stopped in the eastbound left turn lane		Green for Mayfield after impact
15	131 feet northwest, on an excavator at the corner	50 to 62 mph	
16	164 feet southwest pumping gas at the Esso, standing	56 to 62 mph	

Figure 12b

Synopsis of eyewitness geographic distribution at the scene (in U.S. customary units).

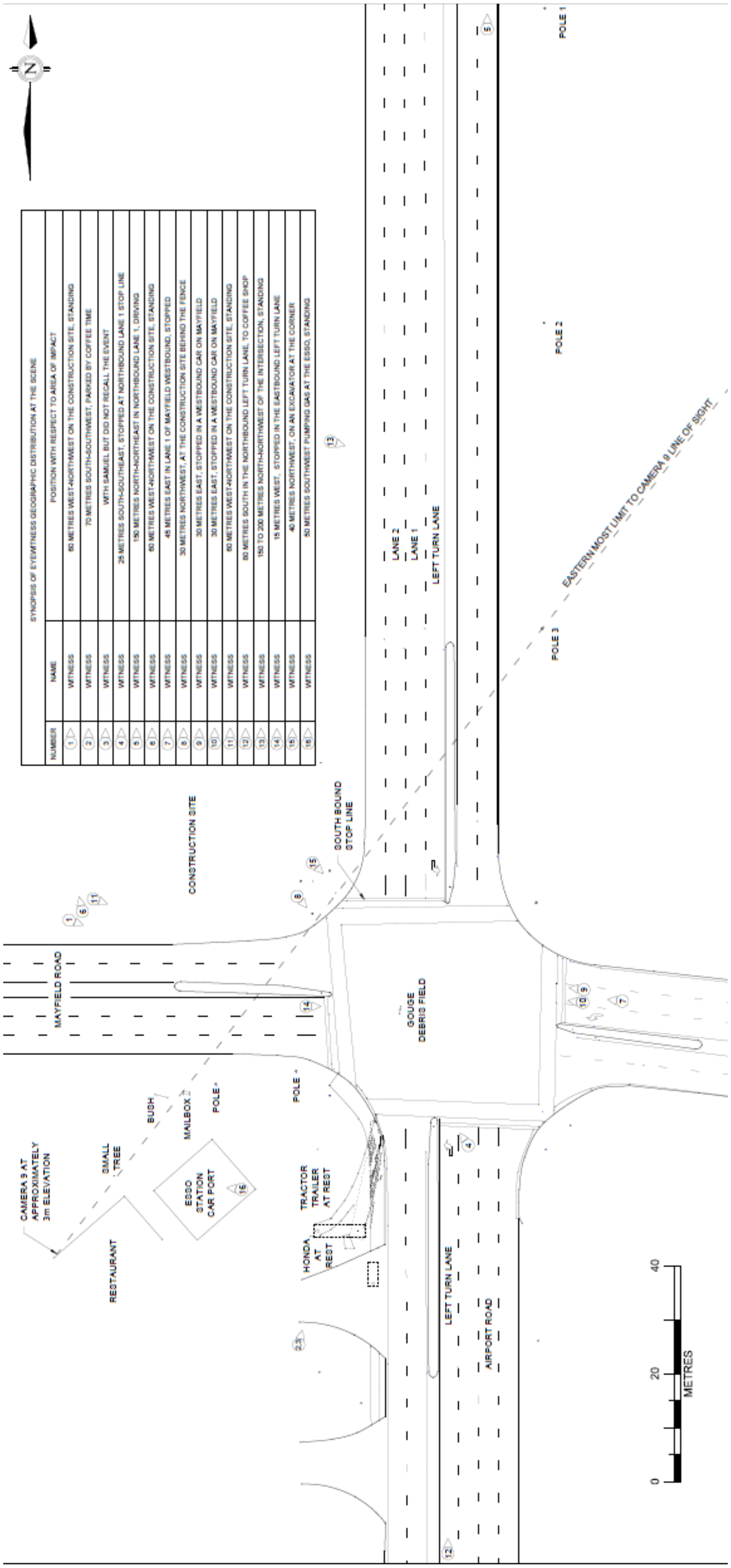


Figure 13
Scale drawing of witness positions at the scene.

Figure 14
Camera 9 was mounted at the southwest corner of the restaurant.

but many recalled that the sound of multiple truck horn blasts had immediately preceded the loud collision noises.

Observations from the Videograph from Camera 9

Camera 9 was located by the air pump at the rear of the restaurant building, as shown in **Figure 14**. The videograph from Camera 9 became available during litigation proceedings, which provided an opportunity to do a motion and time analysis of the positions of the vehicles. The footage was studied with a video player program (DVR.exe, version 1.4.1.23).

The camera viewing angle did not include the intersection or the signal status. The scaled site diagram (**Figure 6**) depicts the eastern limits of the line of sight of the video camera, which was mounted at a height of 3 meters (10 feet) above the sidewalk, 1 meter (3.3 feet) from the southwest corner of the building comprising the coffee shop. The footage of the bright sunny summer day was in color, with a detailed time-stamp number set visible in the upper right of the frame. There was no soundtrack in the copy of the video provided for analysis. **Figure 15** depicts the view from the south side of Mayfield Road by the bushes toward Camera 9.

Application of the Methodology for Assessing Vehicle Behavior

The steps outlined in **Figure 2** were implemented after gathering the information listed in **Figure 1**. A spreadsheet for analysis of the videograph was set up, covering the period from 2:24:00 p.m ("hours:minutes:seconds" format), approximately 6 minutes prior to the event, to 2:36:00, which was about 6 minutes after the collision. A tick system was created in which one unit is equivalent to one second on the videograph, where the first tick was at the beginning of the recording and for which 2:24:00 was equivalent to tick 560. Recall that to determine the number of seconds between two events, subtract the smaller tick from the larger.

The actions of the vehicles were described in a brief summary line (for example, *"white van coming to a stop in lane 1 eastbound"*) as recorded at a particular tick on the videograph. The behavior of vehicles for eastbound, southbound, and northbound traffic were scrutinized — from known positions on the scale diagram of 20 meters (66 feet) west, 20 meters (66 feet) north and 75 meters (246 feet) north of the respective stop lines. This procedure gave a population of 83 sets of observations of vehicle behavior, each of which could be characterized independently.

A two-column set was added on the left side of the spreadsheet with the signal colors for eastbound/westbound and northbound/southbound, using the symbols G, A, R and R-R for green ball, amber, red, and all red

Figure 15
View toward Camera 9 from the south edge of Mayfield Road.

conditions, respectively. An excerpt of the first page of the spreadsheet is shown in **Figure 16**, with categories highlighted in blue. The next step was to determine a phase cycle starting point based on the description of behaviors.

Each event was ranked with validity criteria — that is whether it was reasonable behavior, given the signal phase for the direction the vehicle was traveling. More weight was given to observations in the foreground of the

AA71004		Appendix G				CAM 9 video Time index		Annotations by DPC		
								for CAM 9 Videograph from 2:14:40 PM		
Region of Peel Signal Timing Thursday Sept 13 2007 at approx 2:30 P.M.										
Phase 1	Airport Road		Green Ball 35.0 seconds							
	North/South		Amber 4.0 seconds							
			All-Red 2.9 seconds							
Phase 2	Mayfield		Green Ball 35.0 seconds			Cycle Time		SAE 2001-01-0045		
	East/West		Amber 4.0 seconds					for calculation of estimated positions		
			All-Red 2.9 seconds					after reacting to a green signal with initial		
						Full Cycle Time: 83.8 seconds		and ongoing acceleration		
KEY										
		R	Red							
		G	Green							
		A	Amber							
		R-R	All Red							
Impact occurred during Tick 905						Tractor/Trailer Crosses after beginning of First Second of Red-Red				
										Expected time after signal
Set commencement time of Green signal per three vehicles, to 2:28:23 at Tick 823										8.7 to 10.3 seconds if stopped
		Validity								
Mayfield	Airport	Validity	TICKS	Camera	Elapsed	Eastbound Vehicle behaviour		Southbound Vehicle behaviour		Northbound Vehicle Behaviour
E & W	S & N		second	Clock	Time	(20 m west of intersection)		(20 m north of Sbnd stop line)		(75 m north of Nbnd stopline)
colour	colour	V,X,C,XN		h:mm:ss	mm:ss					
R	G		560	2:24:00		Eastbound		Southbound		
R	G		561							
R	G		562							
R	G		563							
R	A	C	564	2:24:04	00:04					minivan goes through at speed
R	A		565							
R	A		566							
R	A		567							
R-R	R-R	V/C	568	2:24:08	00:08	truck with trailer slows				transport, truck go through at pace
R-R	R-R		569							
R-R	R-R		570							
G	R		571							
G	R		572	Time						Northbound
G Signal	R		573							
G	R		574							
G Phases	R		575							
G	R		576							
G	R		577							

Figure 16
Excerpt of the first page of the spreadsheet for videograph analysis.

camera field of view, which is the eastbound lanes of Mayfield, than for observations of traffic on southbound Airport Road. The northbound traffic observations served as a checking tool only. **Figure 17** lists the range of vehicle activity for the positions in the frame. Each point was verified to affirm whether it matched a corresponding column that set the signal phase, using the known sequence described by the traffic authority in its correspondence. The analysis showed that, at certain times, the vehicles had behaved as if the lights were at specific phases of the cycles.

The sets of observations were further compiled for ease of reference and discussion as shown abridged in **Figure 18**. Observations that matched the choice of phases are described in that manner, while conflicts are highlighted in red. Critical times are highlighted in green.

Signal Phase Sequence Analysis for the Full Cycle Immediately Prior to the Collision

Further consideration of the observations found an eastbound silver-colored pickup traveling through and slowing down at Tick 784 (**Figure 19**), followed by an eastbound black sedan that slowed down near the right frame edge after Tick 796 (**Figure 20)** and stopped at Tick 822 **(Figure 21).**

The positions of the black car and the silver pick-up are shown in plan view at Tick 822 in **Figure 22**.

At Tick 825, the black car was observed (see **Figure 23**) beginning to move in response to a green signal (at 2:28:25.4). Using the criteria in SAE 2001-01-0045[1] (see **Appendix A**), which gave 1.4 to 1.5 seconds as an unanticipated response to a signal for the first vehicle and actual observations of second vehicle behavior in line, the black car was estimated to have moved ahead from 2.2 to 3.0 seconds after the green ball appeared for eastbound traffic. There were no clearing vehicles proceeding to finish their turns westbound from northbound at this time.

Position in the Frame	Observed Vehicle Activity
For Eastbound Mayfield Traffic	Going through to edge of frame, about 20 m (66 feet) from the eastbound stop line.
	Stopping in the through lane (Lane 1), as the driver reacts to an amber or red ball signal.
	Stopping in the left turn lane, as the driver reacts to an amber or red ball signal.
	Accelerating from a stopped position in the through lane, after the driver reacts to a green ball signal.
	Accelerating from a stopped position in the left turn lane, after the driver reacts to a green ball signal, then being seen northbound.
For Southbound Airport Traffic	Can be seen approaching on the screen, behind the time stamp digits.
	Go out of the videograph frame (easternmost limit) at 20 m (66 feet) north of the southbound stop line, near pole three, if in Lane 1, and later if in Lane 2.
	Can be seen going through at pace; going through slowly; slowing to a stop; stopped on the roadway.
	May make a right turn onto westbound, so they disappear and then reappear in the foreground.
	They react to signals by slowing down, by going through, or by starting to accelerate.
For Westbound Mayfield Traffic	Can only be seen after clearing the site line, about 53 m (174 feet) from the westbound stop line.
	Would take 7.3 to 8.0 seconds minimum to arrive at the sight line, if starting from a stop, applying the SAE 2001-01-0045 criteria of 1.4 seconds after a green signal for movement to start.
	May be northbound traffic clearing after a left turn.
	May be southbound traffic coming around the corner at pace, or after being stopped.
For Northbound Airport Traffic	Through traffic moving through at pace may have passed through the intersection at least 73 m (239 feet) south when we see them at the sight line in the video; at 60 to 80 km/h (37 to 50 mph), or 16.6 to 22.2 m/s (54.5 to 72.8 feet/sec), the time could be 3.3 to 4.4 seconds.
	It takes 8.7 to 10.3 seconds to reach the point of view, if the vehicle was stopped at the northbound stop line and has a 1.4 second delay after the green signal.
	Left turns by eastbound vehicles can be seen at the start of the turn in Cam 9 footage, and then again 9 to 10 seconds later as they proceed northbound.
	Right turns eastbound from Lane 2, which is for straight with right turns optional; cannot discriminate these.

Figure 17
Case study decision rules for analysis of vehicle behavior.

	Abridged Summary of Observations				
			Key for codes / Number of Matches	**Percentage**	**Correct Match Percentage**
			Remained Invalid - X 0	0.0%	
	Iteration 10 - using time green signal at 2:28:23 and 2:29:05		Newly Invalid - XN 3	3.6%	
	Impact at 2:29:45.5, Tick 905		Correct with changes - C 69	83.1%	**96.4%**
	Tractor trailer entered the intersection at tick 904 after the southbound red signal		Still Valid -V 11	13.3%	
		Z	TIME OF IMPACT - Z 4		Total points = 83 + 4 = 87
	Commentary or Observations				
Tick			**Eastbound**	**Southbound**	**Northbound**
560	start of analyzed period	C			
688	match	C		silver vehicle comes to a stop	
699	pickup truck appears to go through on a	XN/C	traffic moving througn on red	school bus stops for a green 50 m away	
770	match	C		large truck comes to a slow stop after car	
778	dump truck through at speed, enters on a red signal	C	dump truck through at speed		
783	match	C/V	silver pick up truck coming to a stop	large truck crawling along	
784	match	V	lt brown bob tractor comes to stop left turn lane		
787	match				
789	match	C		large truck keeps moving	
793	match	C/C		large truck goes by edge of frame	transport goes through
800	match	C/C	black car comes to a full stop by	southbound dumptruck goes through at	
815	match	C		white cube van goes through	
823	likely green light time per vehicle analysis, Tick 825, 831				
825	***black car begins to move ahead, followed by others***	C	black car begins to move ahead, followed by others		
831	*westbound car passes edge of frame*				
846	match	C			bobbed tractor seen going north
848	***transport goes through, perhaps after***	XN			transport through
850	match	C	line of traffic, last white pickup drive		
855	match	C	dark vehicles follow through		
860	match	C			
865	start of green signal to match Tick 873				
870	***match***	C		rt turning bus passes; other bus has gone through	
873	white vehicles (2) go through	C			white vehicles (2) go through
876	match	C			vehicle driving through
883	match	C	no eastbound traffic	no southbound traffic	dumptruck passes through at pace
887	match	C			red dumptruck passes at pace
894	white car slowing to stop	C	whjte car slowing to stop		
898	white car stopping, left turn lane	C	white car stopping, left turn lane	A/R	
900	**dark car passes edge at pace at 2:29:40.5**	Z	**no vehicles seen**	**dark car passes edge of frame at pace**	**no vehicles seen**
901		Z	**no vehicles seen**	**involved transport comes into view**	**no vehicles seen**
903	**FR TRUCK AT EDGE OF SCREEN at 2:29:43.8**	Z	**no vehicles seen**	**rear of transport passes a pole in view**	**no vehicles seen**
904	**inv transport exits the camera view 2:29:44.6**	**Z**	**no vehicles seen**	**involved transport exits the camera view**	**no vehicles seen**
905	**LIKELY IMPACT, 20 M SOUTH OF STOP LINE, 2:29:45.5**				
912	**REACTION TO CRASH BY RF PASS RED CAR - points with her arm**				
916	match	V	pickup truck comes to a stop, left turn lane		
926	match	C		school bus approaches intersections, slowing	A/R
938	match	C		dark vehicle coming to a stop behind bus	

Figure 18
Abridged compilation of observations.

Figure 19
Silver pickup slowing at Tick 784.

Figure 20
Black car slowing at Tick 796.

Figure 21
Black car stopped at frame edge at Tick 822.

At Tick 831, the first of three westbound vehicles can be seen (**Figure 24**) at the edge of the frame at 2:28:31.4. It was assumed that this vehicle was first in line, at a position that was 53 meters (174 feet) east of where it can be

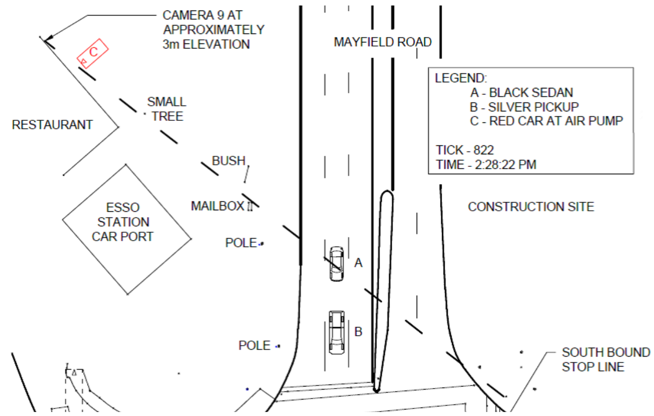


Figure 22
Positions of black sedan and silver pick-up truck at Tick 822.

Figure 23
Black car begins motion eastbound during Tick 825.

Figure 24
First westbound vehicle emerges from the right side of frame at Tick 831.

first seen in the videograph. Using the single-frame analysis technique, the speed of this vehicle was calculated to be from 45 to 50 km/h (28 to 31 mph), which was consistent for acceleration from a stop, using the SAE 2001-01-0045 guidelines. It was then estimated that the earliest this vehicle could appear on screen was from 7.1 to 8.0 seconds after the green signal for westbound Mayfield traffic.

The proposed start time of the eastbound/westbound Mayfield green signal was set to 2:28:23, Tick 823, to coincide with both observations because the analysis showed that it could not reasonably be later than this.

At Tick 873, (or 2:29:13), there were three northbound vehicles in the videograph that had traveled about 73 meters (240 feet) north of the northbound stop line. One is seen in **Figure 25**.

Figure 25
First northbound vehicle seen at tick 873.

Time Stamp (h:mm:ss)	Signal Phase	Tick
2:28:23	Start of green for eastbound Mayfield Road	823
2:29:05	Start of green for southbound Airport Road	865
2:29:40	Start of amber for southbound Airport Road	900
2:29:41	Start of 2nd second of amber for southbound Airport Road	901
2:29:42	Start of 3rd second of amber for southbound Airport Road	902
2:29:43	Start of 4th second of amber for southbound Airport Road	903
2:29:44	Start of 1st second of all-red	904
2:29:45	Start of 2nd second of all-red	905
2:29:46	Start of third portion of all-red, only 0.9 seconds duration	906
2:29:47	Start of green for eastbound Mayfield Road	907

Figure 26
Correspondence between time stamps, signal phases, and tick designations.

If they had been stopped at that position, each would take between 8.7 to 10.3 seconds to traverse the intersection and be seen on the videograph, assuming once again that the criteria in SAE 2001-01-0045[1] can be applied. Had the vehicles not started from a stop, then they could have arrived between 7.2 and 8.3 seconds (earlier, that is) after the appearance of a northbound green signal. The group of vehicles appeared to be clustered together.

These findings led to the setting of the proposed green signal start for northbound and southbound Airport Road at 8 seconds prior — that is at 2:29:05, Tick 865.

Green Ball Start Time for the Cycle Immediately Prior to the Collision

The latest possible moment for the start of the green signals for Mayfield Road was at Tick 823, while for Airport Road it was Tick 865, for the Phased Signal Cycle immediately before the collision event. The limited possibility that it could have been one or two seconds earlier was considered (if the motion of the analyzed vehicles was more aggressive), but was discounted because these two start times fit exactly within the known timing regime published for the incident date.

The hypothesis that these green signal commencement times were correct was accepted. Subsequent analysis of the collision was accordingly based on these times. The 83 sets of observations were compared with typically expected traffic behavior with the hypothesized signal status at any given tick. **Figure 26** lists the designated ticks and corresponding Camera 9 time stamps that arose after the signal phase analysis.

The concordance between observations and signal phases was 80 of 83 sets (96.4%), with one major and two minor exceptions:

1) An eastbound pickup truck apparently runs a red light at Tick 699 (major);

2) A transport moving through northbound at Tick 848 (minor); and

3) Another transport moving through northbound at Tick 1186 (minor).

Given that direct observation of the northbound lanes was impossible from the videograph of the scene, the latter two observations were discounted without undermining the validity of the group. The second and third

Figure 27
Dark vehicle traveling southbound at the end of Tick 899.

Figure 28
The dark vehicle leaving the frame at midpoint of Tick 900.

exceptions could have been by vehicles that turned right on the red signal.

The strong concordance formed the basis for a high degree of confidence with respect to the correctness of the hypothesis of the green signal commencement times for the phase cycle at Tick 823 (eastbound/westbound) and Tick 865 (northbound/southbound) immediately prior to the collision event.

Calculation of Vehicle Speeds by Videograph Frame-by-Frame Feature and Position Comparison

At a playback speed of one frame per 1/30th of a second, the videograph revealed that a dark vehicle, likely a car, passed the edge of the videograph frame. When analyzed in single-frame mode, the time stamp indicates this occurred at 2:29:40.5 in the Tick 900 interval. The author

Figure 29
The front of the tractor/tractor becomes visible behind the time stamp edge at Tick 903.

had to assume that it was in Lane 1. This dark vehicle traveling several seconds ahead of the tractor/trailer had a calculated speed of 18.7 to 20.6 meters per second (61.3 to 67.6 feet/sec), or 68 to 74 kilometers per hour (42 to 46 mph). It is shown in the upper right corner of the frame in **Figures 27** and **28**. This calculation was done at 2:29:39.66 (20th frame of 30) to 2:29:39.93 (28th frame of 30).

In a similar way, the speed of the tractor/trailer was calculated as 19.6 meters per second (64.3 feet/sec), which is equivalent to 71 kilometers per hour (44 mph). It was determined through the author's forensic engineering analysis of the physical evidence that the tractor-trailer was traveling in Lane 1. This determination was consistent with witness statements. This calculation was done at 2:29:42.97 (29th frame of 30) to 2:29:44.0 (30th frame of 30) seconds on the videograph. These positions are shown in **Figures 29** through **31**, which are screen captures. The nominal accuracy was 3%, putting the tractor/trailer speed at 69 to 73 km/h (43 to 45.3 mph). This was well below the estimates by all witnesses.

The tractor had not passed the edge of the frame at the start of the all-red, as shown in **Figure 31**, and the corresponding ground position is shown in the plan view of **Figure 32**. The tail end of the trailer had moved past the edge of the frame by the 14th of 30 frames of Tick 904, as shown in **Figure 33**, confirming that it had not entered the intersection before the all-red phase had begun.

Speed and Position of the Dark Vehicle

On the videograph, the tractor/trailer can be observed at the edge of the time stamp at Tick 843 — about four

Figure 30
The front of the tractor/trailer emerges by the time stamp at the mid-point of Tick 903.

Figure 31
The front of the tractor trailer at the start of all-red, Tick 904.

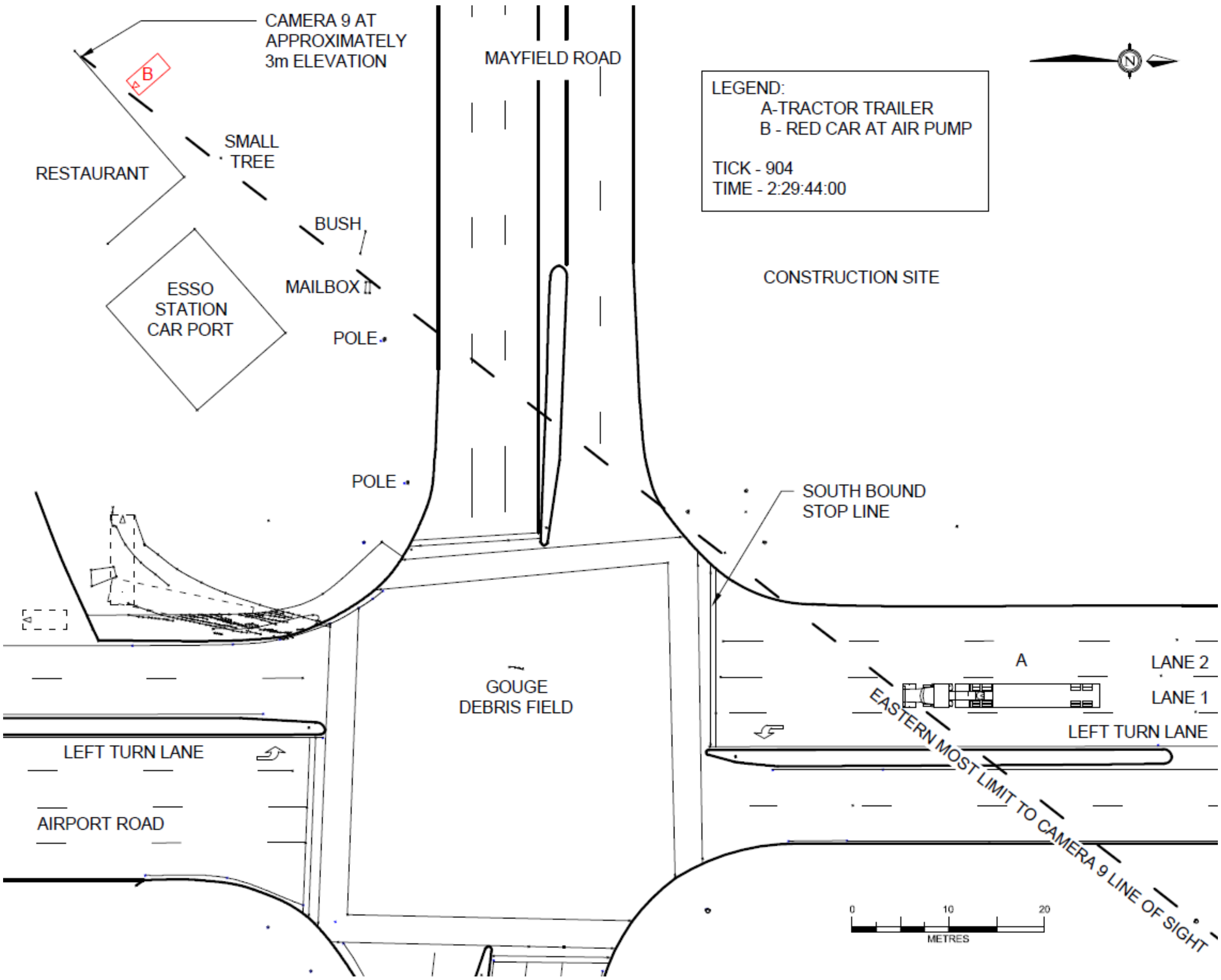
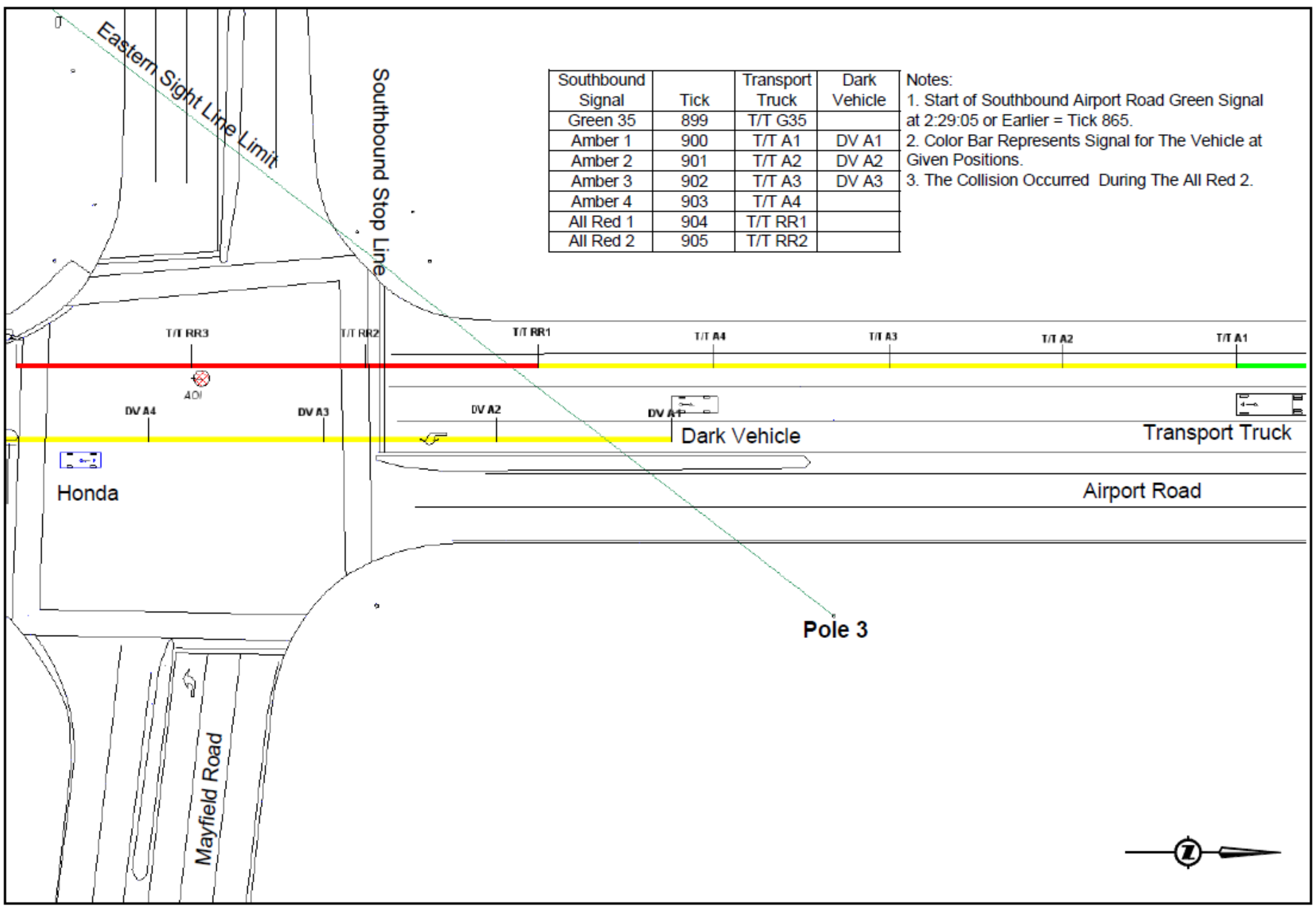


Figure 32
Position of the tractor/trailer at the beginning of all-red, Tick 904.

Figure 33
At the midpoint of Tick 904, the first second of all-red, the end of the tractor/trailer is at the edge of the screen.

full seconds behind the dark vehicle, which has passed the same position at Tick 839. This geometric configuration implied that both vehicles at similar speeds cannot enter on an amber.

The positions of the vehicles are depicted in **Figure 34** (with the key in **Figure 35)** at the intervals from the PC Crash analysis, with the key indicating that the bar corresponds to the signal color at any position for the 4-second-long amber signal and 2.9-second all-red signal for southbound traffic. The dark vehicle crossed the stop line and entered the intersection at 2:29:41.4, during Tick 901, the 2nd second of southbound amber. Since the Honda and the dark vehicle did not collide, this vehicle passed by the Honda as the Honda began its turn left to proceed westbound (**Figure 36**). The position of the dark vehicle restricted the motion of the Honda's turn to after



Southbound Signal	Tick	Transport Truck	Dark Vehicle
Green 35	899	T/T G35	
Amber 1	900	T/T A1	DV A1
Amber 2	901	T/T A2	DV A2
Amber 3	902	T/T A3	DV A3
Amber 4	903	T/T A4	
All Red 1	904	T/T RR1	
All Red 2	905	T/T RR2	

Figure 34
PC Crash analysis diagram showing positions prior to collision.

