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Table of Contents

† **Gas Well Integrity and Associated Gas Migration Investigations in the Marcellus Shale** 1
By J. Daniel Arthur, PE (NAFE 908M)

* **Effects of Evidence Spoliation on Forensic Engineering Analysis of Alleged Brake Servicing Defects** 13
By John Leffler, PE (NAFE 709S)

† **Forensic Engineering Analysis: Biomechanics is an Engineering Discipline** 23
By William E. Lee III, PhD, PE (NAFE 655S)

‡ **Forensic Engineering Tools and Analysis of Heavy Vehicle Event Data Recorders (HVEDRs)** 33
By Jerry S. Ogden, PhD, PE (NAFE 561F) and Mathew Martonovich, PE (NAFE 968M)

‡ **The Impact of the Lack of Marine and Rail Standards on the Transportation of Large Power Transformers** 51
By David Gillingham, P. Eng. (NAFE 935A)

‡ **Forensic Engineering Analysis of Fuel Usage and Thermostat Settings** 63
By John Certuse, PE (NAFE 708F)

‡ **Forensic Engineering Analyses of a Home Fire** 75
By R. Vasu Vasudevan, PE (NAFE 619F) and Jeremy Britton, PE (NAFE 943M)

† **Biomedical Engineering Physical Evidence-Based Analytical Methods** 89
By Laura L. Liptai, PhD (NAFE 339A)

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Gas Well Integrity and Associated Gas Migration Investigations