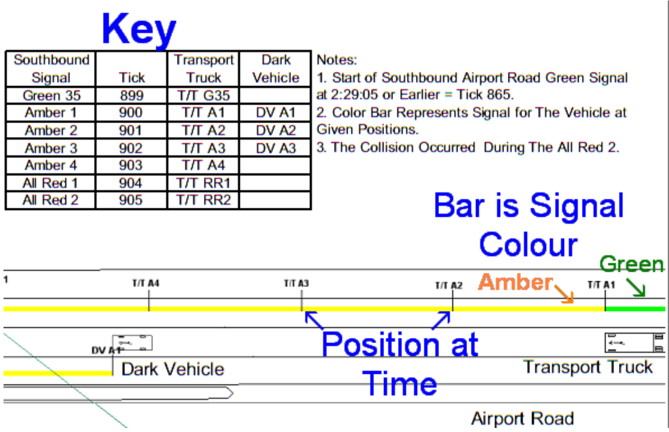


Figure 35
Key to vehicle positions in Figure 34.

2:29:43 because the dark vehicle required 1.5 seconds to travel 30 meters (98 feet) past the Honda's stopped position. This interaction between the dark vehicle and Honda was critical to understanding the context of the collision.

Position of the Tractor/Trailer When It Leaves the Video Screen

From the videograph, the back of the tractor/trailer at the eastern limit of the camera view at 2:29:44.6 can be seen, and given its length of just over 20 meters (65.6 feet), its front end would be at the southbound stop line when it is in Lane 1, as shown in **Figure 37**. At its calculated speed, the tractor/trailer would take another second to travel to the area of impact to the south along the demarcation between Lanes 1 and 2. However, the phase cycle analysis indicated that at Tick 904, 2:29:44, the signal had turned to all-red. Thus, if the truck is entering the intersection boundary at 2:29:44.6 or later, it must have done so in the second portion of the all-red signal. The collision engagement began at 2:29:45.5 during Tick 905, for a vehicle speed of 71 km/h (44 mph) or 19.6 meters per second (64.3 feet/sec). This is within the 2nd second of all-red for the northbound/southbound phase.

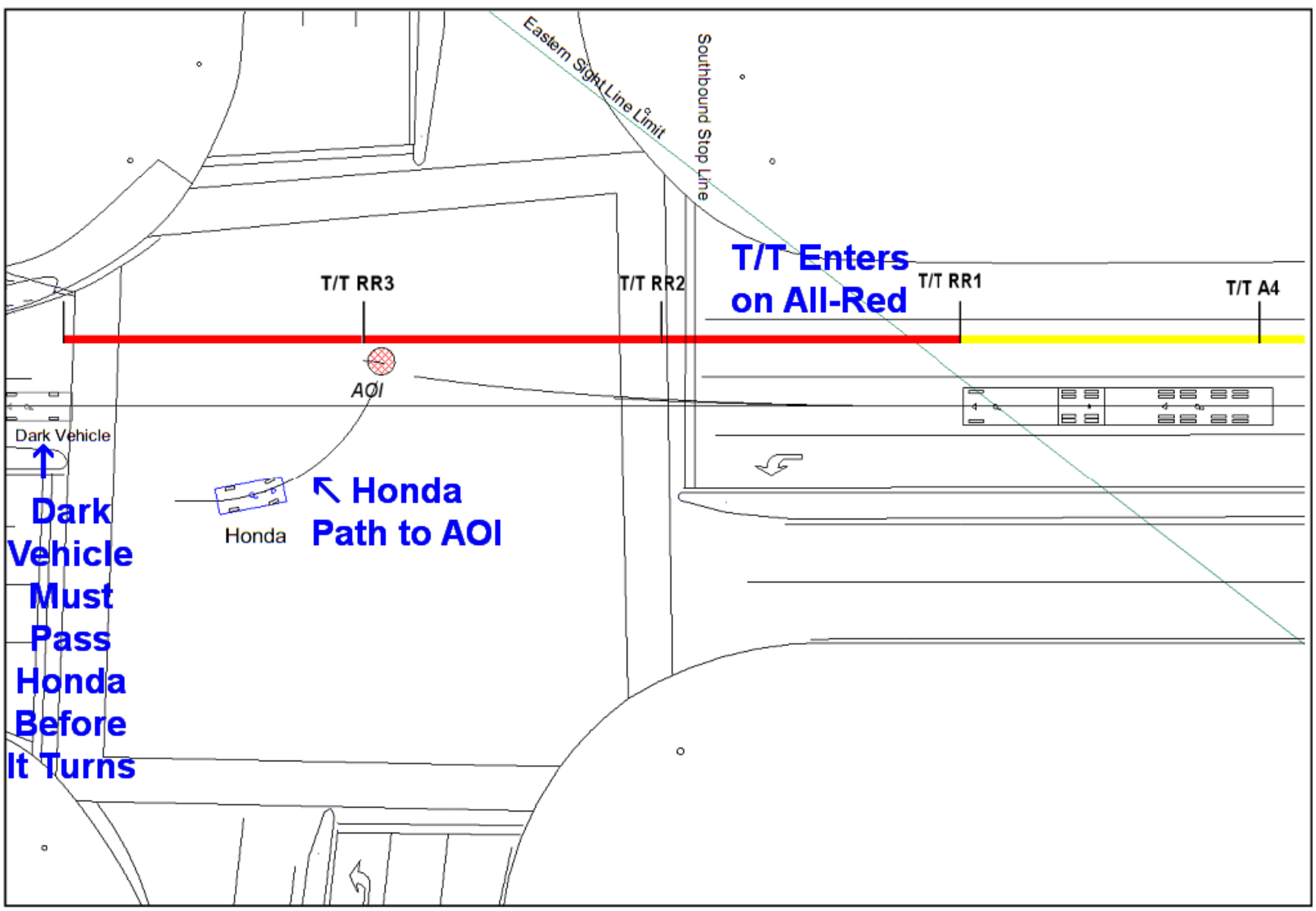


Figure 36
Intersection positions from PC Crash analysis at times listed in Figure 34.

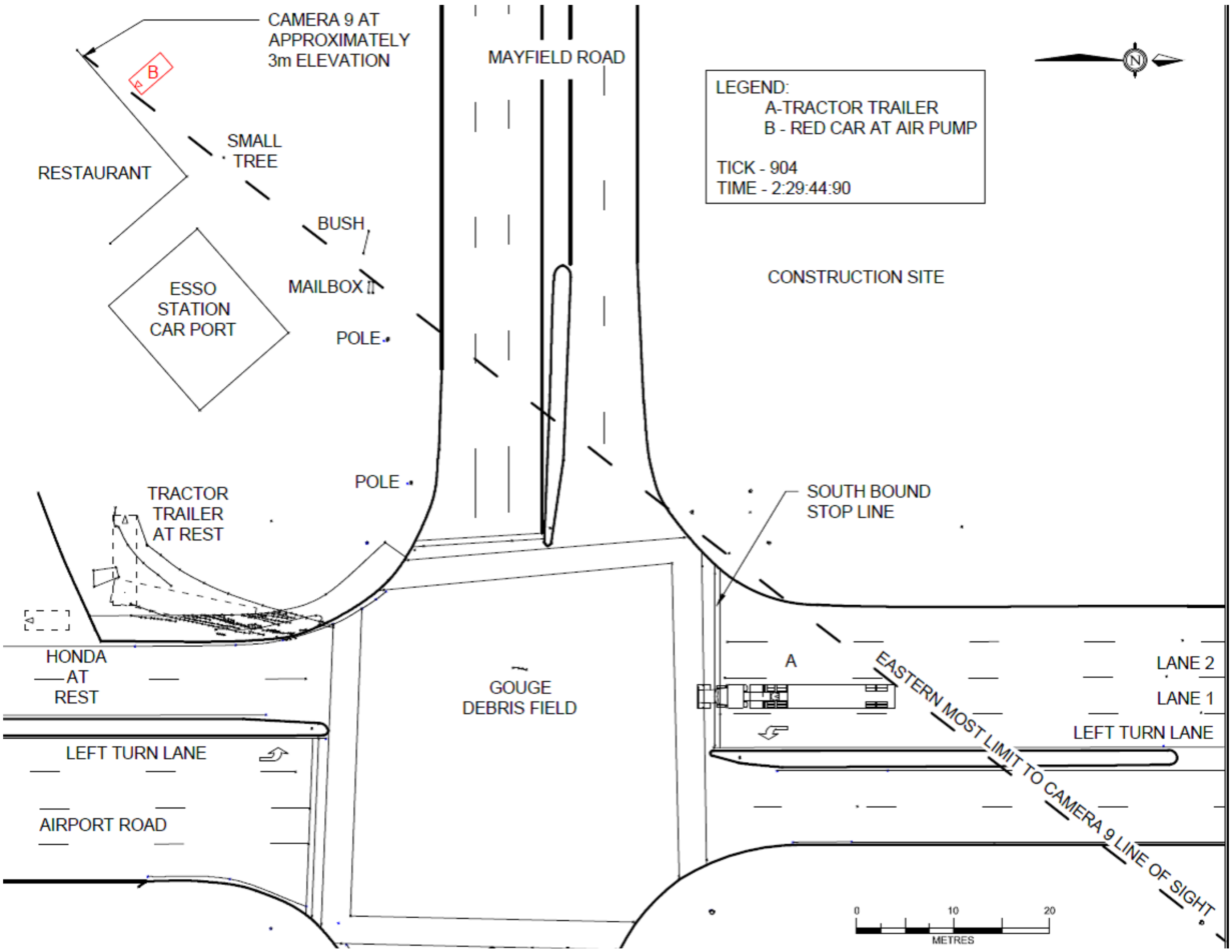


Figure 37

Position of tractor/trailer when it sounded the horn, according to the red vehicle passenger startle reaction analysis.

Supplementary Information from the Videograph Record: Reaction by a Passenger at the Tire-Filling Station

The right front passenger of the red vehicle getting its tires filled, about 70 m (230 feet) away, with the windows down, reacted to an unknown stimulus at 2:29:45.2, according to the frame-by-frame analysis. A few seconds later, she lifted her left arm and pointed to the driver's side of the car.

For a blast sound of a horn to arrive at the right front passenger's position would be approximately 0.20 seconds, at the speed of sound of 342 meters per second (1122 feet/sec) at 20°C (68°F) and one atmosphere pressure. Typical muscular reaction to a startling sound is on the order of 50 milliseconds[2,3], such that the noise that instigated the passenger's reaction would have originated no sooner than 2:29:44.9, in Tick 904, about one half second before the collision event.

Discussion of the Technical Analysis

The technical analysis of the videograph was the basis for discriminating the color of the respective signals for both roads at any given time interval. This was independent of eyewitness information, and therefore was very much less subjective. A variety of rules were used to establish and verify the best estimate of the start of the green signals of the phase cycle prior to the collision.

The findings did not conflict with or contradict any of the witness accounts, with the exception of Witness 5, whose vehicle did not appear on the videograph. The last northbound vehicle seen in the videograph, a red dump-truck, comes into sight at Tick 888, at a position 50 meters (164 feet) north of the intersection. This is more than 15 seconds prior to the ensuing collision at Tick 905. At 20 meters per second (65.6 feet/sec), this vehicle would be 350 meters (1,150 feet) from the intersection at the time of the collision. If this was Witness 5's vehicle, his statement would not align with these facts.

The inferences do have a quantifiable but small margin of error, but by scrutinizing the behavior and position of vehicles, the vehicle behavior could be matched to the inferred signal color. The sources of variation are:

- The unknown correspondence between the signal control time and the video camera time seen on the stamp in the frame;
- The calibration status of the clock on the video camera;
- The choice of the start of tick interval is arbitrary and could be out by half a second;
- The lane position of the dark vehicle (either Lane 1 or Lane 2); and
- The assumptions of vehicle behavior do not account for unexpected inputs such as at Tick 699, less than 4 minutes before the involved collision, where a pickup was observed most likely running a red light in the eastbound direction. This exception may have proved the rule.

An indirect witness, the lady passenger in the red vehicle at the tire filling station, reacted to an unexpected stimulus, which the author assumed to be a loud sound. Since she likely wouldn't react to a stimulus before it happened, her startle reaction gives us the latest time for a loud noise to arrive at her position, some 70 meters (230 feet) away from the area of impact, as 2:29:45.2, in Tick 905. The technical literature on startle responses and the physics of sound indicated that the sound likely originated one quarter second prior at 2:29:44.9. This corresponds closely to the estimated time of entry of the tractor/trailer into the intersection after the start of the all-red signal. It was entirely consistent with multiple witness accounts of first hearing a horn blast or blasts and then seeing a collision.

The method established the commencement of the green signal for southbound traffic prior to the collision. It was determined that the dark vehicle entered and traveled through on southbound amber, followed 4 seconds later by the tractor/trailer entering on the second portion of three of the all-red signal for southbound traffic.

Together with the timing and Total Station, site survey analyses indicated that the transport was 85 to 95 meters (280 to 312 feet) north of the intersection at the start of the amber signal. Using the calculation of the speed as 71 km/h (19.7 m/s, 44 m.p.h.), with the transport at 4.3 seconds travel time to the intersection, an attempt was made to duplicate Figure 20 in Gates et al. (2007), by using its logistic regression Equation 6 and predicted probability Equation 8, with the following values and variables[4]:

- Transport speed of 44 mph (71 km/h);
- Amber (yellow) signal length of 4.0 seconds, as at Airport Road southbound;
- No adjacent vehicles passing through;
- Heavy vehicle type; and
- The presence of an opposing left turn vehicle.

The calculated result of Equation 6 and Equation 8 showed that the probability of the transport going through was 38.8%, and the probability of the transport stopping was 61.2%. This logistic regression function was developed over the nearly 900 observations of vehicles made in that study. The function was plotted with MATLAB, a commercially available validated calculation and graphic program.

This calculated value and corresponding probability is shown in the accompanying **Figure 38** by the intersection of the black arrow and the red curve for heavy vehicles. This was the best-case scenario put forth by another expert (discussed below), while the time/position analysis showed that the travel time was closer to 4.8 seconds, putting probability of stopping near 80%.

The Gates et al. study noted on page 38 that "*most of the red light running vehicles could have stopped comfortably, assuming that the yellow indication was quickly perceived by the driver.*"

Responding Expert's Critique and Analysis

There was general concurrence with the overall analysis of speed by momentum, crush analysis and resting positions in the responding report prepared for counsel of the other party. The tractor/trailer speed of 19.6 meters

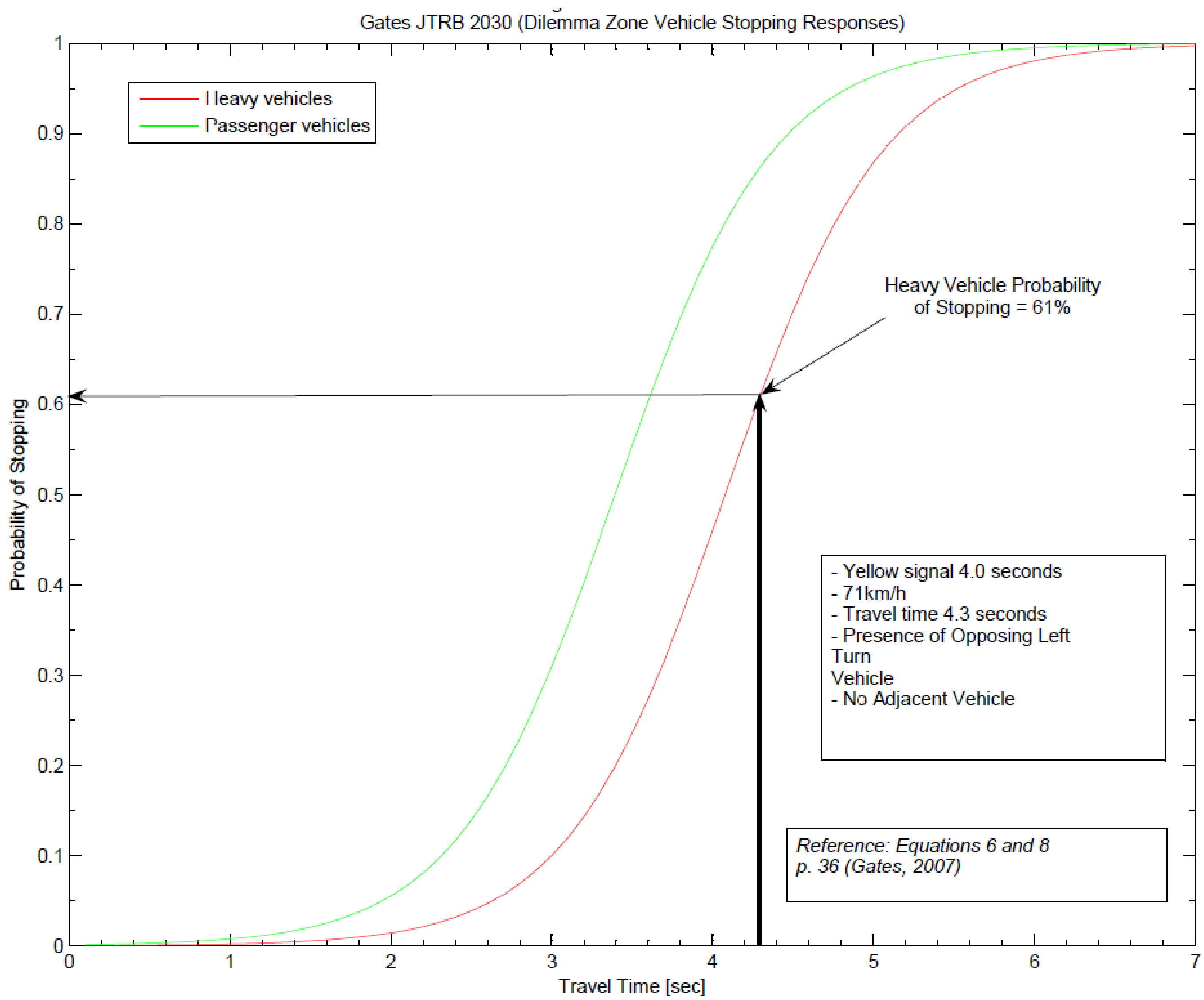


Figure 38
Heavy and passenger vehicle stopping probability from logistic regression.

per second (64.3 feet/sec), or 71 km/h (44 mph), from the videograph techniques compared well with the responding report's "optimal" speed of 69 km/h (43 mph) developed from a suite of widely used reconstruction methods and techniques. These standard techniques were also used by the author and his colleagues during the analysis of the collision. This convergence of speed estimates from technical methods completely contradicted the multiple witness statements clustering around 90 to 100 km/h (56 to 62 mph).

The responding report had differing assumptions pertaining to the start of green for eastbound Mayfield traffic. The principal disagreement concerned the assumption made about the timing of the black car's start-up time as 1.3 seconds before movement at Tick 825 (2:28:25), in contrast with the assumption of a range of 2.2 to 3 seconds based on the author's field trials for second vehicles. The responding report did not account for the presence of the silver pickup in front of the eastbound black car, which could have only delayed the black car's departure. By setting the green signal later than it likely actually was, the amber signal for Mayfield was also moved ahead, inducing an error that cascaded through in the subsequent position analysis.

In the CAM 9 video, two vehicles were observed coming to a stop and waiting in line behind the eastbound Mayfield Road stop line in the moments up to 2:28:20 (a silver pick-up truck and a black car behind it). The black car was in motion in the video at 2:28:25.4. Since there was another vehicle in front of it, it was estimated that the black car began its forward motion at 2.2 to 3.0 seconds after the green ball, to correspond with the field observations of the departure times of second vehicles in line at an intersection.

Underlying this was the assumption that the first-in-line silver pick-up truck would move forward in the typical 1.3 to 2 seconds shown in SAE 2001-01-0045, which published a mean value of 1.66 seconds with a standard deviation of 0.69 seconds for first vehicle reactions to green ball appearance at one intersection and 1.42 seconds with a standard deviation of 0.58 seconds at another intersection.

Given the lack of published data with respect to the mean and standard deviations of departure times for second vehicles waiting at traffic signals, a program was set up to generate field data. The author and colleagues measured the time from the change to a green ball signal to the first detectable motion of the wheel of a vehicle, which would be late in the first phase of acceleration. That motion was for a quarter-to-half rotation of a wheel. First movement of the vehicles in this experiment was being compared with first movement of the vehicles in the video frame analysis, to determine the likely time of the beginning of the green phase for eastbound and westbound. The data can be found in the **Tables A2** and **A3** of **Appendix A**.

The 34 data points for second vehicle departures have a mean value of 2.50 seconds with a standard deviation of 1.15 seconds. Removing the two fastest and slowest times as outliers changes the mean to 2.41 seconds, with a standard deviation of 0.78 seconds. Assuming a normal distribution of points, 68% would be expected to fall between 1.63 seconds and 3.19 seconds. The chosen values of 2.2 to 3.0 seconds fell within this range, and the selection of 2.4 seconds for the analysis of the eastbound green ball timing reflects the distribution of data clustered around that value.

Accordingly, the green ball start value was set to 2.4 seconds prior, that is 2:28:23 (Tick 823), and the calculated arrival time at the southbound Airport Road stop line was during the 2nd second of all-red interval (2:29:45, Tick 905).

Note that the average response by "anticipators" was 1.6 seconds, with a range of 1.3 to 2.3 seconds. These responses were very similar to the 1.3 seconds suggesting that the responding report focused on an anticipated reaction by the driver of black car. This was a specific rather than a general case, and gave the best possible outcome for the transport driver, with respect to whether or not he had entered on a red signal.

The overall analysis of the behavior of the vehicles in the CAM 9 video strengthens the opinion that the eastbound green ball signal occurred at 2:28:23 (Tick 823). This directly underpins a conclusion that the transport entered the intersection during the 2nd second of the all-red interval — the tractor/trailer driver ran a red light.

The interaction between the Honda and the dark vehicle was critical to the context of the collision, but was not discussed by any other technical investigators in their reports or testimony. The Honda's path to westbound Mayfield necessarily passed behind the dark vehicle, or they would have engaged. The Honda started from a stopped position at Tick 902, and moved into Lane 1 southbound after the dark vehicle passed by — well into the third of fourth portions of the southbound amber signal. The Honda was clearing the red signal when it was hit broadside.

As a matter of course, typical drivers assess the gap between their own vehicle and oncoming vehicles, and often pay attention to one oncoming vehicle but not others when making turns. Certainly, the reconstruction analysis showed that the Honda could not have turned sooner than it did, due to the presence of the oncoming dark vehicle. This constraint set the immediate conditions prior to the arrival of the tractor/trailer, and therefore was part of the circumstances of the collision event.

Summary of Contributions of the Method to the Collision Reconstruction

The original goal was to add more information to assist the triers of fact, using the indirect security camera video footage of the collision incident. The forensic team used the eight steps of the rule-based triage method to get to the essence of the matter, which had been obfuscated by the multiple conflicting witness statements. There were four contributions of the method:

- Determination of green ball timing to within 0.5 seconds (0.6% nominal error);
- Resolving the most probable color of the southbound signal at tractor/trailer entry;
- Incorporating the influence of the dark vehicle on the collision dynamics; and

- Allowing assessment of the probability of the tractor/trailer going through in the given set of circumstances.

Based on close scrutiny of the videograph of Camera 9 of the behavior of vehicle traffic for 6 minutes prior to the collision, with a match of 96.4% of observations, the analysis determined that the green ball for eastbound traffic on Mayfield Road illuminated at 2:28:23 (Tick 823), and the green ball for southbound traffic on Airport Road illuminated at 2:29:05 (Tick 865).

It was shown to be more probable than not that the southbound tractor/trailer entered on a red signal, by the analysis of the motion of other vehicles in response to the traffic signal phases at the intersection of Mayfield and Airport Roads. The southbound tractor/trailer entered the intersection after the illumination of the all-red signal, after the first full second (Tick 904) of the 2.9 second duration of this signal, at 2:29:44.6 on the videograph from Camera 9, with its position confirmed by site geometry based on Total Station measurements. The collision between the southbound tractor/trailer and the left-turning Honda occurred at 2:29:45.5, (Tick 905), which was during the 2nd second portion of the 2.9 second duration all-red signal.

The videograph analysis process indicated that a dark vehicle progressed southbound at a speed between 69 and 74 km/h (43 to 46 mph) through the intersection, entering on the second part of the 4-second-long amber signal (Tick 901), whereas this had not been previously considered by the investigators. To begin to make its left-turn to clear the intersection, the Honda passed behind the dark vehicle as it went by during the third second (Tick 902) of the amber signal.

Once the timing had been established, it was demonstrated that the calculated probability of a tractor/trailer combination driver stopping, based on the function in Gates, was 61.2%, in the same circumstances stopping when faced with the amber light at 4.3 seconds travel (equivalent to 85 m or 280 feet) from the stop line, as determined by the videograph. For longer travel times depicted in the time/position analysis diagrams, the probability of stopping would be higher (80%).

Epilogue

In the Province of Ontario jurisdiction under the Highway Traffic Act and its regulations, the onus falls on a left-turning driver to act carefully, and 100% of the liability for a collision that occurs during such a maneuver is assigned to the left-turning driver.

In the criminal case for charges of careless driving against the tractor/trailer driver, the court rendered an acquittal. The subsequent civil case between the truck driver and the family of the left-turning driver settled out of court, but the third-party action between the truck driver and the owner of the vehicle continued, and was tried to determine whether a loss transfer would occur between respective insurance companies. By jury decision, the liability of the left-turning driver was lowered to 70% and that of the truck driver increased to 30%.

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APPENDIX A

Second Vehicle Test Data Tables – February 13, 2012, Toronto

Methodology – time measured by electronic stopwatch from the change to a green ball signal, to the detectable quarter-to-half rotation motion of the vehicle wheel, noting vehicle type and positions

Table A1 - Coded Data Key for Vehicle Departure Study

Vehicle Position		Response	Coded	Vehicle Type	Coded
Lead Vehicle	Column 2	Delay	1	Car	1
Second Vehicle	Column 3	Neutral	0	Pick-up	2
Gap Presence = 1	Column 4	Anticipation	-1	SUV	3
Lane	Column 6			Van	4
				Truck	5
				Bus	6

Table A2 – Coded Data Summary – Second Vehicle Departures

Data Point	Time (sec)	Lead	Second	Gap	Delay/ Anticipation	Lane	Comment
1-1	2.1	5	4	1	0	2	VAN BEHIND TRUCK, ONE CAR LENGTH +; L2 STRAIGHT THROUGH
1-2	3.3	1	1	0	0	3	HONDA CAR BEHIND TAXI L3
1-4	2.9	1	3	0	0	2	SUV BEHIND CAR
1-6	2.2	1	3	0	0	2	SUV BEHIND CAR L2
1-7	2.9	1	6	0	0	3	BUS BEHIND CAR L3
1-8	1.3	1	1	1	-1	3	GAP 5M MOVED BEFORE SIGNAL CHANGE
1-10	2.3	1	1	0	0	3	CAR BEHIND CAR
1-11	2.3	6	1	1	-1	3	BUS IN FRONT OF CAR, ANTICIPATED; STOP, START, 8M GAP
1-13	1.5	4	1	0	-1	3	CAR BEHIND VAN; VAN ROLLED BEFORE GREEN SIGNAL
1-15	1.7	1	3	0	-1	3	SUV BEHIND CAR - CAR MOVED IN ANTICIPATION
1-17	1.7	1	4	0	0	3	VAN BEHIND CAR L3
1-18	1.8	1	1	0	0	2	CAR BEHIND CAR L2
1-19	2.4	3	2	1	0	3	5M GAP PICKUP BEHIND SUV
1-20	1.9	4	1	0	0	2	CAR BEHIND VAN L2
1-21	2.1	3	1	0	0	3	CAR BEHIND SUV L3
1-22	1.8	1	1	0	0	1	CAR BEHIND CAR L1
1-23	1.6	3	3	0	0	3	SUV BEHIND SUV
1-25	1.7	1	6	0	0	3	WHEELTRANS BEHIND CAR L3
1-26	2.0	3	1	0	0	3	CAR BEHIND SUV L3
1-27	1.6	4	3	0	0	3	SUV BEHIND VAN L3
1-28	4.1	6	1	1	1	3	CAR BEHIND BUS GAP 8M BUT CLEARING NTHBND TRAFFIC
1-29	4.4	1	1	0	1	3	CAR BEHIND CAR L3 DELAYED DEPARTURE
1-30	1.8	4	1	0	0	3	CAR BEHIND VAN
2-1	1.9	1	1	0	0	3	CAR BEHIND CAR L3

2-3	1.3	1	1	0	-1	3	CAR BEHIND CAR SECOND VEHICLE MOVED BEFORE FIRST AT GREEN
2-5	1.6	1	1	0	0	2	CAR BEHIND CAR L2
2-6	3.4	1	1	0	1	3	CAR BEHIND CAR L3 SLOW START BY VEHICLE ONE
2-7	2.7	1	2	0	1	3	PICKUP BEHIND CAR; PICKUP DELAYED START
2-9	6.8	1	4	0	1	2	VAN BEHIND CAR L2 LONG DELAY BY VEHICLE ONE
2-10	3.9	3	6	0	0	3	TTC BUS BEHIND SUV L3
2-11	1.8	3	6	0	0	3	TTC BUS BEHIND SUV L3
2-12	4.1	6	3	1	1	3	CAR, GAP OF 10 M, TTC BUS - DELAY FOR CLEARING TRAF-FIC
2-13	3.3	1	1	0	1	3	CAR BEHIND CAR SLOW VEHICLE ONE START L3
2-14	2.9	1	3	0	0	2	SUV BEHIND CAR L2

Table A3 – Coded Data Summary – Second Vehicle Departures Sorted by Duration

Data Point	Time (sec)	Lead	Second	Gap	Delay/ Anticipation	Lane	Comment
1-8	1.3	1	1	1	-1	3	GAP 5M MOVED BEFORE SIGNAL CHANGE
2-3	1.3	1	1	0	-1	3	CAR BEHIND CAR SECOND VEHICLE MOVED BEFORE FIRST AT GREEN
1-13	1.5	4	1	0	-1	3	CAR BEHIND VAN; VAN ROLLED BEFORE GREEN SIGNAL
1-23	1.6	3	3	0	0	3	SUV BEHIND SUV
1-27	1.6	4	3	0	0	3	SUV BEHIND VAN L3
2-5	1.6	1	1	0	0	2	CAR BEHIND CAR L2
1-15	1.7	1	3	0	-1	3	SUV BEHIND CAR - CAR MOVED IN ANTICIPATION
1-17	1.7	1	4	0	0	3	VAN BEHIND CAR L3
1-25	1.7	1	6	0	0	3	WHEELTRANS BEHIND CAR L3
1-18	1.8	1	1	0	0	2	CAR BEHIND CAR L2
1-22	1.8	1	1	0	0	1	CAR BEHIND CAR L1
1-30	1.8	4	1	0	0	3	CAR BEHIND VAN
2-11	1.8	3	6	0	0	3	TTC BUS BEHIND SUV L3
1-20	1.9	4	1	0	0	2	CAR BEHIND VAN L2
2 -1	1.9	1	1	0	0	3	CAR BEHIND CAR L3
1-26	2.0	3	1	0	0	3	CAR BEHIND SUV L3
1-1	2.1	5	4	1	0	2	VAN BEHIND TRUCK, ONE CAR LENGTH +; L2 STRAIGHT THROUGH
1-21	2.1	3	1	0	0	3	CAR BEHIND SUV L3
1-6	2.2	1	3	0	0	2	SUV BEHIND CAR L2
1-10	2.3	1	1	0	0	3	CAR BEHIND CAR
1-11	2.3	6	1	1	-1	3	BUS IN FRONT OF CAR, ANTICIPATED; STOP, THEN START, 8 M GAP
1-19	2.4	3	2	1	0	3	5M GAP PICKUP BEHIND SUV
2-7	2.7	1	2	0	1	3	PICKUP BEHIND CAR; PICKUP DELAYED START
1-4	2.9	1	3	0	0	2	SUV BEHIND CAR

1-7	2.9	1	6	0	0	3	BUS BEHIND CAR L3
2-14	2.9	1	3	0	0	2	SUV BEHIND CAR L2
1-2	3.3	1	1	0	0	3	HONDA CAR BEHIND TAXI L3
2-13	3.3	1	1	0	1	3	CAR BEHIND CAR SLOW VEHICLE ONE START L3
2-6	3.4	1	1	0	1	3	CAR BEHIND CAR L3 SLOW START BY VEHICLE ONE
2-10	3.9	3	6	0	0	3	TTC BUS BEHIND SUV L3
1-28	4.1	6	1	1	1	3	CAR BEHIND BUS GAP 8M BUT CLEARNG NORTHBOUND TRAFFIC
2-12	4.1	6	3	1	1	3	CAR, GAP OF 10 M, TTC BUS - DELAY FOR CLEARING TRAF-FIC
1-29	4.4	1	1	0	1	3	CAR BEHIND CAR L3 DELAYED DEPARTURE
Average	2.5						Average for all data points
Std. dev.	1.15						
Average	2.41						Removed two highest and two lowest data points
Std. dev.	0.78						

Forensic Engineering Assessments of Defective Welds in Mobile Oilfield Fracking Tanks

By Jesse A. Grantham, PhD, PE (NAFE 597F)

Abstract

Hydraulic fracturing (fracking) tanks for oil-well drilling operations were purchased for more than $5 million by a leasing company for use in Alaska and other northern states. The tanks were intended to transport drilling fluids and store liquids. The tank manufacturer warranted that the tanks met all regulatory requirements. The author, who confirmed that the tank welds did not comply with industry standards or satisfy regulations, investigated and reported that the leaking welds were defective, and the tanks did not comply with Environmental Protection Agency requirements.

Keywords

Forensic engineering, oil-well drilling, fracking, tanks, hydraulic fracturing, welding, weld inspection

Background

Hydraulic fracturing (fracking) of an oil well involves forcing large quantities of a liquid (primarily water) under high pressure from a wellbore against a rock formation until it fractures. The fracture lengthens as the high-pressure liquid in the wellbore flows into the formation. This injected liquid contains solid particles or "proppants" that are usually sand (or comparable man-made granular solid) that fill the expanding fracture. When the water injection is stopped, the high pressure is reduced, and the formation attempts to settle back into its original configuration. However, the proppant keeps the fracture open. This opened fracture allows hydrocarbons and natural gas to flow from the rock formation to the wellbore and the surface.

Fracking has been used in the United States for more than six decades; however, it has only recently produced a significant portion of crude oil. This technique, often used in combination with horizontal drilling, allowed the United States to increase its oil production faster than at any time in history. Currently, oil production in the continental United States from fracked wells makes up about half the total U.S. crude oil production.

In 2000, approximately 23,000 hydraulically fractured wells produced about 102,000 barrels per day of oil in the United States, making up less than 2% of the national total. By 2015, the number of fracked wells grew to approximately 300,000. Production from those wells was more than 4.3 million barrels of oil per day — about 50% of the total oil output of the United States. This new oil production primarily came from shale and other rocks in the Denver-Julesburg (D-J) Basin in Colorado, Eagle Ford formation and Permian Basin in Texas, Marcellus Shale in Pennsylvania, and the Bakken and Three Forks formation in Montana and North Dakota.

Figure 1
Typical front view of fracking tanks.

To supply thousands of gallons of water to the remote oil-well drilling sites and inter-connect to the pumping equipment that was used to frack the oil well, many specially designed tanks were required. Since these special types of tanks were not available in the routine U.S. tank market, numerous tank manufacturers established welding facilities to provide fracking tanks and meet the market demands. Typical fracking tank features are shown in **Figures 1** through **4**.

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Figure 2
Typical rear view of fracking tanks.

Introduction

The owner (purchaser) of the fracking tanks always intended — and the tank manufacturer was always aware — that the tanks were to be built for the sole purpose of leasing, renting, or selling to third-party oil-well drilling operations in Alaska and the northern continental United States. The fracking tanks were placed in-service at oil-well drilling sites and oil/gas production operations on properties governed by various jurisdictional regulations. The purpose of each fracking tank was to hold water for fracking and be available as on-site storage tanks for hydrocarbons from the well and elsewhere at the well drilling site.

The tank manufacturer provided verbal assurances to the owner regarding successful experience with the manufacture of fracking tanks and contractually agreed to responsibilities for tank design, materials, welding, and weld quality. It was reasonable for the owner to expect the tank manufacturer would follow tank welding guidelines that have existed for decades and are published by the

Figure 3
Typical storage yard, fracking tanks.

Figure 4
Typical storage yard, fracking tanks.

American Petroleum Institute (API) and American Society of Mechanical Engineers (ASME).

After delivery of numerous fracking tanks to the owner, leaks in weldments became evident on the tanks during the warranty period, and weld repair operations were undertaken by the owner. The clients (who leased the tanks) were oil-well drillers. Both local jurisdictional code enforcement officials and the Environmental Protection Agencies (EPA) became aware that the fracking tanks were not manufactured with weld quality as required by established jurisdictional regulations. These regulations were explained to the owner by drilling clients in Alaska, North Dakota, South Dakota, and Montana. The importance of proper, code-compliant welding of the tanks was initially and clearly stipulated in the contract to the tank manufacturer at the time the owner placed the order for 142 fracking tanks. The tank manufacturer provided a construction booklet for each fracking tank, as requested by the owner, to describe the welding.

The tank owner and his clients, who were oil-well drillers and tank users, did nothing wrong in this matter; they relied on the owner (who leased the tanks to them) and the tank manufacturer to provide fracking tanks that complied with the appropriate requirements for each drilling site. Photographs of the tanks are shown in **Figure 1** and **Figure 2**. Examples of weld defects observed in the subject tanks are shown in **Figures 5** through **8**.

The author's review of the tank manufacturer's construction booklets for each tank revealed that the fracking tanks were welded in accordance with an incorrect welding code.

A result of the author's literature surveys and reviews indicated that the correct welding code for

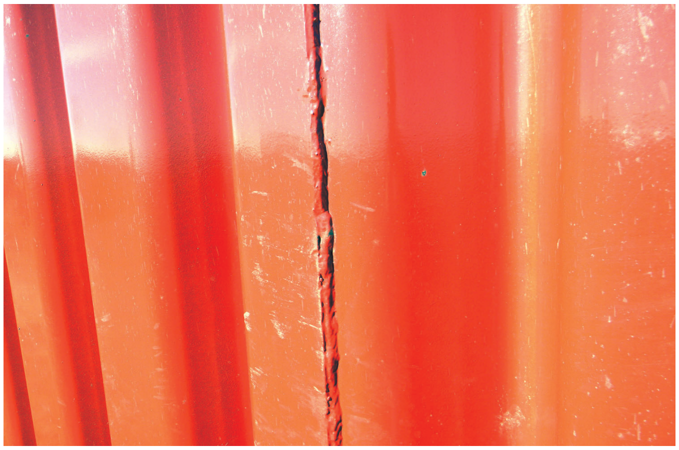

Figure 5
Typical weld defect — open seam.

Figure 7
Typical defective weld — pores.

fracking tanks was ASME Section IX – *Welding, Brazing & Fusing Qualifications of the ASME Boiler & Pressure Vessel Code*[1]. Documentation booklets from the manufacturer for the tank welding revealed that the tanks were welded in accordance with the American Welding Society (AWS) D1.1 *Structural Welding Code – Steel*[2]. The incorrect welding code in the documentation was evidence that the tank manufacturer used incorrect welding procedures, incorrect welder certifications, and incorrect final weld inspection criteria during original tank manufacturing. Many of the fracking tank manufacturer's AWS welder performance certifications were expired. Routine welder continuity verification every six months was a requirement of the AWS and ASME codes. The choice of welding code was defined by the end-use of the product. *ASME Boiler and Pressure Vessel Code* Section VIII, Division 1[3] was required for the construction, including the inspection requirements for welded product containment items. ASME Section IX was required for welding procedure qualifications and welder certifications.

Inspections were performed by the owner's third-party inspection company on selected tanks in Alaska. These inspections were valid and reliable for welds on the subject fracking tanks. The Alaska Department of Environment Conservation (ADEC) reviewed the inspection plans and did not object to the owner's third-party inspector's findings. Numerous welds in the fracking tanks leaked and were not fit for service.

It is well known in the industry that fracking tanks at drilling sites may be used to store all types of products, not just water. The tank manufacturer's fracking tank welds did not meet generally accepted weld profiles for the welding code. The welds on the tanks were not fit for

Figure 6
Typical weld defect — undercut.

Figure 8
Typical defective weld, incomplete and non-fusion.

the intended service as evidenced by a review of fracking tank manufacturer's welding documentation, visual observations of weld photographs, and inspection reports by the owner's third-party inspector. The tank manufacturer's fracking tank welds were required to be in compliance with the intent of the industry standards set forth in the requirements of regulators.

The fracking tanks were mobile, steel containers intended for oilfield service to receive, store, and transport various types of products. The weld discontinuities referenced in the owner's third-party inspector's reports and photographs were a reasonable basis for rejecting the tank manufacturer's fracking tanks.

Proven and accepted methods of exterior welding inspections on the fracking tanks were utilized in the inspection criteria. The tank manufacturer's tanks were examined by recognized professionals with current inspection registrations. These types of visual weld assessments were commonplace for in-situ tanks and include nondestructive and mechanical tests.

Discussion

The author reviewed documents from the tank manufacturer, which provided insights as to its lack of knowledge about uses and misuses of oil-well fracking tank products that resulted in using an incorrect code and defective welding. Industry documents about the proper welding codes to fabricate the fracking tanks were readily available but were not used. The owner's third-party tank inspector maintained current and industry-recognized credentials for weld assessments.

In the author's opinion, there was a lack of management accountability by the tank manufacturer for welding operations on the fracking tanks. The limited number of fracking tanks readily available nearby precluded the author from duplicating all the measurements, sampling, and weld evaluations performed by the owner's third-party inspector. It was agreed that the expense to validate a higher percentage of problematic welds already reported by this firm would be redundant. Metallurgical laboratory analysis might have provided other causes for the defective welds, yet the point remains that a large number of the welds were unacceptable.

There are established, proven methods and techniques recognized and accepted by professional weld inspection experts. The owner's third-party inspector's inspections were considered suitable for the author and addressed the techniques and tests aptly stated as the fundamental reasons for the defective welds in the fracking tanks.

The author's assessments of the documentation and welds on all the available tanks clearly revealed that an incorrect welding code was used by the tank manufacturer.

Conclusions

The author's conclusions were based upon sworn testimony, documented facts of the case, visual observations, photographs, and reliable reports. Conclusions in this matter were consistent with reviews of numerous documents and jurisdictional materials. The weld defects were the result of deficient welding management by the original tank manufacturer.

The author reviewed the manufacturer's fracking tank literature, drawings, specifications, welding symbols, Welding Procedure Specifications (WPSs), Material Test Reports (MTRs), and Welder Performance Qualifications (WPQs). Also evaluated were the tank code requirements, jurisdictional regulations, and welding documents that were provided to ascertain the tank manufacturer's non-adherence to requirements of authorities that had jurisdiction in Alaska and Northern states. Conclusions were based upon accepted definitions, methods, and principles common to welds and testing of welds in commercial, oilfield products. These conclusions were provided with a reasonable degree of engineering certainty for acceptable welds.

Every tank failed to comply with the welding codes and was welded by improperly certified welders. The welding documents that were prepared and presented by the tank manufacturer to the owner were erroneous and incomplete.

The inspections performed by the owner's independent third-party inspector on the subject tanks were valid and reliable. The conclusions in the report for the inspections were correct and consistent with the photographs in the reports. The welding on the fracking tanks and tank repairs should have been closely monitored and signed-off on by an independent American Welding Society – Certified Welding Inspector (AWS-CWI) or American Welding Society – Senior Certified Welding Inspector (AWS-SCWI) in accordance with the contract documents.

References

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2. AWS D1.1/D1.1M-2010. Structural welding code – steel. Miami, FL; American Welding Society.

3. ASME-BPVC-2010. ASME boiler and pressure vessel code: section VIII, division 1, rules for construction of pressure vessels. New York, NY; American Society of Mechanical Engineers.

Forensic Engineering Analysis of Design & Manufacturing Practices for an Automotive Spring

By John Leffler, PE (NAFE 709S)

Abstract

A child fatality case focused on the failure of springs in an automotive control system switch. In the forensic engineering analysis, the actions of the spring manufacturer, switch manufacturer, control system manufacturer, and vehicle manufacturer were of interest. Relevant details included the spring manufacturing drawing, the spring design itself, the Design Failure Modes & Effects Analysis (DFMEA) conducted by the switch manufacturer, apparent absence of quality assurance testing, warranty return failure descriptions, and the actions taken by various entities upon notice of spring failures.

Keywords

Forensic engineering, spring, FMEA, fatigue, validation, quality assurance, control, warranty

Introduction

A child was playing unattended in the cab of a mid-2000s model year vehicle. When the child turned the ignition key, the engine started, and the vehicle rolled forward — striking a toddler playing outside the vehicle. A post-incident inspection revealed that the vehicle could be started without engaging a particular control switch intended to preclude vehicle starting unless the switch was engaged. Further, the inspection revealed that the switch likely jammed in the engaged position due to the failure of compression springs used in the switch. Optical and Scanning-Electron Microscopy (SEM) revealed that the failed spring coils had numerous torsional fatigue fractures, and some regions of the broken spring wire exhibited longitudinal radial cracks that may have acted as stress raisers.

In this case, the following parties were named as defendants (actual company names have been changed): vehicle manufacturer "Alpha," vehicle control system manufacturer "Baker," control switch manufacturer "Crown," spring manufacturer "Delmar," spring wire manufacturer "Echo." Vehicle manufacturer Alpha created performance specifications for the control system. Control system manufacturer Baker subcontracted the control switch design and manufacture to Crown. In turn, Crown created the spring design drawing and production specifications as part of the switch design, and contracted with Delmar to produce the spring. The batch of wire used by Delmar for the subject springs was made by Echo.

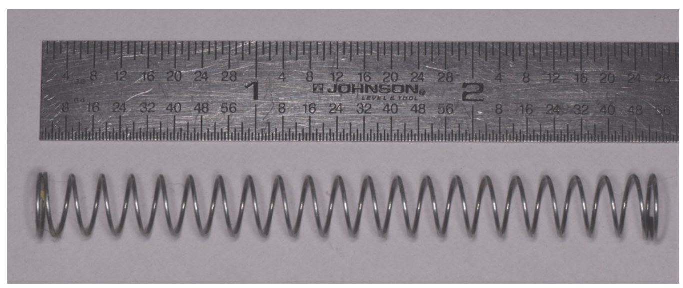

Figure 1
Exemplar compression spring.

The switch was designed to compress two identical parallel springs in a nominally axial manner during control engagement, and the springs return the switch to a non-engaged position once the control is released (**Figure 1**).

The subject spring was designed by Crown and released at revision A in the late 1990s. The design data on the revision A manufacturing drawing, created by Crown, is shown in **Figure 2**. Values have been changed slightly for confidentiality:

Analysis and Findings

<u>Spring manufacturer "Delmar"</u>

- Spring manufacturer Delmar was not involved in the design decisions or risk evaluations pertaining to the spring or its use in the control switch.

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	Nominal value	Tolerance	"Critical" dimension	SPC sampled
Spring length	2.85"	+/- 0.025"		
Coil outside diameter	0.270"	+/- 0.004"		
Number of active coils	20			
Total number of coils	22			
Wire diameter	.018	+/- 0.0005"		
Wire material	Music wire			
Wire plating	Tin			
Load at 1.85" compressed length	0.50 lbf	+/- 8%	•	•
Load at 0.470" compressed length	1.30 lbf	+/- 12%	•	•
Maximum solid height	0.440"		•	

Figure 2
Design data from spring manufacturing drawing.

The testimony and discovery materials reviewed were consistent with this.

- Delmar did not participate in the design of the spring or the switch.
- Delmar had no substantive understanding of the safety risks inherent in the spring application — they knew only that it was for an automotive application.
- Delmar had no contractual obligations to track the performance of springs in use.

• Given the information Delmar was provided by Crown, it was reasonable of Delmar to rely upon (and not question) Crown's spring design information, based on Crown's position as a large "Tier 1" manufacturer of automotive components that Crown sold directly to automobile manufacturers.
  - Delmar's president stated in his deposition that the company would get complete drawings from Crown and manufacture springs in accordance with the drawing. There was no need for further design work.

• Delmar produced the spring using processes typical to the spring manufacturing industry and in compliance with Crown requirements.
  - Material control: Delmar used matched work order tickets to associate individual wire coils with specific jobs. Discrepant materials were quarantined pending resolution.
  - Sampling:
    - Delmar did a full dimensional analysis of Crown-designated spring dimensions and loads during the setup of each production run as well as at the end of the run.
    - During production, Delmar would check the three Crown-specified critical measurements (solid height, minimum and maximum loads) on a minimum of 12 samples per day — or more, if needed, to meet the sample quantity for Crown's "zero acceptance*" requirement chart.
    - Delmar prepared a capability analysis of the load measurements from samples, using Statistical Process Control (SPC) data. SPC data in the form of "X-bar & R" charts were provided with every order.
    - Delmar was not required to inspect every spring; nevertheless, the spring forming machine utilized a noncontact sensor to verify that each spring's free length fell within the specified tolerance (**Figures 3** and **4**). A significant variation in material condition or machine

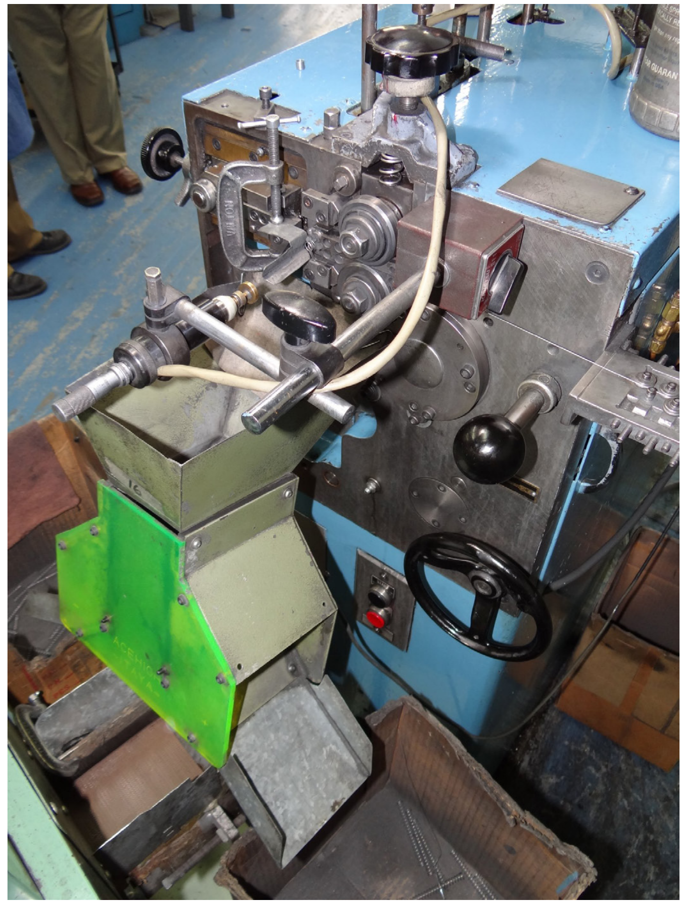

Figure 3
Spring forming machine.

* The term "zero acceptance" refers to quality assurance methodologies utilizing an acceptable quality limit in conjunction with a chart that establishes how many samples must be measured, depending upon manufacturing lot size. If one defect is found among the specified number of samples measured, the entire lot is rejected (i.e., zero are accepted).

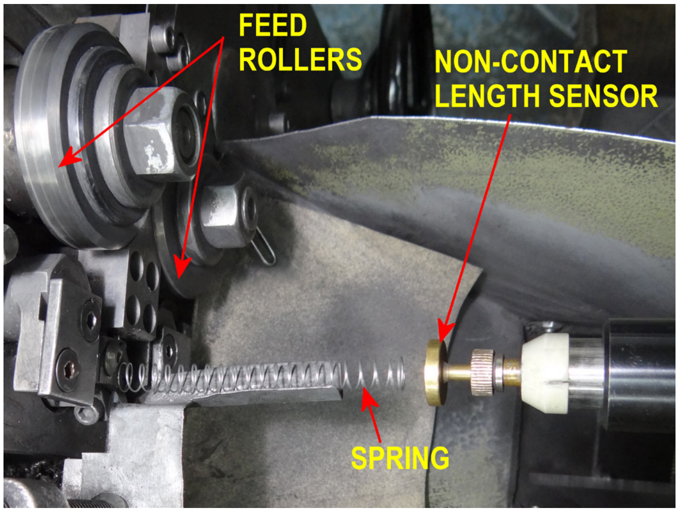

Figure 4
Feed rollers and length sensor.

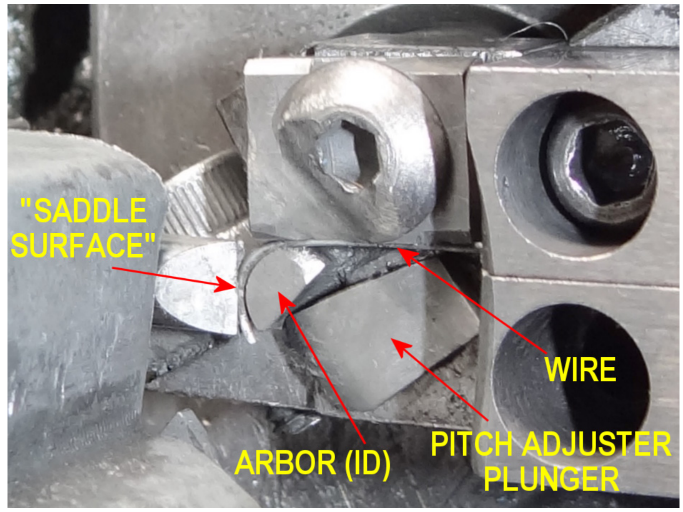

Figure 5
Spring forming surfaces.

performance would cause an out-of-tolerance free length, and the spring would automatically be rejected to a scrap bin. The spring forming machine was set up to automatically adjust itself to correct for the rejected spring's free length discrepancy, on the next spring made.

- The use of sampling is common in mass production of inexpensive parts such as the spring; the subject spring had a production price of $0.03.

- Delmar utilized a typical type of spring forming machine, in which the spring coils are formed through a "wiping" plastic deformation; the coils are not formed by "rolling" plastic deformation. As such, the surface of the wire will exhibit some damage due to localized galling and abrasion of the wire where it rubs the concave "saddle surface" of the spring forming machine, during plastic deformation (**Figure 5**). Additionally, there was an opportunity for minor flattening of the spring wire as it went through the forming machine's feed rollers (**Figure 6**).

- In the litigation, it was asserted by other experts that Delmar was the responsible entity for the fatigue failures, due to the radial cracking of certain portions of the spring wire. Some of this radial cracking was observed to be originating from the "center" of the flattened area of the wire, and some was observed to originate from the galled/abraded area of the wire surface inherent in the forming process. See **Figure 7** for a simplified representation of the cracking. Note that not all fatigue failures showed evidence of this radial cracking in the wire.

- It was asserted by other experts as well that some of the longitudinal radial cracking was found to have slight amounts of tin present within the cracks near the wire surface. In turn, these experts asserted that the wire was improperly manufactured by Echo and improperly inspected

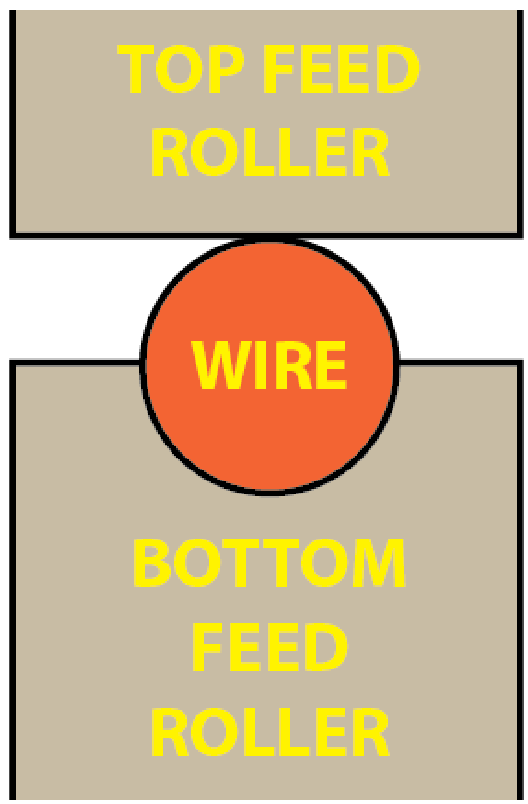

Figure 6
Feed roller configuration.

by Delmar. It was later revealed that Delmar's normal post-forming stress-relieving process, in which the spring is baked to relieve internal stresses, was done at an industry-accepted temperature that happened to be above the melting point for tin. As such, it was possible that surface tin plating wicked into some of the longitudinal cracks during stress-relieving. Regardless, Delmar had no contractual requirement to conduct any microscopic evaluation of Crown's springs or of its incoming spring wire material. The company manufactured the springs for years before any failure concerns were brought to its attention.

Control switch manufacturer "Crown"

- As the designers of the subject spring, Crown failed (in the opinion of the author) to appropriately analyze the safety risks associated with using the spring in its control switches.
  - A Crown engineer conducted a Design Failure Modes & Effects Analysis (DFMEA) for the switch during the spring's design in the late 1990s. This DFMEA document formed the basic safety risk analysis for the switch, given the requirements of Alpha's performance specification. FMEA, in general, was first used in the automotive industry in the 1970s; there are variants, including Process FMEA for manufacturing and FMECA (Failure Modes, Effects, and Criticality Analysis). The purposes of a DFMEA were described in Society of Automotive Engineers (SAE) *Recommended Practice J1739-1994*, an FMEA reference manual jointly developed by U.S. vehicle manufacturers and first published in 1994[1]. It was the current version of J1739 when the DFMEA for this spring design was completed; J1739 was most recently revised in 2009.
    - Per Section 1.1 of J1739-1994: *"An FMEA can be described as a systemized group of activities intended to: (a) recognize and evaluate the potential failure of a product/process and its effects, (b) identify actions which could eliminate or reduce the chance of the potential failure occurring, and (c) document the process."*
    - Per Section 3.1 of J1739-1994: *"In its most rigorous form, an FMEA is a summary of an engineer's and the team's thoughts (including an analysis of items that could go wrong based on experience and past concerns) as a component, subsystem, or system is designed. This systematic approach parallels, formalizes, and documents the mental disciplines that an engineer normally goes through in any design process."*
    - Per Section 3.1.2 of J1739-1994: *"During the initial design potential FMEA process, the responsible engineer is expected to directly and actively involve representatives from all affected areas. These areas should include, but are not limited to: assembly, manufacturing, materials, quality, service, and suppliers, as well as the design area responsible for the next assembly."*
    - The FMEA methodology provides a framework, but the outcome entirely depends upon proactive consideration and contemplation by the responsible engineer and production team.

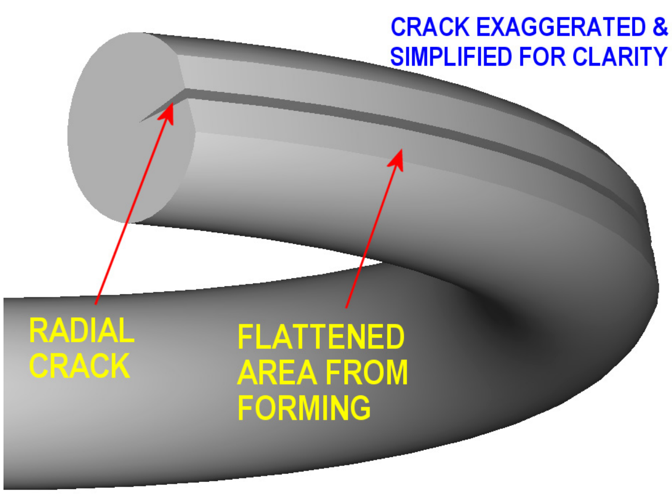

Figure 7
Radial cracking.

  - For a particular potential failure cause and associated effect, a DFMEA involves the engineer & team's appraisal of the severity of the effect and the likelihood of occurrence of the cause. For prioritizing risk mitigation, there is also the factor of detection. In SAE J1739, detection pertains to whether design controls should detect the cause or failure mode before the design is put into production. Design controls may include validation testing, engineering studies, field testing, etc. In the case of the Crown DFMEA, however, comparison with an earlier Crown DFMEA for a similar switch reveals that detection was apparently expected to be done by the end-user. It is reasonable to compare these early and late 1990s DFMEA documents, as they shared identical content for the DFMEA analysis pertaining to the subject failure effect, which was "vehicle starts regardless of the switch position." Identical as well between the old and new documents were the severity, likelihood, and detection ratings — it is unknown whether the Crown engineer properly evaluated this new switch and its new spring design, or simply copied this section in its entirety from the previous DFMEA. The severity rating assigned by the Crown engineer for the failure effect was "hazardous-without warning" — an appropriate choice. The likelihood of occurrence and detection ratings, however, were both "remote." As the DFMEA engineer, he should have had a basis for deciding these causes were unlikely — perhaps he was assuming that specific design controls would be used, and that they would be effective.

- The three potential failure causes included: 1) "debris in the switch;" 2) "broken components in the switch;" and 3) the subject springs were weak, absent, or damaged. Regarding this last potential failure cause, the design controls (i.e., the solution, in theory) were:

  - The spring supplier would incorporate SPC during production. (Author comment: This presupposes SPC will capture all relevant defects, and does not establish which spring feature dimensions are critical.)
  - A periodic sample of the springs would be checked for proper forces and defects at incoming inspection, and each completed switch would be tested for circuit isolation. (Author comment: It is likely that one of these switches could have a missing spring and still pass circuit isolation, though this wasn't tested.)

- Among the three failure causes, the author noted there was no mention of fatigue failure of the springs — one of the most important considerations in using springs for high-cycle dynamic applications. Further, none of the design controls outlined for preventing this catastrophic failure effect do anything to predict or detect spring fatigue. One of the most obvious sources of potential failure in a critical dynamic spring application was not even addressed in Crown's DFMEA for the switch.
- It is particularly ironic that fatigue was not addressed as a potential failure cause for the main switch springs because fatigue was addressed as a potential failure cause for the switch's electrical contact components, under the failure mode "vehicle fails to start." The design controls in place were that the switches must meet Alpha validation tests and that there was to be continuous production line durability testing.
- One could assert that if the electrical contact components undergo durability testing, then the subject springs would "come along for the ride" and be tested as well. But such indirect testing is not the hallmark of a thorough DFMEA, in the author's opinion. Regardless, in a properly-conducted DFMEA, design controls are an integral element of the product's overall validation and control plan. Beyond the discussion of the requirements in the Alpha performance specification, the design controls "inherited" by the springs included ongoing production line durability testing. Such controls can be effective (if practiced).

• Spring design
  - Most of the entities involved in the case (including both manufacturers and experts) had relied at some point upon spring design software sold by The Spring Manufacturer Institute, and currently known as "Advanced Spring Design" (ASD). This software is based on TK Solver from Universal Technical Systems (Loves Park, IL), and version 7.13 was used by the author. Using this software, the spring design created by Crown theoretically had an acceptable fatigue life, using the nominal print dimensional values. However, in the author's opinion, the spring was a marginal design with issues that necessitated higher levels of design control, durability testing, manufacturing quality control, and warranty oversight than were practiced by Crown.
  - Crown's chosen print dimensions did not result in a spring that reached the nominal specified load magnitudes; if the print-specified geometry AND loads are input into the ASD software, it returns an "inconsistent" warning.
  - To meet the print, if a supplier such as Delmar is adjusting its spring manufacturing machine to target these median loads (as the loads are

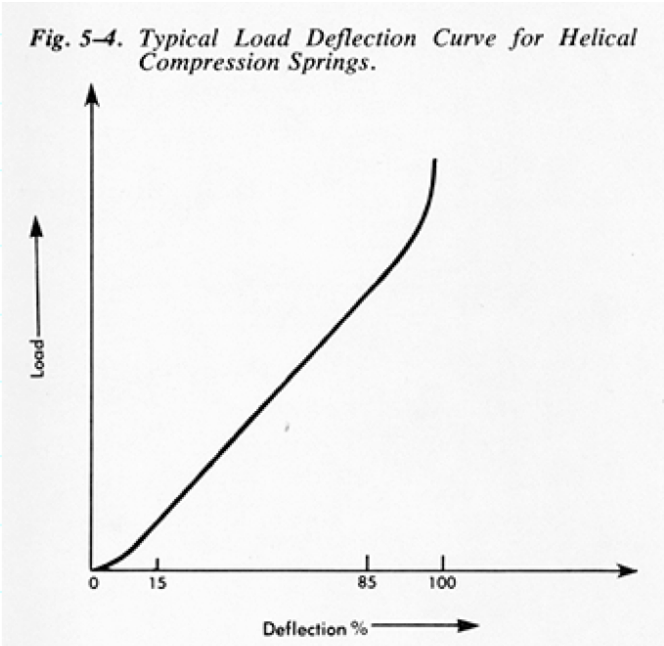

Figure 8
Load deflection versus load magnitude.

monitored through SPC), the machine operator must "juggle" other spring design factors within the tolerance bounds established on the print. If the spring design parameters input into ASD software are focused on the print-specified loads, the ASD software reveals that the "appropriate" spring is shorter and has fewer coils — which would still meet Crown's print, as the number of coils is an untoleranced reference specification. This "juggling" is expected for manufacturing of parts for which there are allowable tolerances. Within the range of spring geometries that are print-compliant, the geometry-dependent fatigue life will vary.

- The maximum Crown-designed working spring deflection was near the solid height (i.e., full compression) of the spring. Standard practice for the recommended extremes of working deflection range for compression springs are between 15% and 85% of full deflection, and as the spring approaches solid height, the effective spring rate, loads, and stresses rapidly increase[2,3]. See **Figure 8** from Associated Spring's *Engineering Guide to Spring Design*[2].
- Per the print dimensions, at full switch driver stroke, the spring deflection was over 98%. Utilizing the print dimensions and tolerances with the ASD software results in the load vs. length composite image in **Figure 9**, which has been visually augmented and enhanced for clarity. As solid height is approached each time the switch is cycled, adjacent coils will clash due to normal variations in coil pitch — as there is less than 0.002 inches of space between each coil at maximum deflection. Additionally, given the force tolerances on the print and recognizing the allowable variability in the spring geometry, it can be seen that at the upper limit of the force tolerance, the spring approaches permanent plastic deformation at full compression (denoted by the green line labeled "Preset Required"). Preset will be discussed below.
- Note that due to the non-linearity of the spring rate as the spring compression approaches 100% (**Figure 8**), the "loads based on print dimensions" trace in **Figure 9** is unrealistically constant in the "NOT RECOMMENDED" area of the plot.
- As facilitated by the near-solid-height maximum deflection of the spring, cyclical coil clashing will over time eventually cause the anti-corrosion plating to deform and/or wear away from the areas of coil contact, potentially allowing corrosion to introduce stress raisers in these areas. Clashing may also cause localized plastic deformation and other surface flaws that create fatigue crack initiation sites.
- As a backup to the ASD software analysis, manual calculations of the peak torsional stress in the spring were performed as follows, based on Spring Manufacturers Institute formulas[4]:

$$\tau = \frac{8(Fmax)D}{\pi d^3} * K_w \qquad K_w = \frac{4C-1}{4C-4} + \frac{0.615}{C}$$

(Equation 1)

D = spring nominal diameter (to wire centerline)

d = wire diameter

C = D/d

- Common practice is to compare these stresses with the minimum tensile strength of the spring wire — in this case (for ASTM A228 music wire) 353,000 psi[5]. The Crown drawing for the spring, however, specified only music wire (not music wire manufactured to ASTM A228). At the upper load tolerance in full deflection,

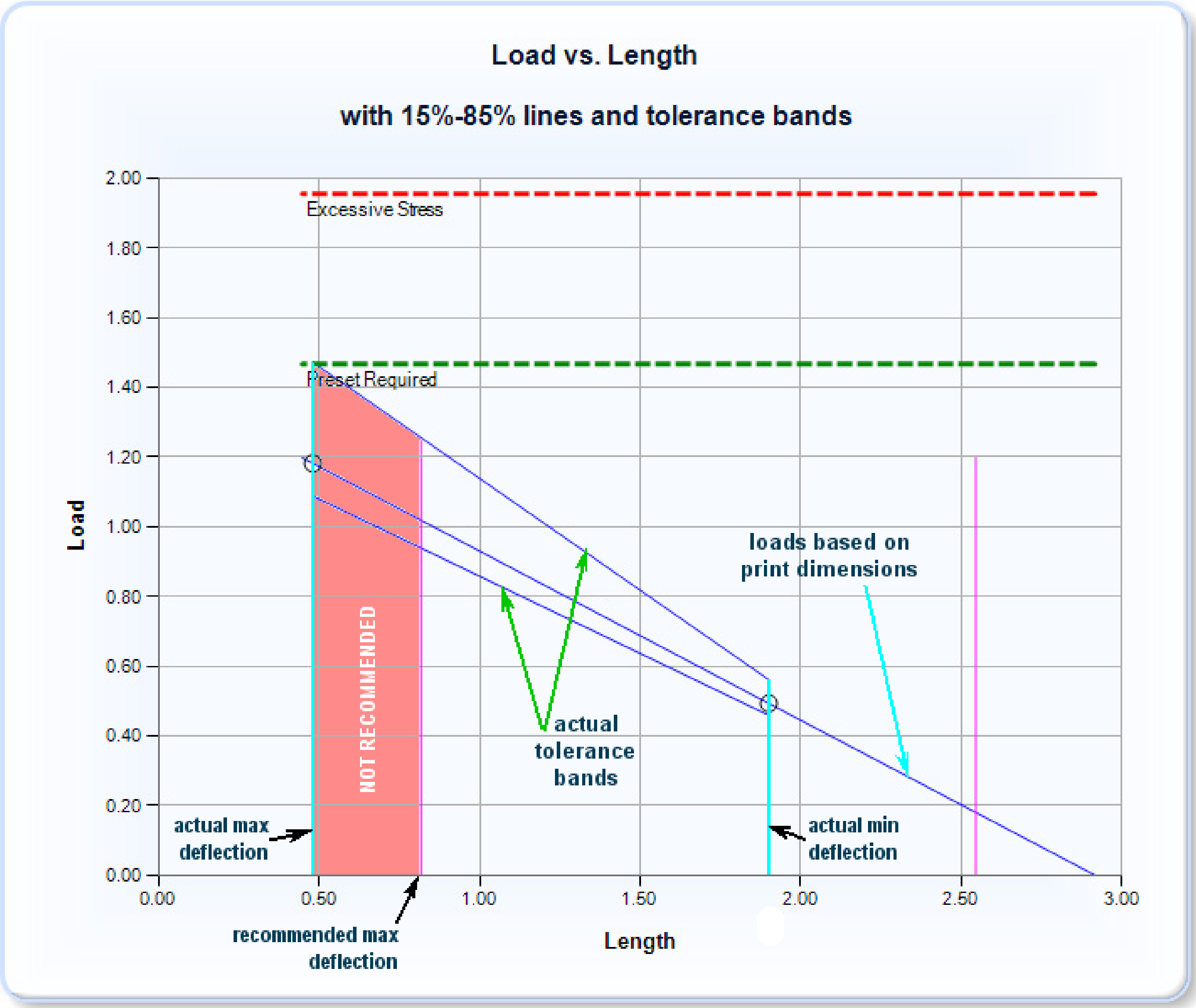

Figure 9
Load vs. length composite image.

torsional stress was 160,000 psi, which when divided by 353,000 = 45.3%. This agreed closely with the spring in **Figure 9** reaching a "preset" (permanent plastic deformation) level of stress, and agrees with Spring Manufacturers Institute documentation of 45% as the threshold of preset[4]. Presetting, in which the spring is intentionally deformed beyond its yield strength, is used in some spring designs to reduce localized stresses, but the subject spring was not designed for preset.

- As to consideration and analysis during design of the previously listed issues of fatigue life variability, over-deflection, buckling, and clashing, no Crown documentation had been provided in discovery that reveals how the design was created. Regarding the ASD estimation of the spring's fatigue life, which again is calculated at nominal dimensional values, the ASD software documentation states *"The estimated fatigue life is applicable to ambient temperature conditions when… springs are preset, material surface is free from seams, burrs, and other stress risers…and the spring does not buckle, have interference, or bind in fixtures"*[3]. In the subject Crown application, the springs were not preset, the spring material quality was not controlled, and the springs had interference. Various references discuss the use of Weibull plots and statistical evaluation of a significant number of tested-to-failure springs, for evaluating fatigue life[6,7]. There is no evidence whether such analyses were performed by Crown during design of the subject spring. The personnel at spring manufacturer Delmar were unfamiliar with these types of analyses.

- Given the marginal spring design, several key elements should have been in place to mitigate the risks of using the design: 1) use top-quality spring wire materials; 2) conduct validation testing to foreseeable conditions; 3) maintain continuous manufacturing oversight through ongoing durability testing and quality assurance; and 4) maintain oversight of field performance through warranty claim monitoring and (as needed) root cause analysis. Elements 1, 3, and 4 will be discussed below, while a discussion of element 2 would require disclosure of confidential information.
  - The Crown drawing specified only that "music wire" be used. There was no print specification that the wire was to be certified to ASTM A228, though Delmar always used ASTM A228 wire from various wire mills. The mills' certificates of compliance for the wire were provided to Crown by Delmar with every order; these certificates included Crown-required basic chemical and physical analyses. No microscopic inspection of wire samples was required by Crown, nor were wire mill certificates required to be provided. Further, there were no Crown controlling documents that set any higher expectations for wire quality, documentation, inspection, or testing beyond what was practiced by Delmar in producing the springs. Additionally, the level of documentation provided by Delmar in its initial Production Part Approval Process (PPAP) submittal was accepted by Crown. If the longitudinal radial cracking originated with wire manufacturer Echo, it would not have been compliant with ASTM A228. But Delmar had no contractual requirement to second-guess the ASTM A228 certification papers (provided by the wire mills) and perform its own verification of compliance.

- After years of spring production beginning in the late 1990s — and about two years before the subject switch was produced — Delmar notified Crown that the supplies of pre-tinned wire available to meet the Crown-specified material requirements had a high scrap rate when used for the subject spring design. Apparently, tin-plated wire was becoming unpopular in the market due to environmental concerns associated with tin, and fewer quality suppliers were offering tin-plated wire. Delmar offered to use a superior-quality zinc-coated wire it had in stock, without a production delay or cost increase to Crown. In production, springs made of this zinc-plated wire had a much lower scrap rate of 5% compared to springs made from the pre-tinned wire, which had a scrap rate as high as 40%. Crown denied the request, and apparently chose not to consult its customer Baker about using the superior wire.
  - Crown was in a unique position among all defendants to understand the safety implications of using other than top-quality wire for this spring design in this high-cycle control switch application, given the marginal spring design. Its decision was not defended by Crown's deponents.

- Crown's engineering witness (a representative speaking for the company, per Federal Rules of Civil Procedure Title V Rule 30[b]6) was asked in his deposition about the continuous conformance testing required for the switch per Alpha's performance specification. The witness believed this consisted of a few thousand cycles of testing that were so brief that they were focused on proper product assembly and not on ensuring continuing compliance with durability requirements. In fact, per Alpha's performance specification, this testing was short-term durability testing to be done on several production samples each day. Continuous conformance testing was a separate requirement in Alpha's specification, consisting of ongoing tests wherein one sample was run several hundred thousand cycles. Upon completion of the test, another test was begun with a new production sample. Several tests could be completed per year, at the testing rate called for in Alpha's spec. Such durability testing would reasonably meet the DFMEA design controls specified for addressing switch component fatigue. But Crown's witness had no evidence that the incident switch's assembly plant performed either the short-term durability testing or the continuous conformance testing required by Alpha.

- With the spring failures that were brought to its attention, Crown failed to reach a competent

conclusion on root cause in every documented case. Indeed, Crown's 30[b]6 witness stated (when deposed 10 years after the initial spring failures) that Crown didn't know the root causes of the failures.
- In his deposition, Crown's quality engineer had exhibits of several different corrective action reports, but was not able to identify any true root cause determinations.
- Baker's quality engineer requested at one point that both Crown and Delmar each conduct independent analysis reports on the spring failures. Delmar hired a test lab, and Crown decided it would simply rely on Delmar's report.

<u>Control system manufacturer "Baker"</u>

- As the manufacturers of the control system that utilized the control switch, and having knowledge of the design of that switch, Baker failed (in the opinion of the author) to appropriately manage safety risks associated with using that switch.
  - Per Baker's 30[b]6 engineering witness, it was not necessary to notify the federal government (re TREAD Act[8] requirements) about the broken control switch springs because the problem description in many switch warranty claims described a failure of the vehicle to start — apparently not a safety concern to Baker. Baker eventually admitted that broken springs could also defeat the safety interlock, presenting a safety issue in vehicles overall.
  - A key source of information regarding the performance and reliability of the switch would be warranty returns. Indeed, warranty returns triggered the initial inquiry into spring issues. Yet Baker apparently did not track all switch warranty claims through to a full understanding of the root cause of the failures.
    - The Alpha warranty database showed that over a two-year period in the mid-2000s there were more than 100 warranty claims with a problem description that the switch was "binding, sticking, or seizing," over 50 warranty claims with a description "grounded" or "short circuited," and over 50 warranty claims with a description that the switch was "making noise." Each of these descriptions was consistent with broken springs, and while many of these warranty claims were likely due to other causes, there does not appear to have been any tangible investigation, cause determination, or corrective action documented for the vast majority of the claims. As the Alpha warranty database provided in discovery only had records for two model years of vehicles, it could not be queried for earlier switch warranty claims that may have preceded what Baker referred to as its first notice of the problem.
  - After Crown finally agreed to accept spring manufacturer Delmar's request to allow the superior quality zinc-plated wire to be used in place of the pre-tinned wire, Crown submitted a change request to Baker a few months later, and Baker rejected this win-win request. Baker had done its own stress analysis of the spring; the reason given for rejecting the spring wire change was that spring redesign was necessary to reduce peak torsional stresses along with a material change — and Baker did not want to simply change the wire material while the redesign was underway. But the net effect of Baker's rejection of Crown's change request was that the superior-quality wire was not used by Delmar until the spring redesign and engineering change was implemented over two years later. There appears to be no rational reason why the change to zinc-plated wire could not have been put in place right away.

- Among nearly all discovery-revealed communications and change notices within and between defendants Alpha, Baker, and Crown, they neglected to highlight that failures of the subject control switches could be dangerous to vehicle owners. The primary conflicts between these parties amounted to discussions of costs and chargebacks.

- Ultimately, there are numerous examples where Baker and Crown personnel recognized the need to redesign the spring. The manner in which these defendants balanced the safety risks inherent in the design involved compromises they did not necessarily need to make, as the subject design was not the only way to create a control switch. The subject spring geometry was obviously not the only geometry that could be chosen. Additionally, at the time the subject vehicle's switch was created, feasible alternative technologies and designs existed with superior durability. Baker had produced all-electronic control switches with no springs in the early 2000s.

Summary of Opinions

- Delmar was not involved in the design decisions or risk evaluations pertaining to the spring or its use in the control switch. Delmar consistently manufactured the springs to Crown's specifications and requirements. Delmar proactively sought to replace the pre-tinned wire with a superior alternative, but this was denied by Crown and Baker. Once the spring was redesigned (slightly shorter overall length, slightly larger diameter wire), the failures generally stopped, despite Delmar using the same manufacturing equipment and processes as before the redesign.

- In designing and manufacturing the subject control switch, Crown failed to properly consider the safety of the end-user, as manifested by its faulty DFMEA, failure to eliminate known spring failure contributors from the design, failure to timely implement the Delmar-recommended change to a higher-quality wire, apparent failure to conduct required production-line durability testing, failure to timely implement the redesign of the spring, and failure to competently evaluate and remedy the root causes of spring failures.

- In utilizing the subject switch in its control system assemblies, Baker failed to properly consider the safety of the end-user, as manifested by its failure to timely implement the Delmar-recommended change to a higher-quality wire, failure to timely implement the redesigned spring, and failure to properly evaluate warranty returns of switches.

- In the case file materials, there were test reports showing laboratory testing of switches to millions of cycles. There were examples provided as well (by other experts in this litigation) of vehicles that had hundreds of thousands of miles on their original switch, yet there was no information about the usage history of these vehicles — for example, if they were used for highway commutes or in urban stop-and-go traffic. Regardless of these issues, the fact that a subset of switches may last a long time is not proof that all switches will do so — and the warranty claims for this switch backed this up. The allowable tolerance variations in the springs would in itself introduce variability in peak stresses with the opportunity for those stresses to be excessive.

- At the time the subject vehicle's control switch was produced, known and feasible alternatives existed that would have reduced or eliminated the hazard that led to the subject fatality.

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Forensic Engineering Analysis of Cervical Spine Trauma, Specifically Quadriplegia and Other Paralyzing Injuries from Diving Accidents

By William N. Rowley, PhD, PE (NAFE 790F) and Laura L. Liptai, PhD (NAFE 339A)

Abstract

Spinal cord injuries from diving accidents are one of the most debilitating and life-altering injuries that can occur in swimming pools as well as in natural bodies of water. Because of the extreme and permanent nature of this trauma, the authors' goal is to move toward "net zero" (elimination) of diving-related injuries. Forensic investigations into cervical spine trauma from diving injuries require both forensic biomedical engineering analysis and forensic trajectory analysis through air and water to the moment of impact in order to determine the cause. Through these analyses, the forensic experts can determine if the physical evidence is consistent with the history of the event or if there is evidence of other causes. Based on the availability of physical evidence in the trauma itself (in conjunction with other forensic evidence), the biomedical engineer and accident reconstruction engineer can collectively assess whether the plaintiff's trajectory is consistent with a slip and fall, push in, or dive in. This forensic investigation will analyze how spinal cord trauma from diving injuries occurs and identify measures that help to prevent these occurrences.

Keywords

Cervical spine injury/trauma, paralysis, quadriplegic diving accident, pool diving accident, aquatic diving accident, diving impact, biomechanics, forensic engineering

Background

Note: In this paper, "dive" and "diving" always denote a headfirst entry into water (**Figure 1**).

Figure 1
Photograph of a 6-inch by 6-inch no-diving pictogram, depicting a headfirst entry into water.

Swimming pools did not become prevalent in the United States until after 1945. Before the Consumer Product Safety Commission (CPSC) was established by Congress in 1972, there was no quantifiable data on diving accidents. In the 1970s, the CPSC began collecting injury information into its National Electronic Injury Surveillance System (NEISS). Around the same time, the National Swimming Pool Foundation (NSPF, a non-profit organization) began sponsoring research into diving accidents (Stone 1980, Egstrom et al. 1986, Egstrom and Rowley 1989, Egstrom et al. 1991, Gabrielsen 1993, Egstrom 2006). In 1973, the University of Alabama in Birmingham began collecting and analyzing what would become the world's largest spinal cord injury research database: the National Spinal Cord Injury Statistical Center (see NSCISC).

Within a 126-page 1980 report on diving to the NSPF, Richard Stone cited a 1978 report by the National Paraplegia Foundation on the incidence of spinal cord injuries in New England (specifically, the states of Connecticut, Maine, Massachusetts, New Hampshire, Rhode Island,

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and Vermont), which determined that diving produced 13% of spinal cord injuries. Stone noted that three-quarters of spinal cord injury accidents in aquatic environments were not in pools — they were in natural aquatic environments, such as ponds, lakes, rivers, and beaches. Stone deduced that 95% of diving accidents in pools occurred in shallow areas of the pool rather than in the deep diving area — and that three out of four diving accidents occurred in less than 4 feet of water (Stone 1980). Stone also presented further statistical and demographic information from several studies that are not reproduced here.

In a 1993 report on diving to the NSPF, Kenneth Solomon compared the accident rate of spinal cord injury from aquatic environments to other specific types of injuries or deaths (**Figure 2**; Solomon 1993). Per Solomon, the accident rate for all causes of spinal cord injuries was 1.6 occurrences per 100,000 people. Spinal cord injuries from aquatic environments constituted a rate of 0.16 occurrences per 100,000 people, which was 10% of all causes of quadriplegia/paraplegia. One quarter of the spinal cord injury accidents that occurred in aquatic environments occurred in swimming pools, which represented 2.5% of the accident rate of all causes of spinal cord injury. This corresponds with Stone's above statistic that 75% of diving injuries occurred in natural aquatic environments as well as with a 1988 paper published by USA Diving (Gabriel 1988).

EVENT	ACCIDENT RATE PER 100,000 PEOPLE (Reflects U.S.data averaged 1972 to 1992)
Death by car accident	18
Suicide	12
Drowning - all causes	1.9
All temporary disabling injuries	3,600
All permanent disabling injuries	130
Poison death by gas	0.40
Death by tornado	0.06
Death by lightning	0.05
Quadriplegic/Paraplegic - all causes	1.6
Quadriplegic/Paraplegic - all aquatic	0.16
Quadriplegic/Paraplegic - all pools	0.04
Quadriplegic/Paraplegic - deeper than about 6'	0.004
Death by meteorite	<0.00001

Figure 2
Excerpt from Solomon's 1993 report (Page v) to the NSPF, showing comparative risks of quadriplegia/paraplegia between 1972 and 1992 (Solomon 1993).

In **Figure 2**, the statistical data shows that, at most, one-tenth of quadriplegic/paraplegic diving accidents occur in pools in water deeper than 6 feet. Therefore, at least 90% of these diving accidents in pools occur in water of a depth of 6 feet or less.

Stone said that the central finding of his study was that "*...only a very small fraction of the diving accidents resulting in spinal injury involve a dive from a diving board into the deep diving area of the pool. The greatest number of diving accidents occur as a result of a dive into shallow water, primarily in the natural aquatic environment rather than in pools. These accidents overwhelmingly involve young adult males during the 'dangerous years' from ages 13 to 23...*" (Stone 1980).

BioMedical Engineering Background

Research indicates that extremely large forces can be applied to the flexed spine when a diver hits bottom at a large enough angle so that the diver's head does not slip. In Stone's 1980 report to the NSPF, he stated "*The most striking finding in this analysis of bottom impact is the extremely large forces that are applied to the flexed spine when the diver hits bottom at a large enough angle so that his head doesn't slip. The forces are far in excess of those required to cause injury. The tolerable speeds are far below those that can be obtained relying only on hydronamic slowing down of the diver during his underwater trajectory*." (Stone 1980).

In 1979, McElhaney et al. produced a biomedical engineering analysis of swimming pool neck injuries for the Society of Automotive Engineers (McElhaney et al. 1979). McElhaney wrote that all but one of the injuries studied involved a compression or flexion-compression fracture of a vertebral body — most often C5.

A 1988 paper cited statistical information produced by the National Spinal Cord Injury Data Research Center (at Good Samaritan Hospital in Phoenix, AZ) that: 1) corroborated that diving injuries represented approximately 10% of all quadriplegic/paraplegic incidents, and 2) recorded that of the 340 diving injuries studied, 164 (~48%) of the victims had consumed alcoholic beverages or drugs prior to diving (Gabrielsen 1988). Alcohol and/or drugs were reported to be involved in 102 (~53%) of a set of 194 diving injuries (Gabrielsen 1990). It is estimated that more than half of all pool-related quadriplegic and paraplegic injuries were related to alcohol or drugs (Solomon 1993). Egstrom and Rowley noted in a 1986 report that even small amounts of alcohol will degrade diving performance (Egstrom et al. 1986). The NSPF's Aquatic Safety Compendium, published in 2006, cited two studies in which alcohol was involved in 57.5% of a set of 160 aquatic accident cases and 57% of a set of 341 spinal cord injury cases that occurred in swimming pools (Egstrom 2006).

Fluid Mechanics

Once a diver takes off, the motion is governed by three forces: gravity, buoyancy, and drag. Gravitational force is the constant force that governs the diver's motion when the diver is airborne. Buoyancy and drag forces only start to come into effect when the diver is submerged 50% to 70%.

Buoyancy is the tendency of a fluid to cause less dense objects to float or rise to the surface. Drag is the net force in the direction of flow due to the pressure and shear forces on the surface of the object. It is dependent on the object's shape, material, and speed, as well as the fluid's viscosity, which is a measure of a fluid's resistance to flow. Most of the information pertaining to drag are the result of numerous experiments that use devices to measure the drag on scale models. The data obtained is then put into dimensionless form by using dimensional analysis to be appropriately scaled for prototype calculations.

Dimensional analysis is a technique that engineers and scientists use to obtain dimensionless groups (Buckingham Pi terms, hereafter Pi terms) that capture the behavior of a system. Pi terms minimize the total number of variables and make the results of an experiment as widely applicable as possible because they allow the measurements made on a system to be used to describe the behavior of other similar systems. The basic theorem of dimensional analysis is:

If an equation involving k variables is dimensionally homogenous, it can be reduced to a relationship among k-r independent dimensionless products, where r is the minimum number of reference dimensions required to describe the variables.

This theorem essentially states that if there are any physically meaningful equations involving k variables, such as:

$u_1 = f(u_2, u_3, \ldots, u_k)$, the dimensions of the variable on the left side of the equal sign must be equal to the dimensions on the right side of the equal sign. This equation can then be rearranged into a set of dimensionless products such that $\pi_1 = \varphi(\pi_2, \pi_3, \ldots, \pi_{k-r})$, where $\pi_1, \pi_2, \ldots, \pi_{k-r}$ are the dimensionless Pi groups. The reference dimensions required to describe the variable are the basic dimensions: force (F), length (L), and time (T).

Once the forces acting on the system are known, Newton's Laws of Motion can be used to predict its motion. Newton's equations can be quite complex and difficult to manipulate when dealing with objects moving on contoured surfaces or under unusual constraints. Instead, Lagrange's equations are used to circumvent the difficulties that arise in attempts to apply Newton's equations to complex problems. Like Newton's equations, Lagrange's equations also constitute a proper description of dynamics of rigid bodies in the form of differential equations. Both the Lagrangian and Newtonian methods are used here to show that both types of equations of motion are correctly derived.

Derivation of Equations

Entry Velocity

Equations used to calculate the speed the diver enters the water, when the hands first touch the water (with d = falling distance, t= time, v= velocity, g= 9.8 m/s^2).

$$d = \frac{1}{2} g t^2$$

$$v = gt$$

Newtonian Method

Obtain coordinates according to **Figure 3**:

$$r_c = x_c E_x + y_c E_y$$

$$v_c = \dot{x}_c Ex + \dot{y}_c E_y$$

$$a_c = \ddot{x}_c Ex + \ddot{y}_c E_y$$

Apply ΣF = ma (and refer to **Figure 3**.)

$$\Sigma F \cdot F_y = F_{drag} + F_{buoyancy} - mgE_y = m\ddot{y}_c$$

Lagrangian Method

These equations are for a rigid body moving in one dimension, where a_i is the basis of the equation below and is associated with the curvilinear coordinate, q^i.

$$\frac{\partial}{DT}\left(\frac{\partial T}{\partial q^i}\right) - \frac{\partial T}{\partial q^i} = (\Sigma F) \cdot a_i$$

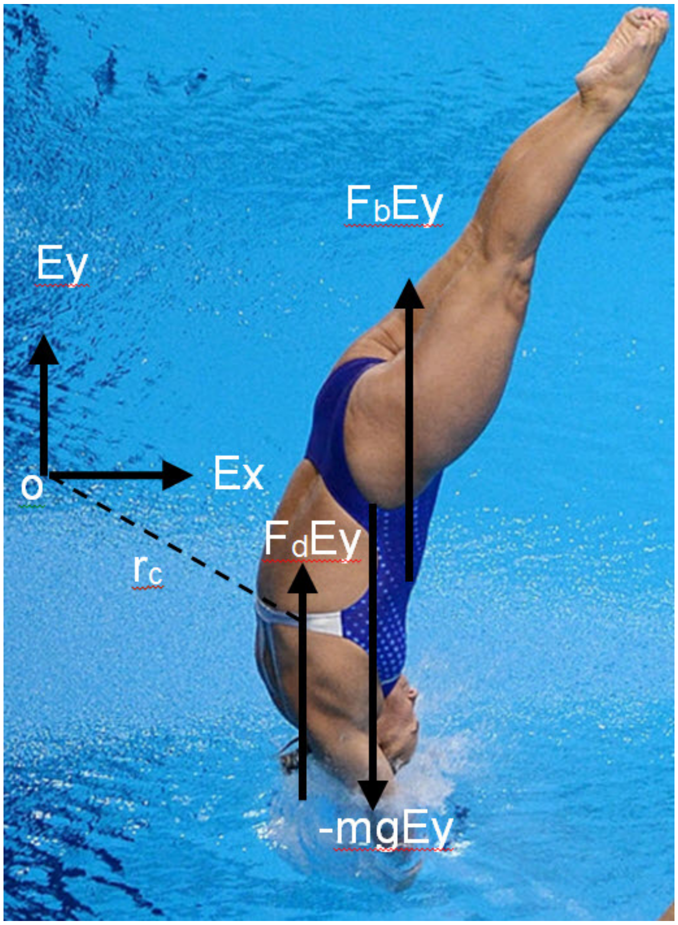

Figure 3
Free body diagram of diver entering the water.

The kinetic energy T can be expressed as (where v_c is the center of mass):

$$T = \frac{1}{2}m(v_c \cdot v_c) = \frac{1}{2}m(\dot{x}_c^2 + \dot{y}_c^2)$$

Choice of curvilinear coordinates and corresponding covariant components:

$$q^i . = y_c$$
$$a_i = E_y$$

Substituting the choice of curvilinear components and corresponding covariant components into the equation for Lagrange for rigid body in one dimension (Note: Simplifying assumption is made that living tissue acts as a rigid body):

$$\frac{\partial}{DT}\left(\frac{\partial T}{\partial \dot{y}_c{}^i}\right) - \frac{\partial T}{\partial \dot{y}_c^2} = (\Sigma F) \cdot E_y$$

$$\rightarrow m\ddot{y}_c = F_{drag} + F_{buoyancy} - mgE_y$$

<u>Drag Force</u>

To find drag force, Buckingham Pi Theorem (dimensional analysis, hereafter Pi Theorem) is utilized. The critical variables involved in the system are D (drag force), L (length submerged under water), μ (viscosity), and ρ (density). Their basic dimensions are:

$$D \doteq F$$
$$l \doteq L$$
$$\mu \doteq FL^{-2}T$$
$$\rho \doteq FL^{-4}T^2$$

In this example, k = 5 and r = 3. As a result, k-r = 2 dimensionless groups, π_1 and π_2, are needed to capture the characteristics of the system. If l, v, and ρ are chosen as the repeating variables, then the format of the Pi terms can be represented as:

$$\pi_1 = D\rho^{a1}v^{b1}l^{c1} = F \cdot (FL^{-4}T^2)^{a1}(LT^{-1})^{b1}(L)^{c1}$$

$$\pi_2 = \mu\rho^{a1}v^{b1}l^{c1} = FL^{-2}T \cdot (FL^{-4}T^2)^{a1}(LT^{-1})^{b1}(L)^{c1}$$

For π_1 and π_2 to be dimensionless, a_i, b_i, and c_i have to be:

$$a_1 = -1,\ b_1 = -2,\ c_1 = -2$$
$$a_2 = -1,\ b_2 = -1,\ c_2 = -1$$

After substituting the dimensionless π_1 and π_2 values, the Pi groups that describe the behavior of the system are found.

$$\pi_1 = \phi(\pi_2) \rightarrow C_D = \frac{D}{\frac{1}{2}\rho v^2 l^2} =$$

$$\phi\left(\frac{\rho v l}{\mu}\right), \left(\frac{\rho v l}{\mu} = Reynolds\ Number\right)$$

Anatomy

The cervical spine is made up of seven vertebrae (C1-C7), located within the spinal column (**Figure 4**). A network of ligaments helps join the intervertebral disks with the rest of the vertebrae. The cohesion of the ligaments allows the elements of the bony structures to behave as a single unit (Yoganandan et al. 2015).

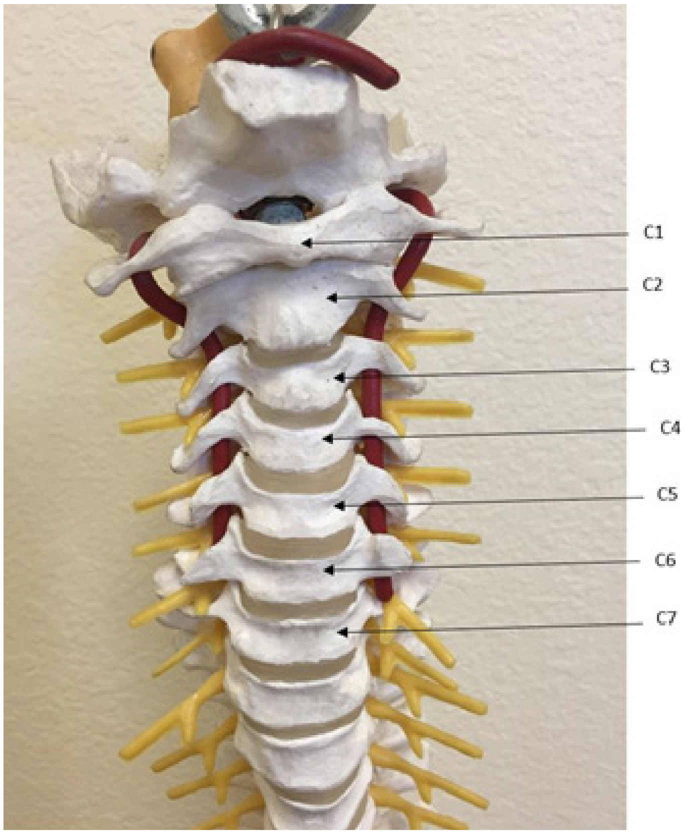

Figure 4
The seven vertebrae of the cervical spine.

The spine is divided into three distinct columns: anterior, middle, and posterior (**Figure 5**). Each column helps reinforce its function to withstand force, protect the spinal cord, and send neural signals between the brain and the rest of the body.

The anterior column is formed by the anterior annulus fibrosis, anterior longitudinal ligament, and the anterior vertebral body.

The middle column of the spine includes the posterior annulus fibrosis, posterior longitudinal ligament, and the posterior wall of the vertebral body.

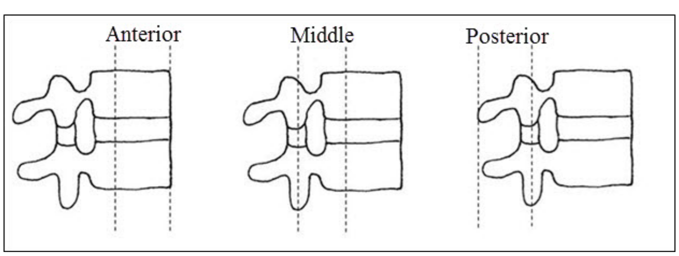

Figure 5
The anterior, middle, and posterior spinal columns are illustrated above, respectively.

The posterior column consists of the posterior ligaments, which includes the capsular ligaments, ligament flava, and the nuchal ligament complex. Also located posteriorly are bony structures such as the lamina, pedicle, spinous process, transverse process, and facets.

By delineating which injuries in the spine are unstable, it can assist biomedical engineers determine the mechanism for the failure. The fracture itself leaves its signature as to how it was loaded and failed.

Spinal injuries may lead to different types of fractures or dislocations. Depending on the type of fracture, it will affect specific or multiple columns. If one column is disrupted, spinal cord injury may be prevented because the other columns may provide sufficient stability. If two columns are disrupted, the chances of spinal cord injury increase, since the spine no longer is stabilized as a single unit.

The structures in the anterior column help the spinal cord resist compression forces through the vertebral body centrum and intervertebral disc. An injury solely to the anterior column is most often a compression fracture. In a compression fracture, the middle column frequently suppresses the fracture from fragmentation into the posterior wall and canal. With the support of the middle column, the rest of the spine often can maintain stability, even after a compression fracture.

If the structures in the middle column and either the anterior or the posterior column fail, it could lead to burst fractures, flexion-distraction injuries (seatbelt-type fractures), or fracture-dislocations. Burst fractures are the result of a failure of the anterior and middle columns under an axial load. When the posterior and middle columns fail, it is often a flexion-distraction injury, with the anterior column as a point of rotation. A fracture-dislocation is the failure of all three columns, which is due to multiple forces. For example, tension and shear may cause fracture dislocation at surprisingly low levels of force in the cervical spine. The cervical spine functions only to support the weight of the head and facilitate motion. These features have clinical relevance that helps professionals evaluate spinal fracture analysis and spinal stability. By classifying the spine into three columns, injuries may be classified and help determine if operative intervention is necessary.

Cervical Spine: Burst Fractures

When the neck experiences a high compressive axial force, the cervical spine may be subject to a burst fracture. Both the anterior and middle spinal columns are compressed, resulting in high shear stress on the vertebral endplates, which could fragment and penetrate the surrounding tissue and even possibly the spinal canal, as seen in **Figure 6** (Denis 1984). Features of a burst fracture include loss of vertebral height on lateral views, retropulsed fragments into the spinal canal, and comminution of the vertebral body, all of which lead to spine instability. These kinds of fractures are classified as the most severe, since there is a possibility of complete paralysis (Aubin et al. 2007).

According to Denis, there are five different types of burst fractures as shown in **Figure 7**. Type A results in the fracture of both endplates. Type B is the most common, and results in the fracture of the superior endplate. Type C, the least common, is the fracture of the inferior endplate. Type D is a burst rotation fracture, which shows evidence of burst fractures but has a rotational component that could be mistaken as a fracture dislocation. Type E is a burst lateral flexion fracture; an axial load on the spine alongside lateral flexion could cause the posterior wall to fracture and fragment toward the spinal canal (Denis 1984).

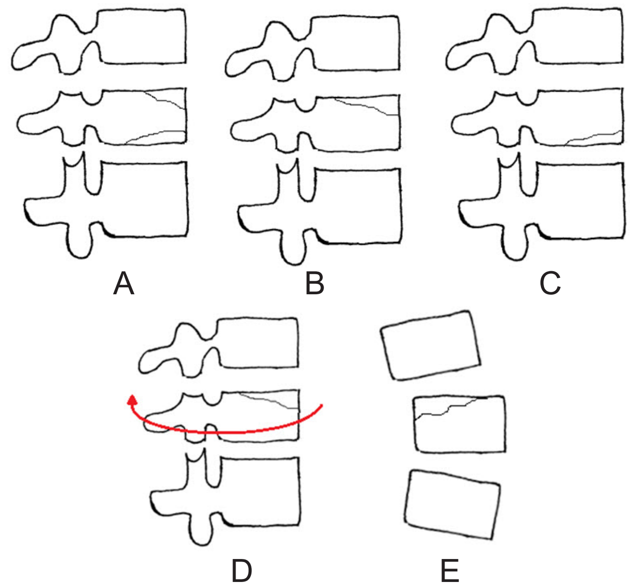

Figure 7
A simplified illustration of the five different types of burst fractures.

Figure 6
Lateral view of a burst fracture.

Cervical Spine Fracture Dislocations

The most common types of fractures are flexion-type fracture dislocations to the cervical spine, which are frequently associated with compressive forces along the vertical axis of the anterior cervical spine. Bilateral facet dislocations and unilateral locked facets are types of tension/compression-flexion dislocations that can result. Compression fractures usually occur in the lower three cervical segments where the flexible cervical spine joins the less flexible thorax and thoracic spine — and thus the region of greatest angulation and bending moment between the vertebrae. Cervical spine tolerance values for bilateral facet dislocations occurred at as low as 108 pounds. Flexion injuries occurred at approximately 440 pounds (McElhaney and Myers 1993).

Locked facet dislocations can occur from bending the neck at too great of an angle when the head impacts the bottom of the pool (**Figure 8**). This causes the upper vertebra to slide up and over the facet on the top of the lower vertebra with the ligaments in the spinous processes torn apart (Damask et al. 1990). Bilateral facet dislocations of bilateral locked facets are relatively common traumatic injuries to the cervical spine. Bilateral locked facet trauma develops from a mechanism of injury involving flexion and translation (Vaccaro 2002). This type of dislocation occurs when a vertebra's inferior facets dislocate anteriorly over the lower vertebra's superior facets (Im et al. 2012).

Unilateral jumped (or locked) facet injuries are

Figure 8
CT scan of C-Spine showing fracture dislocation with C4 on C5 locked facets.

consequences of rotational forces in the setting of hyperflexion (Szentirmai et al. 2008). Unilateral facet dislocations result from an exaggeration of physiological coupling motion of the cervical spine. This can include an exaggeration of flexion, lateral bending, and axial loading, which results in unilateral subluxation or dislocation (Vaccaro 2002).

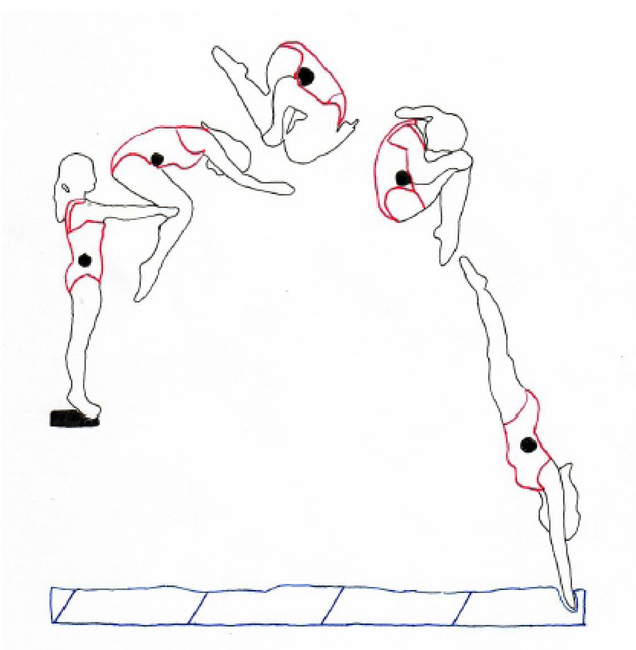

Figure 9
Diagram of forward 1½ somersaults – tuck to open pike into a pool.

Analytical Example of Diving Injury with Impact to Swimmer

The plaintiff was doing a front one-and-a-half somersault. She completed three-fourths of the somersault tuck when she came out of the tuck into a pike out — that is where divers straighten their legs but their body is still bent over the lower extremities (**Figure 9**). The plaintiff's arms went straight out to her sides; she looked over her feet for an entry point, and as she came around she saw a swimmer in her entry path [plaintiff's deposition]. Upon impact, her arms were out protecting her head, head turned to the right, and her left forehead struck the swimmer's hip.

Bilateral facet dislocations are associated with compressive forces along the vertical axis of the front of the cervical spine. The diagnosis to the plaintiff was C4 on C5 with locked facets. The C5 facets "jumped" and "locked" on C4 facets (**Figure 10**). The mechanism to sustain a fracture dislocation is caused by a combination of flexion, rotation, and distraction (Im et al. 2012).

A biomedical engineering analysis determined the mechanics of injury. This included the speed of impact and the plaintiff's principal direction of force as she impacted the swimmer. It was found through calculation that the impact velocity was 22 mph (32.3 fps), and 640 pounds of force was transferred to her neck to cause the facet dislocation injury to her cervical spine. An interesting result was that the fracture mechanics substantiated the diver's testimony that she diverted her neck at the time of the impact in an effort to minimize impact upon the swimmer. The diver became a quadriplegic.

Analytical Example of Dark Pool Bottom at an Evening Social Event: Dove in or Pushed?

One summer evening, the plaintiff was at the defendant's residence by the poolside (**Figure 11**) and had a blood alcohol level of 0.17. After the plaintiff hit her head, she complained of head and neck pain and paralysis below the waist. Her friends held her afloat until professional emergency services arrived. Here, the authors' task was to determine if she dove in or was shoved/pushed.

X-rays of the plaintiff's cervical spine showed multiple fractures from C5 to C7 (**Figure 12**). There was 6 mm of retropulsion of bone at the C6 level, causing spinal canal stenosis. There were also laminar fractures identified from C4 down to C7, probable anterior longitudinal

Figure 10
Plaintiff's CT C-spine.

ligamentous injuries seen at C4-C5 and C5-C6, and also a fracture of the transverse foramen on the right at C5, which raises the possibility of a vertebral artery injury.

Figure 12
Radiology of the fracture at C5-C7.

A biomedical engineering analysis determined the fracture mechanics of the cervical spine as well as the plaintiff's principal direction of force. Given the plaintiff's radiology and the witness statements that she entered into the middle of the shallow end of the pool, it was determined the plaintiff likely dove into the pool at a relatively steep angle and impacted the top of her head, which is consistent with the subtle soft tissue swelling on her high right frontoparietal scalp. The injuries sustained included a burst fracture at the C6 level. She was found approximately 5 feet away from the nearest side of the pool, so impact with the pool side was ruled out. The floor of the pool was a dark color, and, when combined with the lack of lighting during the evening and a blood alcohol level

Figure 11
Photograph of the scene of the incident.

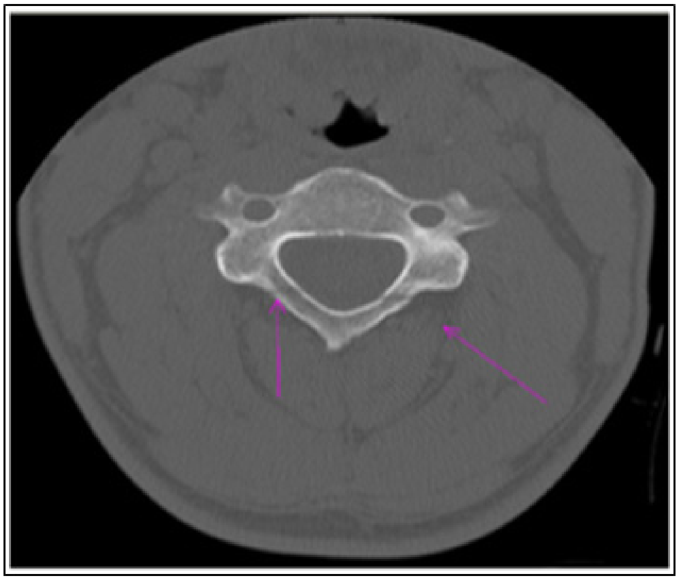

Figure 13
CT scan showing C5 burst fracture.

greater than twice the maximum allowed to operate a vehicle, the plaintiff was not likely able to discern that it was unsafe for her to dive into the shallow end of the pool. Given the principal direction of force, it was determined to be unlikely that she was shoved/pushed into the pool.

Analytical Example of Community Running Race and Obstacle Course through Mud Pit

On the day of the incident, the plaintiff participated in a mud-inspired obstacle course. During one of the mud pit obstacles at the event, he dove into the pit head first, fracturing his cervical spine, immediately rendering him quadriplegic. Medical reports stated that the plaintiff denied any pain, but was unable to get himself out of the pit.

The plaintiff's cervical spine demonstrated multiple fractures. He had undergone a CT scan and an MRI of the cervical spine, which showed a C5 fracture (**Figure 13**). The plaintiff also had a fractured lamina of C2 and a fractured lamina of C4. C5-6 was offset by 2 mm, and C6-7 demonstrated a traumatic, herniated disc

Figure 14
Sketch made from video footage of plaintiff at the scene of the accident.

with cord compression. Using biomedical and mechanical engineering, the authors found evidence of laceration consistent with a rigid object in the pit. The authors also utilized social media to locate video footage that showed the plaintiff diving horizontally into the shallow mud pit, which had less than 2 feet of water on top (**Figure 14**). This research indicated that when the head's movement is restricted (pocketed in the mud/sand), the forces to the cervical spine increase substantially due to the oncoming inertia of the rest of the body.

Analytical Example of Diving into a Shallow Pool at Night

The plaintiff dove into a shallow pool that was 3.5 to 4 feet deep in Central Florida. After hitting his head on the bottom of the pool, he became an immediate quadriplegic with a C6 burst fracture, resulting in incomplete C5-8 quadriplegia. Possible contributing factors included insufficient lighting and lack of proper warning signage/pictograms around the pool (**Figure 15**).

Burst fractures are also known as axially directed crush fractures. This type of injury is associated with high energy trauma, and it is characterized by a vertical loss of the vertebral body height. The mechanism of a burst fracture to C6 is caused by axial compression forces. The plaintiff was diagnosed with a burst fracture of the C6 vertebra with retropulsion as shown in **Figure 16**.

From the radiology films, it was observed that the

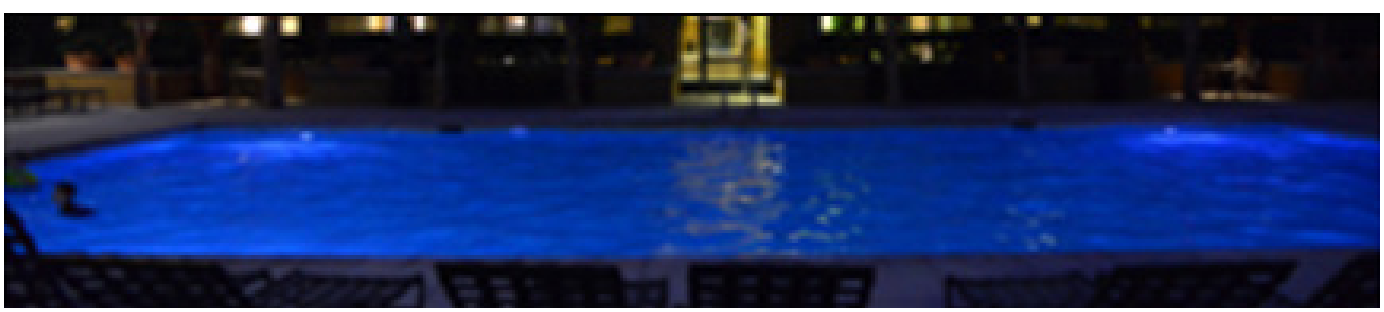

Figure 15
Scene of the pool.

plaintiff hit the top of his head, which was consistent with evidence of layered scalp swelling and fracture mechanics. The authors' principal contributions in this example were analyses of diving angle/force, incident prevention, code compliance, warnings, and underwater/pool area night lighting.

Analytical Example of Diving Head First into Shallow Pool

In this example, a company doing remote work lodged its employees at a hotel close to the work site. The plaintiff (one of the employees), per his deposition, dove head first from a standing start into a shallow pool approximately 5 feet to the right of the stair railing (**Figure 17**). The plaintiff had been drinking prior to entering the pool. In fact, medical records showed the plaintiff had a blood-alcohol concentration (BAC) of 0.058 upon arrival at the hospital. The incident resulted in a C6 cervical spine burst fracture after diving into the pool. He immediately became a quadriplegic with the right side weaker than the left.

Figure 17
Kinematic study of the incident with models in substantially similar positions representing the actual witnesses and plaintiff.

In the subsequent lawsuit, the plaintiff claimed he did not know that the area in the pool he chose to dive into was too shallow for diving, and it looked deep enough for him to safely dive into. The plaintiff also stated that he did a shallow dive.

CT of the neck showed a burst fracture of C6 with fractures of C5 and C6 lamina (**Figure 18**). Burst fractures involve compressive axial-loading forces to the spine, and are characterized by loss of vertebral body height. The mechanism sequence of burst fracture is vertical compression (McElhaney and Myers 1993) with increasing compression to the vertebral body, the end-plates bulge and crack, disc material herniates into the vertebral body, and the body disintegrates, producing a burst fracture (McElhaney et al. 1976).

Figure 16
MRI of the C-Spine shows a burst fracture located at C6.

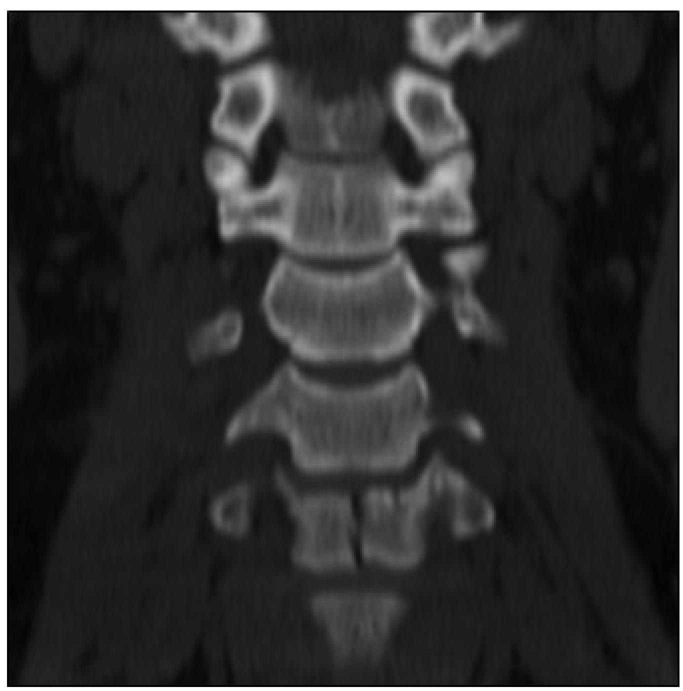

Figure 18
Plaintiff's CT C-Spine.

Through a kinematic study based on the plaintiff's deposition, it was found that the plaintiff impacted the top of his head when he entered the pool, and this was collaborated by analysis of the CT (computed tomography) films that revealed the specific point of impact from the distinctive scalp swelling as well as the fracture mechanics data. Other contributions included identifying the other swimmer as a human depth warning, which supplemented the pool's depth markings. After analyzing the fracture mechanics and principal direction of force, the authors determined that the plaintiff did not do a shallow dive as claimed but instead dove toward the shallow bottom.

The biomedical engineering analysis determined:

- The estimated amount of force necessary to cause the injury.
- From the point of impact on the head and the angulation between head and torso, the angle the diver's body was at (with regard to vertical at the moment of impact) was determined. In this example, the point of impact was near the bregma, and the injury was a straight column compression, with no subluxation. In this example, therefore, the diver's body had been nearly vertically oriented at the moment of impact.
- The amount of elastic and inelastic displacement is the distance that it took to stop the diver. This distance, as shown below, is used to determine the diver's velocity at the moment of impact.

Dive Mechanics

During a dive, a diver's center of mass follows a parabolic trajectory. In Stone's 1980 report to the NSPF, he stated that "*During his trajectory in air, the laws of physics dictate that the diver's center-of-gravity follow a parabolic path determined completely by his speed and direction at the time of takeoff and gravity acting vertically downward. There is nothing that the diver can do after takeoff to change his path*." (Stone 1980)

Once a diver has lost contact with the surface that the dive was initiated from, the diver is in free flight to the high point of the jump, and is thereafter a freefalling body.

The physics equations of motion for freefalling bodies define the characteristics of the freefalling portion of the dive (Sears 1950):

Speed of a falling body: $v=gt$ *(where t=time of fall [sec])*

Height of fall of center of mass: $h= \frac{1}{2}gt^2$ *(where h=height of fall [ft])*

Speed of a falling body: $v^2 = 2gh$ *(where v is in feet per second/fps)*

Per Stone, as a diver enters water, the diver continues to accelerate as in freefall until the combination of the buoyant and hydrodynamic forces on the diver's body exceed the force of gravity, which occurs when the diver's center of mass (i.e., center of gravity) enters the water (Stone 1980).

Per Dreyfuss, a person's center of mass is at approximately 55% of their height (Tilley 2002) when their arms are lowered (**Figure 19**). Using Braune & Fischer's data from 1889, it is calculated that, when a diver's arms are upraised, their center of mass rises to 61% of their height (Braune and Fischer 1889; see **Figure 19**).

From a site inspection of the pool envelope/surroundings (**Figures 17, 20**) and other documents, the following information for the physical analyses was obtained:

- The height of the deck (or launching platform) above water surface: 5 inches
- The depth of water at or near the area of impact: approximately 3 feet, 6 inches
- The diver's forward speed at take-off: 0 feet per second (fps)

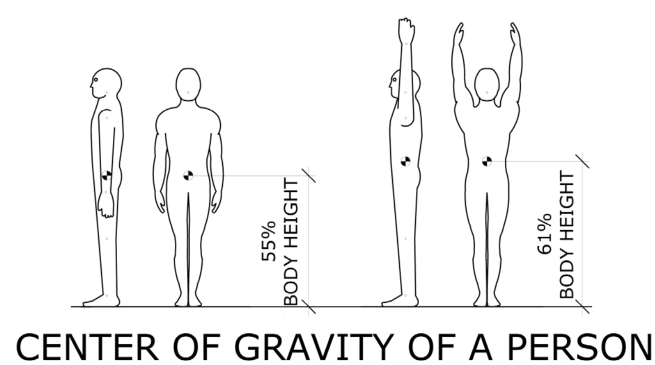

Figure 19
Diagram of a diver showing CG at approximately 55% of height with arms lowered (at left) and CG at approximately 61% of height with arms upraised (at right).

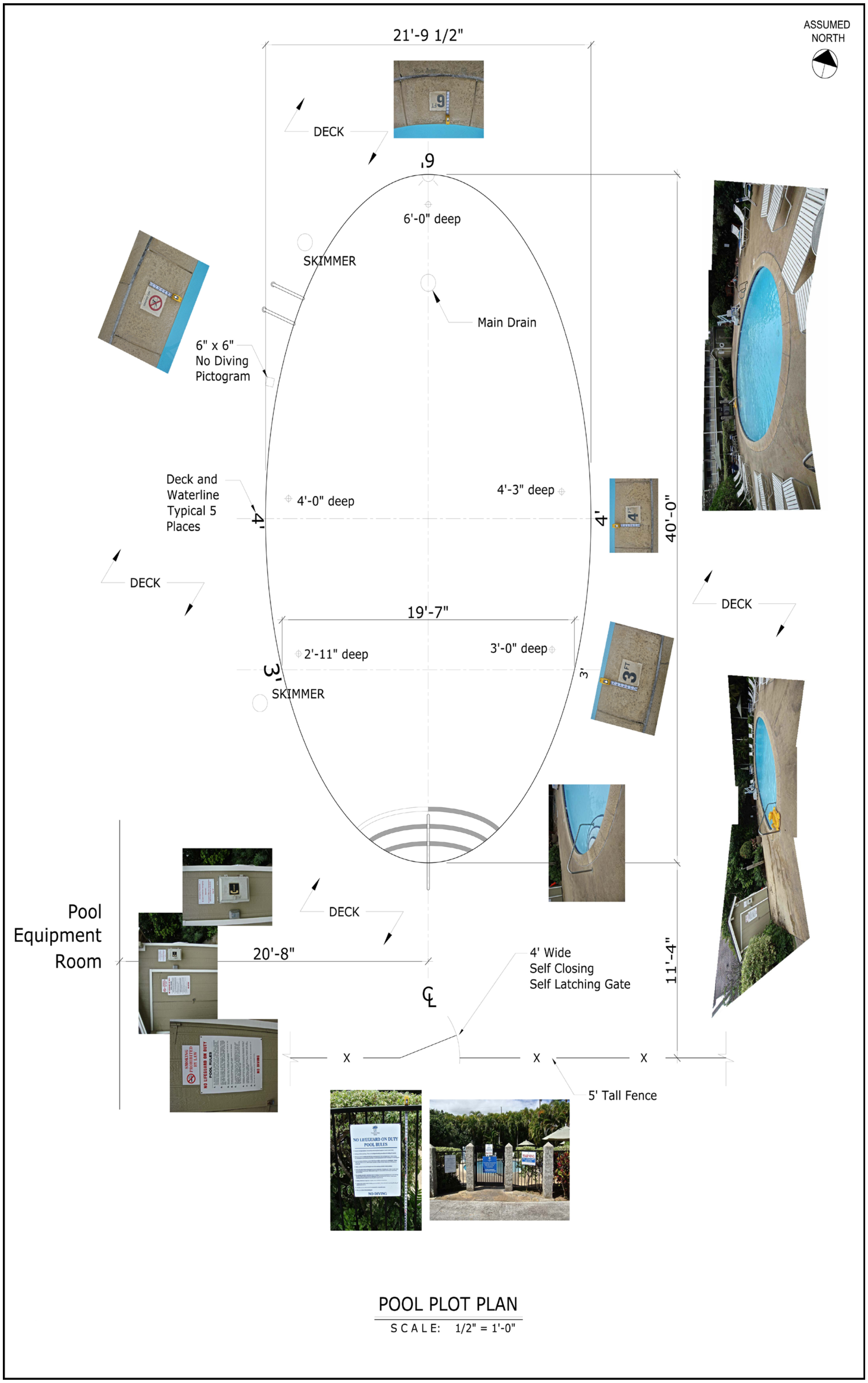

Figure 20
Plot plan diagram of accident pool.

PARAMETRIC ANALYSIS of the AVERAGE FORCE (#)

EXPERIENCED by a 5'-3.5'' DIVER who WEIGHS 187.5#, on CONTACTING the BOTTOM at VARIOUS SPEEDS from 5.0 to 6.7 (fps) and VARIOUS INITIAL CONTACT ANGLES (77° to 90° from horizontal), where the DIVER'S HEAD ROLLS (Flexes) RATHER than SLIPS and the SPINE COMPRESSES 1.25'' along its INITIAL PATH.

INITIAL CONTACT ANGLE(°) =	77	78	79	80	81	82	83	84	85	86	87	88	89	90
CONTACT SPEED(fps) of HEAD	AVERAGE FORCE of IMPACT (lbs)													
5.0	562	565	568	570	572	574	576	578	579	580	581	582	582	582
5.1	585	588	591	593	595	598	599	601	602	604	604	605	605	606
5.2	608	611	614	617	619	621	623	625	626	627	628	629	629	630
5.3	631	635	638	641	643	645	647	649	651	652	653	653	654	654
5.4	655	659	662	665	668	670	672	674	675	677	678	678	679	679
5.5	680	684	687	690	693	695	697	699	701	702	703	704	704	704
5.6	705	709	712	715	718	721	723	725	726	728	729	730	730	730
5.7	730	734	738	741	744	747	749	751	753	754	755	756	756	756
5.8	756	760	764	767	770	773	775	777	779	781	782	783	783	783
5.9	783	787	790	794	797	800	802	805	806	808	809	810	810	811
6.0	809	814	817	821	824	827	830	832	834	836	837	838	838	838
6.1	837	841	845	849	852	855	858	860	862	864	865	866	866	866
6.2	864	869	873	877	880	883	886	888	891	892	893	894	895	895
6.3	892	897	901	905	909	912	915	917	919	921	923	923	924	924
6.4	921	926	930	934	938	941	944	947	949	951	952	953	954	954
6.5	950	955	960	964	968	971	974	977	979	981	982	983	984	984
6.6	979	985	989	994	998	1001	1004	1007	1009	1011	1013	1014	1014	1014
6.7	1009	1015	1019	1024	1028	1032	1035	1038	1040	1042	1043	1045	1045	1045

DIVER'S HEIGHT 5'-3.5''
DIVER'S WEIGHT 187.5 #

Figure 21
Parametric analysis of average impact force based on biomedical engineering force estimate showing the range of possible speeds at possible initial contact angles (from vertical).

- The diver's height: 5 feet, 3.5 inches tall
- The diver's weight: 187.5 pounds

Newton's Second Law:

F=ma (Sears 1950)

Application of Newton's Second Law for average force per Stone (Stone 1980):

$F_{max} = ma$; $F_{avg} = ½ma$

Calculating mass and acceleration per Stone (ibid.):

$m = (w/g)$

$a = (v^2)(\cos \Theta)^2/d$

where

w=weight (lbs)

$g=32.2ft/s^2$ (g is a constant which represents the acceleration of a body in freefall due to the gravity near the surface of Planet Earth)

v=velocity (fps)

d=stopping distance (ft) (in this analysis, the stopping distance is the spinal compression or the amount of elastic and inelastic crush)

Θ=the angle between vertical and the angle of impact

Therefore, $F_{avg} = ½ [(w/g)(v^2)(\cos \Theta)^2]/d$ (Stone Equation 45 [ibid.])

The initial contact angle from the biomedical engineering analysis can be highlighted in a parametric analysis of average impact force (**Figure 21**), as can a range of possible contact speeds from the impact speed analysis

PARAMETRIC ANALYSIS of DIVING IMPACT SPEEDS(fps)

for a RANGE of JUMP HEIGHTS(") of CENTER of GRAVITY, GIVEN a DIVER of HEIGHT 5'-3.5" with ARMS COMPLETELY UPRAISED, CALCULATED for a RANGE of UNDERWATER DISTANCES traveled BEFORE IMPACT('-"), with CENTER of GRAVITY 33.4" ABOVE the WATER at the TIME of TAKE-OFF, off a DECK of HEIGHT 5" with a TAKE-OFF ANGLE to the CENTER of GRAVITY of 45° and FORWARD SPEED of 0 fps while ASSUMING a COEFFICIENT of DRAG in WATER of 1.8.

JUMP HEIGHT of CENTER of GRAVITY(") =	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0
MAXIMUM HEIGHT of CENTER of GRAVITY(') =	2.74	2.78	2.82	2.87	2.91	2.95	2.99	3.03	3.07	3.12	3.16
HORIZONTAL DISTANCE at MAXIMUM HEIGHT(') =	2.37	2.45	2.53	2.62	2.70	2.78	2.87	2.95	3.03	3.12	3.20
TIME from TAKE-OFF to HIGH POINT of C of G(sec) =	0.05	0.07	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17
TIME from HIGH POINT of C of G to HEAD ENTRY(sec) =	0.21	0.23	0.24	0.24	0.25	0.26	0.27	0.27	0.28	0.29	0.29
TOTAL TIME of TRAJECTORY(sec) =	0.26	0.30	0.32	0.35	0.37	0.38	0.40	0.42	0.43	0.45	0.46
VERTICAL ENTRY SPEED(fps) =	-6.9	-7.2	-7.6	-7.9	-8.1	-8.3	-8.6	-8.8	-9.0	-9.2	-9.4
HORIZONTAL ENTRY SPEED(fps) =	1.64	2.32	2.84	3.28	3.66	4.01	4.33	4.63	4.91	5.18	5.43
ENTRY ANGLE(°) =	-76.6	-72.3	-69.4	-67.4	-65.7	-64.3	-63.2	-62.2	-61.3	-60.6	-59.9
HEAD ENTRY SPEED(fps) =	7.1	7.6	8.1	8.5	8.9	9.3	9.6	9.9	10.2	10.6	10.8
HORIZONTAL DIVE DISTANCE(') =	3.19	3.60	3.92	4.21	4.47	4.72	4.95	5.18	5.39	5.61	5.82

UNDERWATER DISTANCE(') BEFORE IMPACT	IMPACT SPEED (fps)										
3 ' 6 "	5.5	6.0	6.3	6.7	7.0	7.3	7.6	7.8	8.0	8.3	8.5
3 ' 7 "	5.4	5.9	6.2	6.6	6.9	7.2	7.5	7.7	7.9	8.2	8.4
3 ' 8 "	5.4	5.8	6.2	6.5	6.8	7.1	7.3	7.6	7.8	8.1	8.3
3 ' 9 "	5.3	5.7	6.1	6.4	6.7	7.0	7.2	7.5	7.7	8.0	8.2
3 ' 10 "	5.2	5.6	6.0	6.3	6.6	6.9	7.1	7.4	7.6	7.8	8.0
3 ' 11 "	5.1	5.6	5.9	6.2	6.5	6.8	7.0	7.3	7.5	7.7	7.9
4 ' 0 "	5.1	5.5	5.8	6.1	6.4	6.7	6.9	7.2	7.4	7.6	7.8
4 ' 1 "	5.0	5.4	5.7	6.0	6.3	6.6	6.8	7.1	7.3	7.5	7.7
4 ' 2 "	4.9	5.3	5.7	6.0	6.2	6.5	6.7	7.0	7.2	7.4	7.6
4 ' 3 "	4.9	5.2	5.6	5.9	6.1	6.4	6.6	6.9	7.1	7.3	7.5
4 ' 4 "	4.8	5.2	5.5	5.8	6.1	6.3	6.6	6.8	7.0	7.2	7.4
4 ' 5 "	4.7	5.1	5.4	5.7	6.0	6.2	6.5	6.7	6.9	7.1	7.3

DIVER'S HEIGHT 5'-3.5"
DIVER'S WEIGHT 187.5 #

Figure 22
Parametric analysis of diving impact speeds from measurement of pool depths and deck height near estimated point of impact, as well as information regarding diver's height and weight. The calculations used in this chart are the equations of motion.

(**Figure 22**). In the example represented in **Figure 21**, the biomedical engineering analysis had given an estimated force at impact. The additional bracketing information is helpful in assessing what could have happened. These numbers were calculated using Stone Equation 45 (ibid.).

A parabolic trajectory analysis of the diver's center of mass during the dive from take-off until the diver's head enters water can be calculated with the equations of motion (**Figure 23**). This information can be plotted into a curve as shown in **Figures 24, 25,** and **26**.

The investigation and analyses proved that the plaintiff did not make a shallow dive as he had claimed. The biomedical engineering and forensic evidence proved that the plaintiff's body was nearly vertical when his head impacted the swimming pool floor.

When a person dives into water, the diver at some point will steer up (**Figure 27**). If divers steer up quickly, their hands may possibly produce cavitation, which adds significantly to the drag resistance (**Figure 28**).

From Egstrom et al. (1991), *"An additional factor in the understanding the importance of the hands as steering surfaces is encountered when the video tapes are reviewed. The hand path, upon entry of the hands into the water, is marked by the development of turbulence to the point that heavy concentrations of bubbles are seen streaming off of the upper surfaces of the hands and forearms. This formation of bubbles has been thought to be the result of "carrying air into the water" but careful examination of the tapes reveals that the bubbles form as a result of cavitation forces developing on the upper surfaces of the hands and forearms. Hoener, in his classic works on dynamic lift and dynamic drag (18 & 19) discusses the subject in detail. Cavitation refers to voids or cavities formed in water when and where the static pressure is reduced below the vapor pressure of water. Cavitation occurs when gas nuclei, which are normally present in*

TRAJECTORY ANALYSIS of DIVE

until HEAD ENTRY into WATER for a RANGE of JUMP HEIGHTS(") of CENTER of GRAVITY, GIVEN a DIVER of HEIGHT 5'-3.5", CALCULATED for a RANGE of POOL PATH LENGTHS('-"), with CENTER of GRAVITY 33.8" ABOVE the WATER at the TIME of TAKE-OFF, off a DECK of HEIGHT 5" with a TAKE-OFF ANGLE to the CENTER of GRAVITY of 45° and FORWARD SPEED of 0 fps.

JUMP HEIGHT of CENTER of GRAVITY(") =	1.0	2.0	3.0	4.0	5.0	6.0	7.0	8.0	9.0	10.0	11.0	12.0
MAXIMUM HEIGHT of CENTER of GRAVITY(') =	2.74	2.78	2.82	2.87	2.91	2.95	2.99	3.03	3.07	3.12	3.16	3.20
HORIZONTAL DISTANCE at MAXIMUM HEIGHT(') =	2.37	2.45	2.53	2.62	2.70	2.78	2.87	2.95	3.03	3.12	3.20	3.28
TIME from TAKE-OFF to HIGH POINT of C of G(sec) =	0.05	0.07	0.09	0.10	0.11	0.12	0.13	0.14	0.15	0.16	0.17	0.18
TIME from HIGH POINT of C of G to HEAD ENTRY(sec) =	0.21	0.23	0.24	0.24	0.25	0.26	0.27	0.27	0.28	0.29	0.29	0.30
TOTAL TIME of TRAJECTORY(sec) =	0.26	0.30	0.32	0.35	0.37	0.38	0.40	0.42	0.43	0.45	0.46	0.47
VERTICAL ENTRY SPEED(fps) =	-6.9	-7.2	-7.6	-7.9	-8.1	-8.3	-8.6	-8.8	-9.0	-9.2	-9.4	-9.6
HORIZONTAL ENTRY SPEED(fps) =	1.64	2.32	2.84	3.28	3.66	4.01	4.33	4.63	4.91	5.18	5.43	5.67
ENTRY ANGLE(°) =	-76.6	-72.3	-69.4	-67.4	-65.7	-64.3	-63.2	-62.2	-61.3	-60.6	-59.9	-59.3
HEAD ENTRY SPEED(fps) =	7.1	7.6	8.1	8.5	8.9	9.3	9.6	9.9	10.2	10.6	10.8	11.1
HORIZONTAL DIVE DISTANCE(') =	3.19	3.60	3.92	4.21	4.47	4.72	4.95	5.18	5.39	5.61	5.82	6.02
TIME OF FALL (sec)	ELEVATION (y coordinate)											
0.000	2.74	2.78	2.82	2.87	2.91	2.95	2.99	3.03	3.07	3.12	3.16	3.20
0.033	2.72	2.76	2.81	2.85	2.89	2.93	2.97	3.01	3.06	3.10	3.14	3.18
0.067	2.67	2.71	2.75	2.79	2.84	2.88	2.92	2.96	3.00	3.04	3.09	3.13
0.100	2.58	2.62	2.66	2.70	2.75	2.79	2.83	2.87	2.91	2.95	3.00	3.04
0.133	2.45	2.49	2.54	2.58	2.62	2.66	2.70	2.74	2.79	2.83	2.87	2.91
0.167	2.29	2.33	2.37	2.42	2.46	2.50	2.54	2.58	2.62	2.67	2.71	2.75
0.200	2.09	2.13	2.18	2.22	2.26	2.30	2.34	2.38	2.43	2.47	2.51	2.55
0.233	1.86	1.90	1.94	1.98	2.03	2.07	2.11	2.15	2.19	2.23	2.28	2.32
0.267	1.59	1.63	1.67	1.71	1.76	1.80	1.84	1.88	1.92	1.96	2.01	2.05
0.300												
TIME OF FALL (sec)	EXTENSION (x coordinate)											
0.000	2.37	2.45	2.53	2.62	2.70	2.78	2.87	2.95	3.03	3.12	3.20	3.28
0.033	2.42	2.53	2.63	2.73	2.82	2.92	3.01	3.10	3.20	3.29	3.38	3.47
0.067	2.48	2.60	2.72	2.83	2.94	3.05	3.15	3.26	3.36	3.46	3.56	3.66
0.100	2.53	2.68	2.82	2.94	3.07	3.18	3.30	3.41	3.52	3.63	3.74	3.85
0.133	2.58	2.76	2.91	3.05	3.19	3.32	3.44	3.57	3.69	3.81	3.92	4.04
0.167	2.64	2.84	3.01	3.16	3.31	3.45	3.59	3.72	3.85	3.98	4.10	4.23
0.200	2.69	2.91	3.10	3.27	3.43	3.58	3.73	3.88	4.02	4.15	4.29	4.42
0.233	2.75	2.99	3.19	3.38	3.55	3.72	3.88	4.03	4.18	4.32	4.47	4.61
0.267	2.80	3.07	3.29	3.49	3.68	3.85	4.02	4.18	4.34	4.50	4.65	4.80
0.300												
DIVER'S HEIGHT	5'-3.5"											
DIVER'S WEIGHT	187.5 #											

Figure 23

Parametric trajectory analysis of the diver's center of mass during the dive from take-off until the diver's head enters water, calculated with the equations of motion (Figures 24, 25, 26).

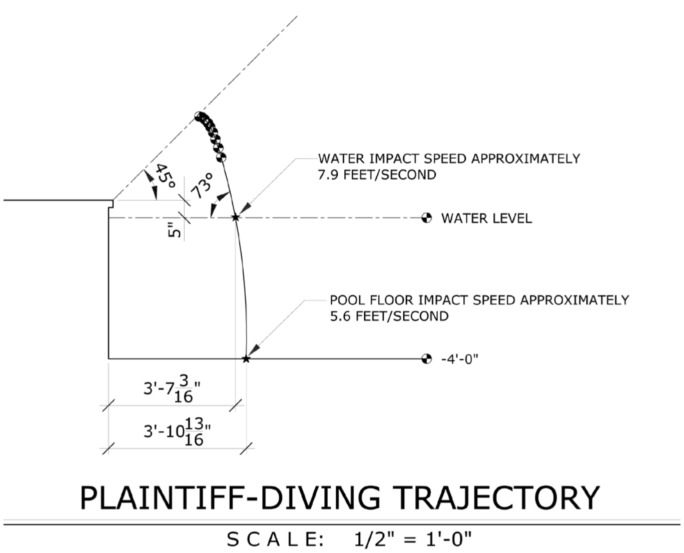

Figure 24

Section view diagram of trajectory plotted in Figure 23.

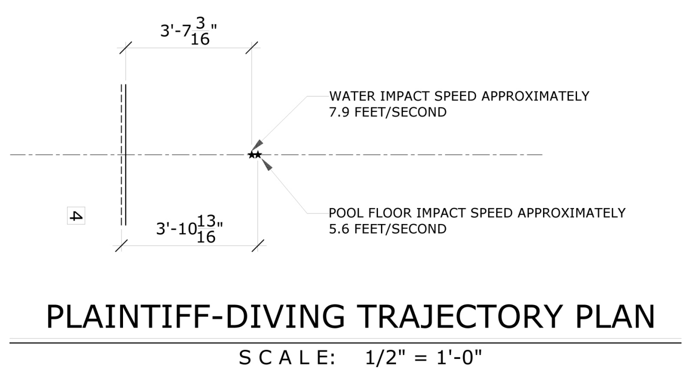

Figure 25

Plan view diagram of trajectory plotted in Figure 23 showing location and speed of the diver's contact with water.

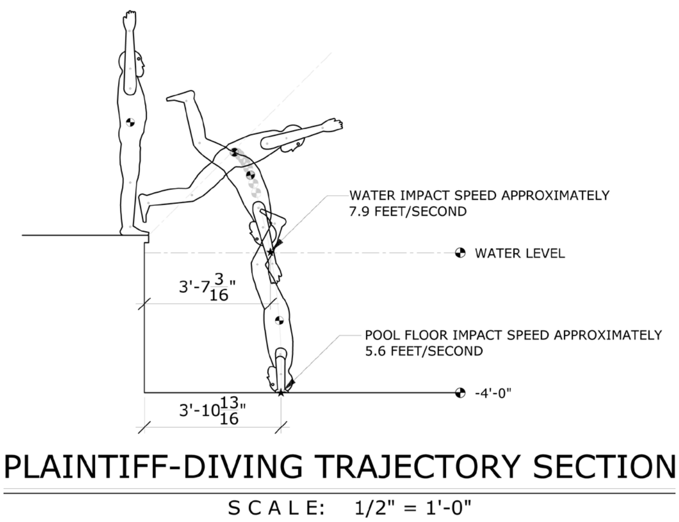

Figure 26
Diagram of the plaintiff's dive based on the calculated center-of-gravity trajectory information plotted in Figure 23.

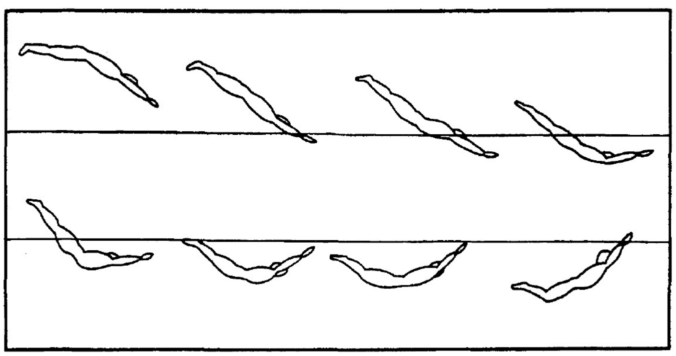

Figure 27
Diagram of a diver entering water and steering up (Egstrom et al. 1991).

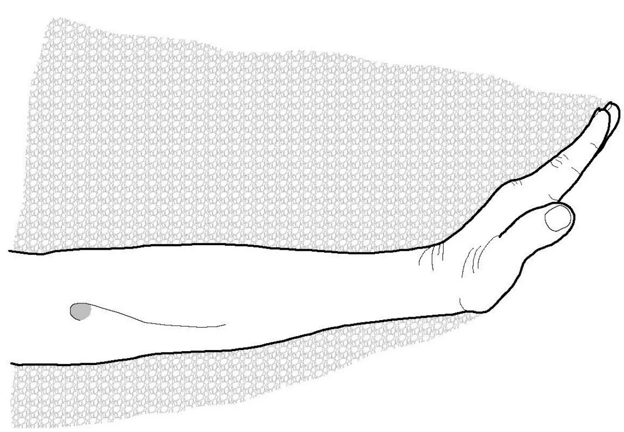

Figure 28
Diagram of cavitation produced by a diver's hand as it is used to do a quick steer-up.

fluids, separate and develop into bubbles which, under conditions such as those found in diving, vaporize into continuous and larger voids. These areas of voids then appear as streams of bubbles. Since water vapor pressure is quite low (below .016 atmospheres at 59 degrees F) it appears that the pressures developed on the upper surface of the hand during a dive result in cavitation. Cavitation adds significantly to the drag resistance. The quantification of this effect is another issue to be resolved before understanding of dive dynamics is complete."

Summary

There is more than enough kinetic energy in every headfirst dive into shallow water to cause cervical spine trauma and paralysis if the diver were to strike the pool floor headfirst at a sufficiently steep angle.

Diving is an acquired/learned skill similar to driving a car. It takes little effort to learn how to enter water headfirst, just as it takes little effort to learn how to start a vehicle and drive. However, the skill and attentive care required to safely prevent and/or avoid injury while conducting either activity is much greater and more complex. Pool use can also be dangerous if used irresponsibly.

Because of the possibility of human error, swimming pools cannot be made completely safe. Alcohol and/or drugs are often a contributing factor in diving accidents that result in cervical spine trauma — both in the decision-making process and in the performance of the skilled activity of diving.

General Recommendations to Help Reduce Diving Accidents:

Divers:

1. Do not drink and dive.
2. Do not take drugs and dive.
3. Make certain the water is deep enough before diving (if in doubt, enter feet first initially). Elevated starting positions require greater water depths.
4. Do not dive into water that is not clear. In a swimming pool, the main drain should be visible.
5. When diving, always steer up immediately upon entering water.

6. Always have your hands raised above your head when diving so that you can steer up.

Pool Owners/Operators:

1. Strictly enforce posted pool hours.

2. Post multiple "No Diving" signs in conspicuous places.

3. Illuminate pools, pool decks, and pool signs at night (if open).

4. Put multiple "No Diving" tiles/pictograms in the pool deck (**Figure 1**).

5. Have sufficient lighting to read the pool deck pictograms at night (if open).

6. Make sure the swimming pool is code-compliant (varies by administrative authority).

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Solid Fuel-Burning Appliance Fire Investigations

By Joseph G. Leane, PE (NAFE 524F)

Abstract

Solid fuel-burning fireplaces and wood stoves are popular because they provide heat and aesthetically pleasing environments. They also provide backup heat to gas, electric, and oil building heating systems. However, if they are not properly installed and maintained, they pose a risk of structure fires. This paper describes the basics of conducting a forensic engineering investigation of a building fire involving a suspected fireplace or wood stove. The paper examines the types of appliances available, the types of chimney systems, and related design standards and building codes. Case studies (highlighting common failure modes) are also presented.

Keywords

Solid fuel, fireplace, wood stove, chimney, cellulose insulation, creosote, forensic engineering

Introduction

Typical residential solid fuel-burning appliances include fireplaces and wood stoves, which this paper focuses on. There are other types of solid fuel-burning appliances, which may be the subject of a future paper. When in use, these appliances and their chimneys are sources of heat. Accordingly, they can cause ignition of nearby combustible building materials and structural components when they overheat. An important difference between solid fuel-burning appliances and other heat-producing appliances (electric, gas, or oil) is that solid fuel appliances cannot be simply turned off if a problem develops, since the fuel in the firebox will continue to burn until it burns itself out or is externally extinguished.

After a fire has occurred, and an origin and cause (fire) investigator suspects the area of origin to be near a solid fuel-burning appliance, a forensic engineer is often called upon to investigate whether the appliance caused the fire.

NFPA 921 *Guide for Fire and Explosion Investigations*[1] states:

In planning a fire investigation, specialized personnel may be needed to provide technical assistance including chemical, electrical, materials, mechanical, and fire protection engineers. (NFPA 921-2014, 15.5)

The use and operation of an appliance should be well understood before it is identified as the fire cause. More complicated appliances may require the help of specialized personnel to gain a full understanding of how they work and how they could generate sufficient energy for ignition. (NFPA 921-2014, 26.4.2)

The purpose of this paper is to provide information and general guidelines to the forensic engineer for inspecting residential solid-fuel burning appliances and chimneys involved in fires. Since each investigation is unique, the engineer may need to deviate from these guidelines. The paper also provides case studies that demonstrate the application of these guidelines.

Relevant Codes and Standards

Codes and standards are typically consensus-approved documents for technical issues related to human-made structures and systems, with a significant difference being that codes may be adopted into law.

Standards

Standards exist that provide guidelines for technical forensic investigations of solid fuel-burning appliance fire investigations. The following listing is intended to assure the engineer is aware of these standards. Investigators should use whichever ones are relevant to their particular investigation, and should have complete copies of the relevant standards available during their investigation.

NFPA 921 *Guide for Fire and Explosion Investigations,* a generally accepted overall guide to fire

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investigation, is the central standard an investigator should be aware of. The other standards are for particular appliances or components that may be the subject of an investigation. Accordingly, these standards would be relevant when the products they address are at issue. Some commonly used standards are (in alphabetical order):

ASTM C1015 *Standard Practice for the Installation of Cellulosic and Mineral Fiber Loose-Fill Thermal Insulation*[2] provides procedures for the installation of loose-fill thermal insulation in ceiling, attics, walls, and floors of new and existing buildings. It requires installers to block around heat-producing devices, including flues and chimneys, to prevent the insulation from contacting those devices. It requires clearances specified in NFPA 211.

NFPA 211 *Standard for Chimneys, Fireplaces, Vents, and Solid Fuel-Burning Appliances*[3] applies to the design, installation, maintenance, and inspection of chimneys, fireplaces, vents, and solid fuel-burning appliances. It provides construction and installation requirements for those systems. It also includes the inspection of existing chimneys, including specifying particular requirements of Level I, II, and III inspections.

- Level I inspection verifies suitability of the chimney for continued service under the same conditions with the same or similar appliance, including examination of readily accessible portions of the appliance and chimney.

- Level II inspection verifies suitability of the chimney for changed conditions of service, including examination of accessible portions of the chimney interior and exterior, as well as attics, basements, and crawl spaces.

- Level III inspection includes examination of concealed areas of the chimney (suspected of damage or malfunction) that can be access only by removal of portions of the chimney or building structure.

NFPA 921 (previously mentioned) provides guidelines and recommendations to assist individuals responsible for investigating fire and explosion incidents and rendering opinions as to the cause and origin. The document is intended to provide a systematic framework for fire and explosion investigation.

UL 103 *Standard for Factory-Built Chimneys for Residential Type and Building Heating Appliances*[4] provides design, construction, and performance requirements for factory-built chimneys intended for venting gas, liquid and solid-fuel fired residential type appliances in which the maximum continuous flue gas temperature does not exceed 1,000°F. The chimneys also are to comply with a limited duration 1,700°F or 2,100°F temperature test, with type HT (high temperature) chimneys required to comply with the latter test. The standard, which requires installation to be in accordance with NFPA 211 and national building codes, includes installation and maintenance requirements.

UL 127 *Standard for Factory-Built Fireplaces*[5] provides design, construction, and performance requirements for factory-built fireplaces, including the firebox, chimney, roof assembly, and other related parts. It is intended for fireplaces burning solid wood or coal. The chimneys comply with either the 1,700°F or 2,100°F (Type HT) temperature test. The standard, which requires installation to be in accordance with NFPA 211 and national building codes, includes installation and maintenance requirements.

UL 1482 *Standard for Solid-Fuel Type Room Heaters*[6] covers room heaters that are freestanding fire chamber assemblies for use with solid fuels, which are intended to be attached to residential type chimneys.

UL 1777 *Standard for Chimney Liners*[7] covers metallic and nonmetallic chimney liners for field-installation into new or existing masonry chimneys, for use with solid fuel fired residential-type appliances with maximum continuous flue gas temperatures not exceeding 1,000°F.

Building Codes

When investigating a fire of a structure, one of the first steps is to determine which building codes are applicable. Whether the product at issue was installed and maintained pursuant to the applicable building codes is an important part of most investigations. Building codes are periodically updated; therefore, the editions of those codes relevant to the particular issue must be determined. The codes adopted by (and being enforced by) the authority having jurisdiction at the time the product at issue was installed or modified must be utilized by the investigator when determining code compliance.

The International Residential Code[8] (IRC) is a typical building code adopted by governing bodies. The 2012 IRC specified masonry fireplaces and chimney construction details and materials, including required clearances to combustible material. The IRC requires factory-built fireplaces be listed and labeled, installed in accordance with the listing, and tested in accordance with UL 127. Chimneys provided with factory-built fireplaces must also comply with UL 127. The IRC requires factory-built chimneys to be listed and labeled, installed in accordance with the manufacturer's instructions, and compliant with the Type HT requirements of UL 103.

Solid Fuel Consumption

Since only gases or vapors burn, solid fuel (such as wood, coal, or similar organic material) needs to be heated before it can burn. Heating the material creates vapors that will burn in a region above the surface. The fuel vapors can burn only if properly mixed with air and exposed to a competent ignition source, or if they are heated to their auto-ignition temperature.

A solid fuel-burning appliance needs an adequate supply of air to operate properly. The fuel vapor and air are mixed together and then ignited within the firebox of the appliance. The products of combustion are exhausted from the appliance through a chimney.

Burning wood produces water vapor, tar, carbon monoxide, carbon dioxide, and other organic vapors. These products combine to form creosote, which condenses, deposits, and accumulates on the inner surfaces of the chimney and chimney connector. A slow-burning fire, a fuel rich fire, or a cool chimney can increase the rate of creosote buildup. Burning unseasoned wood with high moisture content can also increase the generation of creosote.

Creosote is combustible material and can be vaporized and ignited by heat from the appliance, causing a chimney fire. Research described by Peacock[9] indicates creosote chimney fires have been documented to burn at temperatures as high as 2,500°F. These fires can damage the chimney and extend to nearby combustible structures of the building. Burning creosote can also be ejected out of the top of the chimney and drop onto the roof or nearby areas. Accordingly, it is important to periodically inspect and clean a regularly used chimney to minimize the accumulation of creosote.

NFPA 211 requires that solid fuel-burning appliances be installed with sufficient ventilation and combustion air supply to allow for proper combustion of fuel, facilitate chimney draft, and maintain safe temperatures[10]. Accordingly, combustion air kits, which provide outdoor air directly to the appliance, are typically available for fireplaces and wood stoves.

Complete venting of the products of combustion from solid-fueled appliances is necessary to assure the proper operation of those appliances — and to prevent the accumulation of the combustion products within a building. A chimney system is based on the principle that hot air is buoyant and rises. A proper chimney system conveys the products of combustion to the outdoors, prevents damage from the condensation of water in the flue gases, prevents overheating of nearby combustible materials, and provides fast priming of natural draft venting to minimize flow of combustion products into the building. A chimney that condenses water is more likely to accumulate creosote. Conversely, a fast priming chimney heats up quicker and is less likely to accumulate creosote. Common chimney systems for residential solid fuel-burning appliances include masonry and factory-built chimneys.

Appliances and Chimneys

Masonry Fireplace and Chimney

A typical masonry fireplace is constructed of solid masonry units, reinforced Portland cement, or refractory cement concrete. It is comprised of a firebox with a hearth (floor) and right, left, and rear walls made of fire-rated masonry materials. The firebox is usually equipped with a grate to keep the logs up off the hearth. It may be equipped with an outdoor combustion air supply as well as a gas starter or gas log set. The front opening may be equipped with a screen or glass doors. A manually operated damper is located at the top of the firebox and leads to a smoke chamber above the damper. A non-combustible hearth extension extends from the lower front edge of the fireplace outward into the room.

The smoke chamber narrows at its top and connects to a chimney flue that extends upward above the roof of the building. A masonry chimney is normally lined, and the flue size is based on the fireplace opening size. The top of the chimney is typically equipped with a cap that keeps rain and animals out and may be equipped with a screen to reduce the chance of sparks and embers escaping. Codes and standards relevant to masonry fireplaces and chimneys include NFPA 211, UL 1777, and local building codes.

Factory-Built Fireplace

A factory-built fireplace is a mass-produced appliance constructed of sheet metal or steel. It may be equipped with a factory-built chimney system provided by the same manufacturer, or installed with a chimney obtained from a different manufacturer (see the section on factory-built chimneys below). Codes and standards relevant to these fireplaces and chimneys include UL 127, NFPA 211, and local building codes.

An identification plate is included which provides basic information such as the manufacturer, model, serial number, date of manufacture, and relevant standards. Installation and user instructions are provided by the manufacturer, which contains information on proper clearances to combustibles.

A factory-built fireplace has a firebox with features similar to a masonry fireplace. Unique to a factory–built fireplace is the common construction that includes inner and outer metal cabinets separated by an airspace, which may or may not contain insulation. Firebrick may be replaced with refractory panels that cover the hearth (bottom) and sides of the firebox. Some factory-built fireplaces contain an integral grate on the hearth, and others intend for the firewood to be placed directly on the hearth. A non-combustible hearth extension, which is separate from the fireplace unit, is required to be provided by the installer. An air circulation blower may be installed to circulate room air through the unit and supply that heated air to the room. Similar to a masonry fireplace, an outside air supply kit and/or a gas log lighter, or gas log set, may be installed in the fireplace.

A typical chimney system, provided by the fireplace manufacturer, includes a double-wall or triple-wall air insulated chimney, firestops, attic insulation shield, radiation shield, support provisions, roof flashing, a storm collar, and a termination cap. The chimney must terminate a minimum of 3 feet above the roof and 2 feet above any portion of the roof within 10 feet.

The chimney may be equipped with an offset/return if it has to be jogged to avoid an overhead obstruction as it extends upward through the building structure. It may also be equipped with a chimney outside air kit to supply outdoor cooling air directly to the chimney.

Wood Stove

A wood stove is essentially a mass-produced firebox constructed of steel plate mounted on a pedestal or legs. An identification plate is included, and installation and user instructions are provided by the manufacturer. Codes and standards relevant to wood stoves include UL 1482, NFPA 211, and local building codes.

A glass door is located at the front of the stove, and a flue extends out the top. The interior bottom hearth and sides are covered with firebrick. A baffle may be located in the upper area, just below the flue, to increase efficiency of the appliance.

The wood stove may be equipped with an outside air kit to provide combustion air directly to the appliance, and controls to adjust the amount of air entering the firebox. The stove may also be equipped with an electric blower to circulate and heat room air.

If the stove is intended to be installed on a combustible floor, it may be required to be set on top of a hearth pad floor protector so that it complies with its listing. If a pad is not utilized, the floor may be exposed to excessive temperatures that may cause a fire hazard. Wood stoves are utilized with chimneys manufactured by companies other than the stove manufacturer. The chimneys may be masonry or UL-listed factory-built. A chimney connector attaches the wood stove to the chimney. Chimney connectors may be single-wall or air-insulated double-wall. Typical clearance to combustibles for single-wall connectors are 18 inches, and double-wall connectors are to be pursuant to the manufacturer's instructions (normally 6 inches). A "thimble" is utilized where the chimney or connector passes through a wall to maintain proper clearances.

Factory-Built Chimney

Codes and standards relevant to prefabricated factory-built metal chimney systems include UL 103 HT, NFPA 211 and local building codes. Type HT factory-built chimneys are tested to withstand a 1,000°F continuous flue gas temperature and a 2,100°F flue temperature for 10-minute intervals. Typical factory-built chimneys include air cooled triple-wall and insulated double-wall types. Air-cooled chimneys may be equipped with outdoor air supplies to their bases to provide required air. The engineer should determine the expected flue gas temperatures being generated by the appliance and vented through the chimney.

A basic system includes a chimney connector, chimney, supports, an attic insulation shield, radiation shield, firestops, roof flashing, a storm collar, and a termination cap. The cap prevents entry of rain, snow, and animals, and may be equipped with a spark arrester. An adapter may be provided to transition between the stove flue and the chimney connector. The chimney system is provided with manufacturer installation instructions.

Common Fire Causes

Clearances to Combustibles

A major cause of solid-fuel appliance-caused structure fires is inadequate clearances to combustibles. For factory-built appliances, appliance manufacturers provide the proper clearances to combustibles for installation in their installation instructions. Clearances to combustibles typically refer to combustible construction of the structure (i.e., wood structural members, plywood, oriented strand board [OSB], roofing materials, etc). Combustibles can also include thermal insulation.

Only cellulose insulation is discussed in this paper because, in the author's experience, it is common for that insulation to be the first fuel ignited in a structure fire. Typically, fiberglass insulation will smoke and melt, but will not burn. Loose fill cellulose thermal insulation is basically shredded newsprint treated with boric acid as a fire retardant. It is mechanically blown into place to a desired density and thickness. An engineering resource well known to the fire investigation field is the *Ignition Handbook*[11]. This text indicates loose fill cellulose insulation is known to combust in smoldering mode, and the generally accepted minimum hot surface ignition temperatures for cellulose insulation is approximately 450°F (232°C). Therefore, the external surface of the chimney would need to reach that ignition temperature from internal heating by the hot flue gases being vented from the appliance, and remain at that temperature long enough to ignite a fire.

Overfiring of Appliance

Even if there are proper clearances, the operating appliance can produce temperatures great enough to ignite nearby combustibles. Overfiring of the appliance may occur from burning too much wood, trash, or flammable liquids — or allowing too much air into the appliance, causing too intense of a fire. Overfiring may cause the chimney connector to glow red hot and/or ignite creosote deposits in the connector or chimney and cause a chimney fire. Evidence of overfiring may be witness observations of the size and intensity of the fire in the appliance, observed glowing hot components, information on the rate of fuel (wood) consumed leading up the fire event, or observed localized overheating damage to the appliance or chimney.

Chimney Fire

A chimney fire can overheat and damage a masonry or factory-built chimney, which can ignite adjacent combustible building construction. Type HT factory-built chimneys (as mentioned) are tested to withstand 1,000°F continuous flue gas temperatures and 2,100°F flue temperatures for 10-minute intervals. However, actual chimney fires can reach higher temperatures and/or last for longer durations. Non-HT factory-built chimneys are tested to withstand 1,000°F continuous flue gas temperatures and 1,700°F flue gas temperatures for 10 minutes.

Maintenance

Improper maintenance of fireplaces, wood stoves, and/or chimneys can lead to deteriorated or damaged units remaining in use, which may not perform as intended and create a fire hazard.

Inspection of Appliances

The purpose of the initial portion of a scene investigation is to document the location and condition of wood-burning appliances within a building. The level of detail of an examination of an appliance at a fire scene is dependent on the conditions at the scene, including the accessibility and physical condition of the appliance and the suspected involvement of that appliance in the occurrence. If conducting a thorough examination of an appliance at the scene is not feasible, then a more thorough examination may be conducted at a later date in a laboratory. Normally, only nondestructive inspection and testing would be performed on an appliance at the fire scene. A typical examination of the appliances would include the following steps:

1. The location and condition of each appliance should be documented and photographed. Distant photographs should be taken that depict the location of the appliance with respect to easily recognizable reference points within the building. Photographs of all accessible sides of the appliance should be taken. Inaccessible sides of the appliance should be photographed if or when the appliance is moved. Inspect and document heat and burn patterns and any other fire and/or heat damage to the appliance and adjacent objects.

2. Document the area around the appliance for clearances to combustibles, including the walls and floor of the room and storage materials, including flammable liquids. Also, check for proper clearance between the chimney piping and combustibles (walls, ceiling, etc.) of the room.

3. Photograph and document the means of supplying combustion air to the room containing

the appliance(s). Determine whether adequate quantities of air were supplied to the appliance for proper combustion. Document the layout and dimensions of any combustion air kits.

4. Photograph and document the chimney system, including its configuration, components, and dimensions (including the portion on the exterior of the building). Determine the condition, including if the chimney is unobstructed and pulling a draft. Inspect for blockages such as leaves or animal nests. Determine the configuration of a factory-built chimney, including clearances where it passes through a wall, ceiling, or roof. Inspect for damage, corrosion, or separation at joints. Record any loose or detached joints. Inspect for evidence of creosote (gray ash after a chimney fire) inside the chimney or connector. Document the presence and condition of a chimney liner. Verify that the cap/termination is properly located relative to the roof and other obstructions. Confirm whether all components of the chimney system are from the same manufacturer, and if there are mismatched parts.

5. A solid fuel-burning appliance may be equipped with a gas starter or gas log set. This configuration does not eliminate the necessity for the appliance and/or chimney to comply with the relevant solid fuel codes or standards. Record the position of any electrical switches and controls. Examine the electrical wiring for damage or evidence of modifications, which could include cut or disconnected wires or the presence of jumper wires/wire nuts.

6. Inspect and record the configuration of the gas supply piping if the appliance is equipped with a gas starter or gas log set. Document the presence of a manual shutoff valve, sediment trap (drip leg), and/or a flexible gas connector. Record the position of the manual shutoff valve. Document if the opening in the firebox around the gas pipe is sealed as well as the clearance from the gas pipe to combustibles. When feasible, measure the incoming gas pressure to the building at flow and no-flow conditions.

7. When inspecting the exterior of the appliance, document whether any access doors or panels are present and properly installed. Open or remove the access doors or panels only if they can be easily removed without altering the condition of the appliance.

8. Record identification and information labels and plates on the appliances, including manufacturer, model, serial numbers, date of manufacture, installation and operation instructions, warnings, and references to standards. Movement of the appliance or removal of debris from the appliance to accomplish that task should be kept to a minimum.

9. Document evidence of abnormal firing or overfiring, flame rollout, or excessive shooting/creosote within the appliance or its chimney. Document evidence of damage to the appliance (including internal explosion damage) and presence of excessive corrosion.

10. If the integrity of a solid fuel-burning appliance and chimney system is an issue, a smoke test of that system may be warranted. A smoke test involves sealing all openings of the system (including the fireplace front opening and chimney termination), pressurizing the system with colored smoke from smoke generators, and observing for smoke discharging through any breaches or openings.

Notification of Other Interested Parties

Reasonable efforts should be made to notify all other interested parties of an occurrence, and invite them to participate in the investigation. The forensic engineer's client, attorney, or insurance company representative normally performs actual notification of other parties. The other interested parties should be given a reasonable opportunity to inspect the scene before it is significantly altered or disturbed and participate in the formulation of plans to remove, preserve, and test the artifacts.

Removal of Evidence from Scene

Effort should be made to collect loose parts of an appliance and preserve the entire unit together. Wrapping an appliance in plastic before it is removed from the scene is an effective way to retain the debris or objects on or within the appliance. Some or all of the chimney system may need to be removed, especially if it is suspected of causing the occurrence. Prepare and distribute a chain-of-custody list of artifacts that are removed from the scene and preserved.

Figure 1
Rear of house showing chimney and chase debris in yard.

Case Study No. 1: Improper Installation of a Factory-Built Fireplace Chimney System

Incident: A husband and wife were in their house with a fireplace operating during early November. The fireplace had been operating for approximately 3 hours when a fire was discovered in the attic of the single-story ranch-type house. The attic and roof portion of the house sustained damage.

Figure 2
Family room showing fireplace and chase.

Figure 3
Chimney pipes in yard.

Investigation: The house had been recently completed, and the owners occupied the house in April of the same year **(Figure 1)**. At that time, a factory-built fireplace and chimney system was installed in a chase in the corner of a family room **(Figure 2)**. The chimney was a double-wall type. When the homeowners used the wood-burning fireplace for the first few times that spring, they smelled burning wood in an attached garage. They did not use the fireplace during the summer, and had a natural gas log set installed in September. Between the gas conversion and the date of the fire, they had used the gas fireplace several times. The use of a natural gas log set in the fireplace did not eliminate the necessity for the fireplace and chimney to comply with the original relevant codes and standards.

The sections of chimney pipe and remnants of the wooden chase were found to be lying in the backyard. No termination cap was found for the top of the chimney. Discoloration of the chimney pipes indicated that they had gotten very hot **(Figure 3)**. The chimney had extended through a vertical wooden chase. The configuration of the chase and chimney were documented in detail **(Figure 4**). Those components had sustained substantial damage from the fire and extinguishing activities of the fire department. Modeling the configuration of the chimney and chase revealed that the top of the chimney pipe did not reach the top of the chase **(Figure 5)**. Further, heat patterns and nails at the top of the chase suggested that a plywood cover might have been located over the opening at the top of the chase.

An inspection of an exemplar house that had been constructed by the same builder revealed that the upper portion of the fireplace chimney and rain cap clearly extended above the top of the wooden chase **(Figures 6** and **7)**.

Figure 4
Top of chimney assembly in house attic.

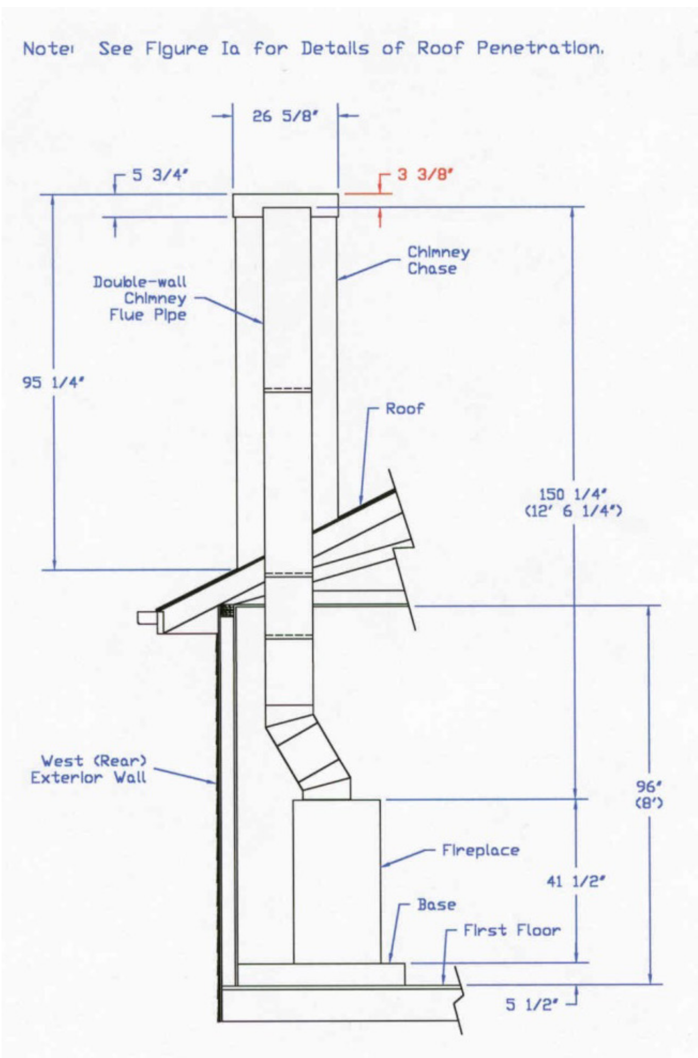

Figure 5
Elevation view of fireplace, chimney, and chase installation.

Figure 6
Exemplar house showing chimney chase.

During the investigation, a next door neighbor produced a photograph from a party that had occurred in their backyard that summer **(Figure 8)**. The photograph showed the subject chimney chase in the background, and clearly showed that nothing extended from the top of the chase. In other words, no fireplace chimney pipe and/or rain cap extended from the chase.

Since the fireplace unit was undamaged, it was later set up at the author's laboratory with a new and identical chimney system. The fireplace was then operated with the same gas log set installed, and the flue gases' temperatures were measured.

Figure 7
Exemplar chase showing chimney and termination cap extending above.

Figure 8
Subject chase before fire.

Figure 9
Family room showing fireplace and chase.

Conclusion: The fireplace chimney system had not been properly installed. The upper portion of the chimney and the rain cap were not present — and the chimney did not extend above the top of the chase. Further, it was likely that the top of the chimney chase had been enclosed. Consequently, the products of combustion from the fireplace flowed into the attic where they impinged on and heated the combustible construction and eventually started the incident fire.

Case Study No. 2: Loose-Fill Cellulose Insulation Contacting Chimney

Incident: The two-story house involved in the subject fire was constructed in 2009, and the owners moved in during the fall of that year. The house was equipped with a factory-built wood-burning fireplace and chimney within a wood framed chase (with a stone fascia) along a wall in a first floor family room, and the chase extended from the floor to the peak of the vaulted ceiling **(Figure 9)**. A second chimney was also present within the chase for a future wood-burning appliance in the basement. This second chimney had no part in the fire. The structure fire occurred in the house in February of 2010. The subject first floor fireplace had been used during the afternoon and evening of the fire, which was discovered at about 10:30 p.m. The fire was limited to the attic in the area of a wood fireplace chimney chase.

The upper portion of the fireplace chase was common to a second-floor bedroom wall. Drywall had been removed from that wall, exposing the chimney assembly **(Figure 10)**. Significant fire damage was present in the second-floor portion of the chase and the attic above, and fire damage to the house was limited to this area. Cellulose insulation was located on top of framing that surrounded the original location of two sheet metal firestop spacers located slightly below the second-floor ceiling level.

Several openings existed between the chase and the surrounding attic. Those openings were not blocked or covered with plywood, netting, or any other insulation barrier, and they permitted cellulose insulation to be blown into the chase and against the chimney at the upper firestop spacer shelf position.

Warning labels affixed to the chimney sections stated "*Fire Risk. Insulation and Combustibles must not touch pipe. Consult manual for clearance requirements."* Information labels stated, *"Caution maintain 2 inches minimum air space clearance to combustibles and building insulation*."

Figure 10
Second-floor level showing subject chimney pipe (left).
Red line indicated original firestop spacer shelf position.
An undamaged "protected area" was present
on the unused (right) chimney pipe above the shelf.

Fire patterns on the exterior surface of the subject chimney pipe, directly above the firestop spacer shelf, indicated an area of relatively intense heat located within a larger triangular shape, which was an area originally covered with insulation that burned away during the fire **(Figure 11)**. A light coating of ash was located on the interior surface of the inner pipes of those sections. The termination cap contained black-colored deposits and loose material.

On the second (unused) parallel factory-built chimney, the portion located directly above the upper firestop spacer contained a "protected area" that was not heat/fire damaged. The maximum height of that protected area was approximately 18 inches above the firestop spacer. A pile of cellulose insulation had been located there during the fire, and protected that portion of the chimney section

Figure 11
Subject (left) and unused (right) chimney pipes.
Red line indicates original firestop spacer shelf position.

from the fire.

The fireplace and chimney installation manual instructed the installer to install an attic insulation shield around the chimney where there was a possibility of insulation coming into contact with the chimney. Also, the local building code required the fireplace and chimney to be installed pursuant to the manufacturer's instructions.

Chimney fires were a reasonably foreseeable use of the subject fireplace and chimney system, and the system was designed to safely contain a chimney fire and not permit it to spread to the building. Specifically, the fireplace and chimney system was designed and tested to comply with UL 127 *Standard for Factory Built Fireplaces*. This standard required the chimney system to successfully pass a 2,100°F flue gasses temperature test, where the adjacent combustible construction could not be heated to an unsafe temperature (the maximum permitted temperature was 175°F above room temperature). That test simulated the conditions of a chimney fire.

Factory-built chimney fire tests, involving the igniting and burning of creosote deposits on the interior surfaces of the chimneys, revealed peak chimney outside surface temperatures ranging between 278 and 811°F[8]. Those temperatures exceeded the generally accepted minimum hot surface ignition temperatures for cellulose insulation (approximately 450°F). None of the test chimneys were externally insulated during those tests. External insulation would have increased those temperatures. The only potential ignition sources in the area of origin were the heated fireplace chimney, the building electrical system, or a

Figure 12
Outdoor masonry fireplace and chimney in veranda.

lightning strike. The author's investigation eliminated the electrical system, and a lighting strike analysis eliminated that potential.

Conclusion: The point of origin of the structure fire was at and directly above the upper firestop spacer shelf location on the fireplace chimney. Fuel available at the point of origin was loose-fill cellulose insulation. The cause of the structure fire was the ignition and burning of loose-fill cellulose insulation in contact with the chimney, which ignited nearby combustible framing. The first fuel ignited was the loose-fill cellulose insulation. The ignition sequence was a likely chimney fire heating the chimney pipe, followed by the heated pipe igniting the insulation, which ignited combustible framing.

Figure 13
Wall of family room showing fire damage common to outdoor fireplace.

The subject fireplace and chimney system was improperly installed, which created a defective and unreasonably dangerous fire hazard condition. Specifically, the required attic insulation shield was not installed on the fireplace chimney. That shield was required to be installed on the top side of the firestop spacer, and its absence did not comply with the aforementioned fireplace owner's manual, codes and standards, and the standard of care.

The combustible loose-fill cellulose insulation was improperly installed in the area of the fireplace chimney in the attic. Specifically, blocking was not installed around the chimney to keep the insulation a safe distance away from the chimney.

Case Study No. 3: Improper Clearance of Masonry Fireplace

Incident: The subject house had been recently constructed. An outdoor veranda contained a masonry fireplace **(Figure 12)**. That fireplace had been built common to the east exterior wall of the house. The wall of the house was frame construction with a brick veneer. The fireplace had been used approximately 20 times previously. That fireplace had been used from approximately 5 p.m. to 10 p.m. the evening before the structure fire, burning cut hardwood logs. At approximately 2:30 a.m. the next day, smoke detectors in the house activated. The owner saw smoke and fire behind a cabinet in the family room along the exterior wall common to the outdoor fireplace.

Investigation: The east wall of the family room, common to the outdoor fireplace, had sustained fire damage (**Figures 13** and **14**). The frame wall was located directly adjacent to (and in contact with) the masonry rear wall of the fireplace. This frame wall was comprised of: house wrap fabric, ½-inch OSB sheathing, wood 2x6 studs on approximately 16-inch centers, cellulose blown-in insulation in the stud spaces, and ½-inch drywall (interior surface). The OSB sheathing was contacting the masonry at the rear side of the exterior fireplace. A burn pattern

Figure 14
Fire damaged wall common to outdoor fireplace.

through the OSB sheathing was aligned with the firebox of the outdoor fireplace.

A section of the interior frame wall, containing the fire damaged area, was removed, exposing the surfaces of the OSB plywood and masonry wall. Soot was found to be located on both surfaces. The integrity of the masonry fireplace and chimney was determined by conducting a smoke test. The front opening and chimney outlet of the outdoor fireplace were sealed, and smoke generators were placed in the firebox and ignited. No smoke was observed leaking through the rear wall.

A portion of the rear wall of the fireplace was removed, which provided access to the entire cross-section of the rear wall of the fireplace (**Figure 15**).

The overall thickness of the rear wall of the fireplace was measured and found to be about 7 inches. It was comprised of a 2½-inch-thick single row of firebrick, which was the back wall of the firebox, and a 3½-inch-thick single row of concrete masonry units (CMUs). A gap measuring between ¾ and 1 inch, between the CMUs

Figure 15
Rear wall of fireplace with portion removed, showing dimensions.

and firebrick, was partially filled with mortar. Electrical components within that wall were inspected by an electrical engineer and eliminated as a cause.

Conclusion: The subject fire was caused by heat energy from the firebox of the outdoor fireplace conducting through the rear wall of the masonry fireplace and igniting combustible building materials directly adjacent to, and in contact with, the masonry wall. The construction of the masonry fireplace and wall was improper, dangerous, and a fire hazard. The construction violated the standard NFPA 211 and the local building code. The 7-inch thickness of the masonry back wall of the fireplace was less than the minimum required 8 inches. The OSB sheathing of the interior wall was contacting the inner surface of the masonry wall for zero clearance to combustibles, which was less than the minimum required clearance of 4 inches. The thickness of the back wall and the absence of an air space clearance to combustibles provided much less thermal resistance between the firebox and the combustible wall than the building code required. This permitted an unsafe elevated temperature of the combustible wall, which resulted in its ignition.

Conclusions

When a forensic engineer is called upon to investigate whether a solid fuel-burning appliance caused a fire, the engineer should have a thorough understanding of the equipment and structures involved, the potential failure modes, and utilize a generally accepted methodology. The methodology should include application of the relevant codes and standards that provide reliable guidelines for fireplace and chimney design and installation. As the case studies showed, frequently the fire causes violated recognized codes and standards.

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Landfill Operations and Off Highway Construction Vehicle Visibility Impairment Issues Result in a Serious Injury: A Case Study

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Abstract

This case study reviews the hazards involved with the work procedures and work environment combined with large mobile equipment associated with a landfill operation. An active landfill is a very busy work environment. There typically is a constant stream of municipal solid waste (MSW) trucks of various sizes and dimensions approaching and dropping their waste load onto the landfill active work area, which is referred to as the landfill face or tipping area. In addition to the MSW delivery truck traffic, the active face in this case study was being traversed back and forth by two large industrial vehicles: a bulldozer (or "dozer") and a steel-wheeled compactor vehicle. The injured party, who was just transferred to the job of "waste spotter," or just spotter, had the responsibility of directing the incoming stream of MSW trucks as to where to dump their loads while also directing (and avoiding) the tracked loader and the steel-wheeled compactor vehicle as they operated on the landfill active face. Additionally, due to the dumped MSW, the active landfill face topography is constantly changing, and the pedestrian spotter therefore must constantly be moving on the active face to avoid being struck by the vehicular traffic. The bulldozer manufacturer acknowledged that the loader travels in reverse approximately 50 percent of its operating time on the landfill space. Hence, any static visibility impairments were further compounded when the dozer traveled in reverse over changing topography. Other issues that negatively affected the landfill face hazardous environment were a lack of any safety procedures for the landfill operations and a lack of hazard training and instructions provided to the waste spotter working the landfill face.

Keywords

Landfill training, spotter, crawler, bulldozer, loader, compactor, visibility, midden, tipping area

Purpose

This paper hopes to introduce readers to some of the many hazards involved in the operation of a landfill. Additionally, it will be shown that the necessity for proper safety, planning, and training for all phases of landfill operations cannot be overemphasized. Also addressed will be the need for providing adequate operator visibility in both the forward and reverse directions of large vehicles working on the landfill face. These vehicles include specifically large bulldozers and steel-wheeled compactors. The topic of the necessity for regular and ongoing communication among all people working the landfill space (including the spotter and all drivers and machine operators working on the landfill face) will be discussed.

Introduction

This case study involves the assessment of a serious worker injury that occurred on the active face of a landfill. The term landfill is presently also known as a tip dumping ground, garbage dump, and rubbish dump. Historically, landfills were known as middens. Indeed, middens are presently utilized by archaeologists to study the living and dietary habits of previous generations. Landfills are often the most cost-efficient way for organized waste disposal by designed burial of waste material. Modern landfills are benefiting from modern study and technology and are subject to various regulations. The landfill and/or rubbish dump active face is that location where the trash or garbage trucks of different sizes and configurations bring and dump their loads for delivery to the landfill active face and then leave the area. In addition to the garbage truck traffic entering the landfill active face, compactors (steel-wheeled vehicles) and/or bulldozers are used to spread and compact the deposited waste on the working face. The machines working the active face will typically make three to five passes over a single area in different directions (both forward and reverse) to assure proper compaction of the waste material (Walsh et. al. 2002). Compactors are steel-wheeled vehicles whose wheels are studded with various designs of steel load concentrators or studs. They are utilized to maximize waste compaction and are typically found on medium to large sites that can

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support more than one machine working the active face.

Bulldozers (also known as dozers and crawler tractors) and crawler loaders are track type vehicles that are also utilized to compact waste, but also serve in relocating waste on the active face as well as face cover application and excavation (Walsh et. al 2002). The tracked vehicle's freedom of movement — and its designed function of moving and flattening materials, often in tight quarters — requires that these vehicles travel in reverse approximately half the time. This situation is further exacerbated due to its large size, which causes the operator to lose some of his visibility when driving forward and even more so when traveling in reverse. Thus, when traveling in reverse, the machine operator (attempting to observe traffic, pedestrians, obstructions, etc.) must turn in his seat and continually look over his shoulders, typically an industry-suggested practice. Therefore, the range of operator visibility while operating the vehicle deteriorates due to driver fatigue, stress, neck and back pain, or any combination of these factors. Further visibility deterioration is generated when the vehicle must traverse hills of trash while traveling in reverse. Traveling in reverse accounts for at least 50 percent of fatalities from being run over by construction equipment (Pegula 2004). This physically demanding rear-view viewing approach is also applicable to other large industrial vehicles, such as large forklift trucks (Josephs 2003).

As the compressed waste starts to decompose, gases are produced by microbial anaerobic digestion of the waste. This gas, although "dirty," is primarily composed of methane and is typically collected and used. The gas collection uses a series of pipes buried within the landfill, with some pipes exiting the landfill surface. In this case study, there was a gas pipe located in the active face, which necessarily had to be avoided by vehicles.

Coordinating all this traffic on the landfill face is the "waste spotter." The spotter is responsible for directing the incoming garbage truck traffic to the active face and the compactor and dozer traffic to properly compact the waste — while at the same time trying to keep vehicular traffic on the active face away from any gas pipe.

The physical shape, geometry, and configuration of the active face are in a constant state of flux. The specific area that was previously a hillock of recently dumped garbage can become flattened and now present as a depression after a few passes of the compactor and dozer. It is apparent that being a landfill spotter presents numerous hazards due to the nature of the work, the constantly changing terrain, the types of vehicles, the vehicle traffic, and its changing direction in close proximity.

There are a far greater proportion of accidents and fatalities at landfills than in many other industries purely because of the nature of the work. Many accidents and injuries that are suffered by those who work within the industry are transport related (Durham 2013).

In 2015, the New York State Fatality Assessment and Control Evaluation (FACE) program reported:

"The EPA states that the number of landfills decreased substantially over the past years from nearly 8,000 in 1988 to 1,654 in 2005 ... while average landfill size increased. Although many town dumps had closed, they were replaced by fewer, but larger regional ones" (FACE 2015).

This, of course, indicates that the increasing number of larger regional landfills would require and therefore utilize larger types of construction vehicles in landfill applications with all the hazards that are associated with such vehicles.

Dr. Ross A. MacFarland of the Harvard School of Public Health is quoted in a 1964 SAE publication (Connolly et al 1964), stating the importance of the driver machine relationship by:

"*The human engineering approach to highway safety can be more effectively carried out when data on the capabilities and limitation of drivers are done; it is only a matter of time before some 'design failure' results in 'driver failure' and an accident.*"

This statement, written more than 50 years prior to the occurrence of this case study's injury accident, prophetically described the unfortunate serious injury accident resulting from a lack of a visibility-enhancing safety feature incorporated into initial vehicle design in view of operators' limitations and capabilities.

The Environmental Industry Association's 2001 *Manual of Recommended Safety Practices* provides a more specific statement describing workplace hazards where there is interaction between workers and motor vehicles in the work environment. Excerpts from this document are presented below:

"Overview of the Subject

Traffic through landfills, transfer stations material recovery facilities (MRFs) and at hauling operations can create hazardous work environments if they are not managed properly.

According to the Bureau of Labor Statistics, more than 2,000 deaths a year result from occupational motor vehicle incidents, more than 30% of the total annual number of fatalities from occupational injuries. These deaths include driver and passenger deaths in highway crashes, farm equipment accidents, and industrial vehicle incidents as well as pedestrian fatalities.

In an analysis of data for 1990-92, NIOSH found that the industries with the highest average annual rates of death per 100,000 from traffic-related motor vehicle crashes were:

- *Trucking (12.1 deaths per 100,000 workers), logging (9 deaths per 100,000 workers)*
- *Fuel dealers (5.6 deaths per 100,000 workers)*
- *Petroleum products (5.2 deaths per 100,000 workers)*
- *Agriculture crop production (4.2 deaths per 100,000 workers).*

Occupations with the highest annual average fatality rates per 100,000 workers were:

- *Truck driver (12.2 deaths per 100,000 workers)*
- *Garbage collector (11.5 deaths per 100,000 workers)*
- *Sheriff/bailiff (7.1 deaths per 100,000 workers)*
- *Farm worker supervisor (5.2 deaths per 100,000 workers), and*
- *Surveying and mapping technician (5.1 deaths per 100,000 workers).*

NIOSH found that from 1980 to 1992, motor vehicle crashes were the leading cause of work-related deaths in U.S. workers. During this period, traffic-related motor vehicle crashes accounted for the deaths of 15,830 workers — or 20% of all fatal workplace injuries. Also during that period, 1,997 worker deaths were associated with motor vehicle crashes that were not related to traffic on a public highway. The number of traffic-related deaths was eight times the number not related to traffic.

Duties and Responsibilities

Employers

Employers should develop and implement an appropriate traffic control plan for their facility operations. They must also provide supervision, through appropriate contract conditions, with a means to enforce the traffic plan with non-employee drivers (visitors).

Supervisors

Supervisors are responsible for implementing the employer's traffic control plan and enforcing employee/ visitor compliance with traffic speed limits and other traffic safety rules. In addition, supervisors should review traffic flow on a frequent basis to accommodate changing conditions such as wind, rain, sleet, snow, etc. (Legler et. al. 2001)

Busy construction sites, although entirely different from landfills, contain many of the same types of hazards. Hence, statistics of fatalities at road construction sites can shed some light on the hazards found when working on a landfill, due to the similarities of the hazards presented by large industrial equipment working and moving in the vicinity of otherwise occupied pedestrian workers.

Road construction workers face many hazards on the job. In addition to many of the hazards present on a "traditional" construction site, road workers also need to contend with moving vehicles — both in and around the job site. Road construction workers, like landfill workers, risk injury from construction equipment operating within work zones. From 1995 through 2002, 844 fatal occupational injuries occurred at road construction sites. The majority of these fatalities, 693 (82 percent) cases, were reported to be transportation incidents. Fatalities involving a ground worker being struck by a vehicle or equipment accounted for 509 (73 percent) of the transportation incidents. Victims were as likely to be struck by construction equipment (32 percent) as by highway vehicles (28 percent) (CDC 2011).

Scenario

A cement finisher who suffered a back injury was temporarily transferred to a "light work" job at a sister company in an interwoven number of corporations. This job consisted of being the "waste spotter" or "spotter" on an active landfill face. The transferred spotter received no training, reading materials, or instruction in the duties and potential hazards of being a spotter. His only instruction was to direct the vehicles on the landfill face to avoid striking a vertical gas pipe that protruded from the landfill surface. The vehicles involved in the landfill face traffic included:

- Trucks of various sizes and geometry continuously dumping trash and garbage on the face.
- A steel-wheeled compactor utilized for compacting the garbage and debris by making numerous forward

Figure 1
Accident site showing the steel-wheeled compactor and the gas vent pipe. Note the mounds of debris on the landfill face.

and reverse “passes” over the mounds of heaped garbage and debris. The subject compactor at the accident site is shown in **Figures 1** and **2**.

- A crawler loader utilized for moving the trash/debris and compacting the trash and debris by making numerous back and forth passes.

Figure 3 shows the subject crawler loader at the accident site. The loader was being operated that day by a replacement operator who received no training in the safe operation of the loader on the landfill face. The loader, while traveling in reverse over a hillock of trash, struck and seriously injured the trash spotter. The incident was observed and witnessed by a truck driver delivering trash to the site. Other workers who observed the incident stood by in apparent disbelief/shock and offered no assistance. The injured worker himself called 911, describing his injury and requesting a heli-vac transfer to the closest hospital while drifting in and out of consciousness. The injured worker lost both legs so close to his hip that he was not a candidate for prosthetic surgery.

At the day and time of the injury accident, the spotter was not wearing any high-visibility clothing or vest but rather standard work clothes and a standard red-colored vest, but not a “dayglo” vest.

The subject crawler loader was equipped with the following:

- A fixed operator’s seat facing forward.
- A single internal rearview mirror (no external mirrors).
- A constant level audio back-up alarm that sounded automatically when the vehicle traveled in reverse. The back-up alarm was mounted below a crossmember and behind a mounting plate that significantly reduced the back-up alarm audio output.

Figure 2
Close-up view of the steel-wheeled compactor and the gas vent pipe at the accident site.

- A large vertical exhaust stack in the center of the rear of the vehicle.
- A “landfill package” as sold and provided by the manufacturer, indicating knowledge by the manufacturer of the ultimate use of the dozer.

Elements of Analysis

The primary focus of any landfill management team is succinctly stated below:

“… *Assuring the safety and well being of employees and running an efficient site that complies with all legal and environmental requirements are number-one priorities for the waste management team.”* (Bliss 2006)

Figure 3
Subject crawler loader at the accident site.

However, with respect to this case study, there are a number of different hazard-related issues whose combination resulted in the serious injury accident. They can be conveniently represented by the following major task areas:

- Pre-Accident – Training and Instruction
- Work Environment – Landfill Face
- Task/Job – Waste Spotter
- Equipment – Large Moving Tracked and Wheeled Vehicles
- Post-accident – Training and Instruction

As noted earlier, the spotter was transferred from another corporate sister entity to the landfill for "light-duty" work while recuperating from a back injury. In this scenario, the waste spotter received absolutely no safety training or instruction with respect to the hazards involved when working on the landfill space. The spotter had never previously been on a landfill space and was not aware of any of the hazards involved in landfill operations in general and specifically, those involved in this landfill face. The employer did have a number of videos on general topics of workplace safety. However, even these videos, which addressed general issues of workplace safety, were not shown to the prospective waste spotter, nor did he know that they even existed. Indeed, his only specific instruction was to focus on the vertical gas vent located in the landfill face and to direct the landfill face traffic away from the pipe so that it would not be struck. Landfill management's directions with respect to maintaining the vent pipe structural integrity, as opposed to focusing on worker safety, contributed to the hazard elements on the work face.

The spotter was also not informed of the necessity for communicating by hand signals to direct the crawler loader and compactor operators. Additionally, even though the landfill operation had a person on staff identified as the landfill's "safety director," the person so identified admitted that he had no training in safety, that he was not really responsible for safety, and that indeed there was no knowledgeable individual in the company responsible for safety at the landfill operation at the time of the accident.

Work Environment – Landfill Face

The landfill did not have any written procedures or training to coordinate the equipment operators' work with that of the spotter or the delivery drivers who would often appear in the driver's blind spot as part of their work procedures. The working landfill face is in a constant state of activity, as the debris and waste are being brought by the incoming garbage trucks dumping garbage, the crawler loaders are moving and compacting the material, and the wheeled compactors are compacting the material. Hence, while performing his duties of directing the vehicular traffic on the landfill face, the free-ranging pedestrian waste spotter had to avoid being struck by the vehicular traffic in his relatively small work location. Additionally, as the material is dumped by the stream of incoming garbage trucks, small hills of debris are created, which can conceal the location and direction of motion of the tracked and wheeled vehicles working the face.

As the vehicles move and compact the material, the vehicles move up and down while going over the garbage mounds. The driver's field of vision can be severely obscured depending upon the orientation of the vehicle as the vehicle tilts upward or downward on the mounds. This compounds the visibility impairments created by the vehicle's large size. **Figure 4** depicts a generic bulldozer (equipped with a moldboard for pushing and back-dragging material) and its orientation while working on the landfill face. Additionally, this figure demonstrates the significant reduction in the operator's field of vision due to the typical operation of a crawler tractor on a landfill face.

There are numerous stressors that could cause the spotter to be distracted and therefore not be fully cognizant of the moving vehicle hazards in his proximity including:

Noise: The landfill face is a high noise environment given the close proximity of the constant back and forth traffic of large off highway diesel powered equipment. The noise level is exacerbated by the constant sound level back-up alarm, which is part of the

Figure 4
Generic-type bulldozer showing typical orientation while working on the landfill face. Note the reduction in visibility due to traveling over the trash mounds.

cacophony of sound on the landfill face.

Slip and trip: The varying types and configuration of the debris on the landfill face can cause the spotter to be distracted due to the slip and trip hazards they represent. This is further exacerbated by the constantly moving and shifting of these hazards as the landfill face is constantly being changed and modified.

Cuts and punctures: Much of the debris on the landfill space has sharp edges protruding from the landfill face surface or lying about. In addition, the presence, location, orientation, and type of sharp or pointed edged surfaces change as the landfill face changes.

Dust: The dust raised by both the crawler loader and the steel-wheeled compactor could cause stressors that diminish the spotter's attention to his hazardous surroundings.

Structure or physical formation: There may be occasions in given landfills where some structure or other physical formation in or near the landfill face requires special attention from the spotter during operations. In this case study, the spotter was directed to make sure that the moving equipment did not strike the vertically exposed gas vent pipe. This caused an additional stressor that somewhat diminished the spotter's attention to the moving hazards in his changing work environment.

Task/Job

The spotter is required to work in a hazardous environment that is ever changing with respect to the type and location of the moving vehicle hazard but also in the very configuration and shape of the workplace itself (i.e., the landfill face or the tip). The major effort involved in maintaining a safe work environment on the landfill face is for the spotter or any other workers on the landfill face to "see and be seen." That is, the spotter must see and observe all the moving vehicles in the landfill face, and similarly the spotter must be seen by the truck drivers and vehicle operators at all times. If the spotter were to turn his back to one vehicle while directing another, he would not be able to see any oncoming traffic. By the same token, if an off-highway vehicle is hidden by some trash (as it could be when traveling in reverse over a large trash mound), then the vehicle operator would not be able to see the spotter.

The landfill space, due to its many hazards, can be among the most hazardous of environments, yet the spotter in this case study was placed into this hazardous and changing environment with:

- No radio to communicate with the vehicle drivers.
- No direction or requirement for wearing high-visibility garments.
- No closed circuit TV (CCTV) system provided with the bulldozer, requiring the operator to essentially drive "blind" when traveling in reverse.
- Little knowledge of the workplace hazards.
- No instruction.
- No training.
- No established protocol for communicating with the waste spotter by hand signaling.

In addition, the corporate individual responsible for safety and training never had any safety training or specific knowledge of landfill face work hazards. He testified that there was no one in the corporate organization who was responsible or knowledgeable for the training and instruction of workers of the hazards involved in working on a landfill face.

Equipment

The other factor involved in this hazard analysis is the equipment that is utilized on a daily basis on the landfill face. In the instant case, there were two specific pieces of equipment working the landfill face: a steel-wheeled compactor and a bulldozer. Because of the size of the bulldozer, the driver's blind spot in a static mode could be as much as 35 feet behind the driver if indeed he were looking in that specific direction. **Figures 5, 6**, and **7** show the size of the vehicle relative to a nearby pedestrian worker.

Figure 5
Left oblique static blind zone as depicted by the standing individual, who is invisible to the operator.

In all these figures, the individual outside the bulldozer is invisible to the loader operator.

The bulldozer manufacturer indicated that visibility tests of the bulldozer are performed. However, this testing is performed in a purely static manner, using light sources to represent the operator's eyes and the shadow created by the blockages associated with the vehicle, such as door posts and mufflers to represent the blind area thereby creating a blind-area diagram (ISO 5006 2006).

In 2001, NIOSH began developing and evaluating interventions to reduce the number of ground workers being struck by road construction equipment.

NIOSH had blind-area diagrams developed for three different planes: ground level, 900 mm (36 inches) above ground, and 1,500 mm (59 inches) above ground. The blind area associated with each plane corresponds to the area at which an object on that plane cannot be seen from the operator's position. The 900-mm plane was chosen because it represents the height of a construction barrel. The 1,500 mm plane is slightly less than the shoulder height of 95 percent of the U.S. adult female population, representing the height at which enough of the head is visible for an operator to recognize a person (CDC 2011).

Figure 6
Rear view static blind zone as depicted by the standing individual who is invisible to the operator. Note exhaust stack further limiting operator's rearward visibility.

When traveling in reverse, the bulldozer manufacturer suggested that the tracked vehicle operator perform a visual scan, first to look over one shoulder then at the centrally located in-cab mirror, and then to look down and backward — all this reverse traveling visual scan to be performed while the vehicle is traveling in reverse at approximately 10 ft/sec.

Since the subject bulldozer was sold with a specially installed "landfill package," the loader manufacturer knew at the time of sale of the specific intended use of the subject bulldozer.

Requiring an equipment operator to enhance his rearward visibility by looking backward over his shoulders requires the operator to resort to the energy-consuming and physiological stressful activity of turning his/her upper body, hips, and head alternatively in both directions. This suggested rearward viewing activity recommendation will quickly decrease as the work shift increases — fatigue increases as the operator's age increases or as the driver experiences increasing stress.

In contrast to the static visibility tests, driving a construction vehicle on the landfill face is obviously a dynamic activity. Driving the vehicle rearward creates a constantly changing visual environment for the operator, with people and/or vehicles entering or leaving his field of vision. To compensate for this constantly changing visual environment, one operator's manual recommends that the operator should continuously shift his shoulders and hips from side to side while alternately switching his head

Figure 7
Left view of bulldozer, showing static blind zone of pedestrian worker, who is invisible to the loader operator in the location shown.

position from one shoulder to the other as the dozer travels in reverse. This is clearly an imposition on human physiological capabilities that can seriously compromise safety of a laborer working at ground level.

It is foreseeable that off-highway vehicles working on landfills both in the forward and reverse direction will operate in noisy environments. Furthermore, the vehicles themselves are noisy. Tracked vehicles often are particularly noisy because of track noise. Hence, a bulldozer traveling in reverse using both a fixed sound level beeper and a flashing beacon to indicate its approaching presence is foreseeably obscured to busy and otherwise occupied workers who are facing away from the vehicle.

The subject bulldozer was not equipped with rear vision closed circuit TV systems. It had been reported as early as 1998 that rear vision camera technology was available to prevent the rear traveling blind spot as well as the common right side turning blind spot hazard (Browning and Simpson 1998).

The concern of the potential visual degradation of CCTV systems used in industrial environments caused by the raised dust and debris has been addressed by the National Mine Health and Safety Academy (MHSA), which, in 1999, proposed mandatory placement of video equipment on all surface mine haulage equipment (Reilly 1999). Additionally, the hazard created by the lack of CCTV systems for use with large industrial vehicles when traveling in reverse was addressed and previously published by this author for use on large forklift trucks (Josephs 2003).

Obviously, accidents will happen, especially in a hazardous place such as a landfill. Yet there was no instruction and/or training provided to the landfill employees as to what steps to follow in the event of an accident. Additionally, there was no target medical facility identified for the landfill employees with whom they could communicate and direct any of their questions and/or direct injured employees to a nearby hospital.

Analysis

There are three interrelated factors that affect the visibility of a construction vehicle operating on a landfill face (i.e., machine/environment/worker interface). The subject bulldozer was examined post-accident, and an attempt was made to determine the blind spots and blind zones of the vehicle while seated in the fixed forward-facing operator's seat. It was immediately apparent that the internally mounted rear-view mirror was woefully inadequate for providing any reasonable visibility for driving in reverse.

Variable blind zones were noted in a static mode in each vehicle direction. Rearward visibility was especially compromised wherein in some rearward directions a worker would not be visible until located approximately 40 feet from the bulldozer. In a dynamic mode, any attempt to look over one's shoulder to gain rearward visibility would immediately cause the other shoulder (or other side) to become totally blind and obscured. This one side developed blind zone was also created when the driver/operator would attempt to look down and back at hip level. Hence, following the manufacturer's scan procedure as a stratagem to gain rearward visibility would assure that at any given instant of time, one entire side of the vehicle would be totally hidden. Other types of large industrial vehicles also share this rearward traveling visibility issue, such as in large forklift trucks (Josephs 2003).

Environment

The construction vehicle rearward visibility deficits are even more pronounced when in a dynamic state (i.e., traveling in reverse on the landfill face). Here, the dozer is traveling in reverse (not necessarily in a straight line) over constantly changing terrain with the geometry of the terrain in a constant state of flux. Hence, an area that was previously a hillock may have been compressed to a depression, and what was previously a depressed area may now have a newly dumped truckload of waste, creating a small hill. Hence, the pitch of the loader can be constantly dipping up or down, which can further reduce its rearward visibility.

Worker

The dozer rearward visibility shortcomings are further amplified by the laborers and truck drivers working or present on the landfill face. Not only is the spotter moving about the landfill space, but also the delivery truck drivers will occasionally leave their trucks to perform some work-related task, such as cleaning their truck, replacing or retying cover tarps, or other covers, etc. While performing their tasks, any individual working on or near the landfill face can have his back facing the vehicles working the landfill face. In this case study, the spotter did have his back to the rearward traveling bulldozer when he was struck. In this case, therefore, neither the backward-facing spotter nor the operator of the rearward-traveling bulldozer saw each other, resulting in the serious accident. It is imperative that in order to maintain a minimum acceptable level of safety, it is necessary to maximize a "see and be seen" rule. The "see and be seen" rule (SABS) is a safety engineering concept applied to many types of traveling vehicles. The SABS was presented and expanded upon by the author during years of teaching safety engineering. The "see and be seen" rule can be categorized as four separate components, as follows:

See and Be Seen Components		
Industrial Large Construction Vehicle Operator	**Pedestrian Worker (Spotter)**	**Relative Safety Range (4 is highest level)**
Equipment operator sees pedestrian worker	Spotter sees equipment	4
Equipment operator sees pedestrian worker	Spotter does not see equipment	3
Equipment operator does not and/or cannot see spotter	Spotter sees equipment	2
Equipment operator does not and/or cannot see spotter	Spotter does not and/or cannot see equipment	1

Each of the components of the "see and be seen" matrix can present a hazardous situation when considering the ongoing daily operations on the very busy and noisy landfill face. However, the most hazardous situation by far is that situation where neither the spotter nor the equipment operator see each other. This is that precise combination of hazardous events that led to this case study serious double amputation injury as described in this paper.

An obvious approach to enhance the "see and be seen" rule is for the worker to wear high-visibility garments. Until recently, there was a lack of definition in this regard. However, in 2009 OSHA clarified where workers are required to wear high-visibility garments in work zones wherein workers are exposed to the danger of being struck by vehicles operating in their vicinity. This construction work zone requirement is logically applicable and transferable to the landfill tip work zone.

Road and construction traffic poses an obvious and well-recognized hazard to highway/road/construction work zone employees. OSHA standards require such employees to wear high visibility garments in two specific circumstances: when they work as flagger (29 CFR 1926.201[1]) and when they are exposed to public vehicular traffic in the vicinity of excavations (29 CFR 1926.651[d]). However, other construction workers in highway/road construction work zones are also exposed to the danger of being struck by the vehicles operating near them. For such workers, the OSHA general duty clause applies (*…employment and a place of employment must be free from recognized hazards that are causing or are likely to cause death or serious physical harm to his employees…*) (OSHA 2009)

Conclusions

This case study reviews a serious double amputation injury resulting from a rearward-traveling bulldozer striking a backward-facing employee working on a landfill face as a waste spotter. Specific to this case study, it has been noted that a landfill face is a busy, noisy, hazardous work location with noisy work vehicles traveling in both the forward and reverse directions continuously. This case study outlined how each of the major contributing job activities was potentially defective and contributed to the resulting injury accident to include the following:

- Lack of a responsible individual on staff who is trained and knowledgeable in landfill safety issues.
- Defective and/or nonexistent safety procedures.
- Defective and/or nonexistent training.
- Defective and/or nonexistent worker communications guidelines.
- Defective and/or nonexistent approaches to enhance vehicle dynamic visibility.
- Defective and/or nonexistent approaches to enhance visibility of workers.
- Lack of recognition of the importance of the "see and be seen" visibility safety guidelines.

Landfill hazards and their countermeasures have long been noted and cited in the literature, and a typical succinct summary of landfill hazard countermeasures is given below.

"… it goes without saying that adopting safe procedures including the correct use of warning lights, mirrors and alarms on refuse collection vehicles together with the use of CCTV and radio communication on mechanical diggers on landfill sites which given the driver good all-round vision and the ability to communicate with those working at ground level have all had a dramatic impact upon reducing the number of accidents and injuries that occur." (Durham 2013)

The safe procedures noted above should include a properly designed hazard control program. This comprehensive hazard control program should include the following more specific elements from Legler et al (2001):

1) Survey Hazards and Employees Affected

a. List the various hazard classes to which employees are subjected in the workplace. This can be done in general terms or can be listed by equipment type;

b. List the classifications of employees, who are affected by exposures to these hazards. Distinguish between those who will actually be authorized to work with machinery or processes with which the hazard is associated, those who are affected by the actions of authorized employees, and others whose duties might bring them into contact with the hazardous area or operation.

2) Catalog Preventive Measures

a. For each hazard, machine class, process or operation, list the preventative steps that must be taken to adequately control these hazards. Reference can be made to operator manuals which contain appropriate procedures, or a step-by-step process can be outlined;

b. Specify the types of special equipment or tools that must be used during the work process;

c. Specify who is responsible for ensuring that the procedures are followed, particularly if there is responsibility for a line employee over another.

3) Compile and Organize Control Policies and Procedures

a. State company identification and general safety policy regarding the hazard;

b. Organize preventive measures according to classes of machines, processes or operations and employees to be protected;

c. Specify policies for review of program performance, training of new or transferred employees, and recurrent training of authorized employees; delineate authority for supervision, training and review.

4) Designate Authorized Employees

a. Set out training and experience levels required for an employee job description to include authorization to control equipment of operations involving identified hazards;

b. If limited authority is given to certain employees, such as drivers or machine operators, so define;

c. Organize authorizations by classes of machines or hazards.

5) Conduct Training for Authorized and Affected Employees

a. Each job classification should receive complete training prior to being assigned to equipment service duties, or duties that involve potential hazards;

b. Other classes of employees should receive training in recognition of hazards as part of general orientation;

c. Employees should be provided with or have ready access to written procedures and/or equipment operating handbooks for reference while performing their job functions.

6) Document Training

a. List names, whether authorized, affected or recognition classification, and the dates of training. If employees work on different types of equipment or operations, documentation should cover training for each major category of equipment;

When employees are transferred or promoted, training records must document that training is updated.

7) Follow-Up Evaluation of Effectiveness (Periodic Review)

a. Review accident and incident reports for evidence of injuries or dangerous occurrences involving failure of the hazard control program;

b. Supervisory review of employee performance should cover proper use of energy isolation devices, locks and tags, and understanding of *company procedures.*

8) *Continuing Modifications and Revisions*

a. *Review new types of equipment or applications introduced since the last review to determine if new hazards exist and if established procedures are appropriate;*

b. *Document that procedures are changed to reflect inadequacies discovered during the review.*

Recommendations

Typically, a single case study (such as the one described herein) being a sample of one, provides insufficient support from which guidance in the area of safety can be statistically extrapolated to the general landfill population at large. However, it is the author's belief that many of the safety issues uncovered during the analysis of this case study are potentially so fundamentally ingrained in the environment/machine/worker relationship found in landfill operations that general safety recommendations can be made, many of which can be applied to other landfills and/or other operations involving large construction and industrial vehicle operations. Furthermore, another landfill accident — this one involving a fatality on a landfill — was reported as occurring in 2002 (FACE 2015). In this fatality, it was the wheeled compactor traveling in reverse that struck a truck driver, whose back was turned toward the compactor, causing his death six days later.

The close parallels between the two accidents again support the concept that many of the fundamentally ingrained operations of landfill operations deserve and indeed require safety review and enhancement. Some of the specific recommendations listed below are adapted from FACE (2015).

Recommendation 1

Landfill owners should have in their employ a safety director and/or consultant who is responsible for the health and safety of all landfill employees. Given the nature and severity of the hazards existing on the landfill face, the safety director position should be a high level or staff position, preferably reporting to the president or CEO of the company.

Discussion

The safety director and/or consultant shall have overall responsibility of safety to include but not be limited to:

- Design and develop, implement, and enforce a comprehensive landfill health and safety program.
- Perform a hazard analysis for all employee tasks and design and implement countermeasures to these hazards.
- Design and develop a set of safety procedures which address landfill hazards, their control, and countermeasures.
- Create a traffic control plan for all landfill traffic, including that of the delivery truck drivers, that minimizes potential pedestrian-vehicle conflicts.
- Create a communication plan that provides for the means for communication between all individuals working near or on the landfill space, be they pedestrian workers, delivery truck drivers, or landfill equipment operators.
- To interface with the companies of the MSW delivery trucks to introduce them to the landfill hazard control plan and have them "buy-off" on their safety obligations as dictated on the plan.

Recommendation 2

The landfill safety and health plan should include a task description of each of the jobs that are present on the landfill. The task description should include hazard assessment, hazard countermeasures, vehicle and personnel movement analysis, and depictions of all potential landfill face traffic.

Discussion

The comprehensive landfill safety and health plan should include but not be limited to the following elements:

- Minimum time required for safety training and hazard countermeasure classroom training for each landfill task/job.
- Minimum physical training required for each landfill task/job.
- Requirement for periodic and regular formal review of safety issues germane to landfill safety.
- Organization chart depicting responsibilities and chain of command for all employees working the landfill.
- Due to its high hazard potential, an individual should be specifically trained and assigned as landfill face safety director.
- The specific responsibilities and place in the company organization chart of the landfill face safety director should be described and defined.
- A communications plan as to how the various vehicle operator and pedestrian workers on the landfill face can communicate.
- An accident emergency plan with a listing of the emergency medical health providers. Included in this

listing should be listed emergency ambulance or delivery services.

Recommendation 3

Pedestrian access must be limited to those needed to be on the face. Given the high hazard risk present on the landfill face, it is obvious that by minimizing the number and number of pedestrian workers and/or vehicular traffic would accordingly reduce the land face traffic hazards.

Discussion

Aside from the tracked and wheeled vehicles working the landfill face, there are, of course, the municipal solid waste (MSW) trucks delivering waste to the landfill site. On occasion, drivers of the MSW trucks will exit their trucks to open or close trailer doors to remove covers or to sweep out some waste stuck in the truck bed. This results in additional pedestrian workers on the landfill face, thereby increasing the hazard risk level. A number of approaches to reduce this hazard risk level would include the following:

- There should be only one waste spotter on the landfill face at any one time.
- All MSW truck drivers should open and secure the trailer door(s) prior to entering the discharge point at a working face.
- While at the landfill face discharge point, drivers should remain inside the truck cab while unloading.
- After unloading the waste, the truck should be pulled well away from the working face area to a designated, isolated cleaning or transfer area, where the truck can be cleaned and doors secured.

Recommendation 4

It is imperative that ongoing communication between the waste spotter and drivers of vehicles working the face be instituted and maintained.

Discussion

Aside from standard and agreed-upon hand signals between the face spotter and the vehicle operators, all workers and vehicle operators on the landfill face should be issued hand-held communicators (walkie-talkie) and maintain an open net with ongoing communication as to identify their location and direction and intended moves and/or actions.

Recommendation 5

All off highway construction vehicles working the landfill face must have rear-viewing closed-circuit TV (CCTV). Equipment manufacturers should be encouraged to test the effectiveness of forward and side view CCTV in conjunction with rear-viewing CCTV in reducing pedestrian injury in those equipment applications where pedestrians are required to regularly work in close proximity to construction equipment with blind zones.

Discussion

The size of the vehicles working the landfill face dictates that these vehicles (both wheeled and tracked) will have large areas or zones that are blind to the operator, even in a static mode. These blind zones are further exacerbated when considering the forward and reverse motion of the vehicles; the effects of the landfill face changing terrain; and the effects of a developing blind zone of a moving vehicle. Hence, readily available CCTV cameras should be mounted on the landfill face working vehicles to monitor blind zones at the rear of the vehicle.

Recommendation 6

Policies should be crafted and implemented by landfill management that require all landfill employees, visitors, and MSW truck drivers during delivery at the landfill site to wear high-visibility safety vests.

Discussion

Landfill management should require that all employees, visitors, and the MSW truck drivers during delivery on the landfill face wear high-visibility safety vests if it is absolutely necessary for them either to be present as a pedestrian or to exit their vehicles. Obviously, such a move would enhance worker visibility relative to the muted earth tone colors of standard work clothes.

For initial guidance in the proper choice of high-visibility work gear, ANSI/ISEA 107-2010 should be reviewed. Both OSHA and the U.S. Federal Highway Administration recognize the American National Standards Institute (ANSI) International Safety Equipment Association (ANSI/ISEA 107) standard as the industry consensus standard for the performance requirements of high visibility work gear. However, it cannot be overemphasized that ANSI standards are minimum consensus industrial standards. As such, they should be considered only as a starting point for determining guidelines for any specific safety evaluation and/or directives. Additionally, and more importantly, the waste spotter or any other pedestrian worker on the landfill face should wear a lighted safety vest, which are readily available, at all times when on the landfill face. Also, the waste spotter or any other pedestrian worker on the landfill space should wear a hard hat with a blinking light affixed. Such blinking lights are readily available and typically used by bicycle riders to enhance their visible presence.

Recommendation 7

The landfill safety director should work with his regular MSW trucking company to develop and implement a common safety protocol and program.

Discussion

The landfill safety director should work and coordinate the landfill safety program with each of the landfill MSW trucking companies. The coordinated safety program should be formally accepted by each of the landfill regular trucking customers. This comprehensive safety and health program should be designed, developed, formally accepted, and enforced to minimize potential landfill hazards. The program should detail the approaches and methodology to train the MSW drivers to recognize and avoid hazardous work conditions and environments in a landfill. The truck drivers should be instructed by this document to identify hazardous situations and the chain of command on the landfill face. Standard landfill unloading and egress procedures should be defined and followed.

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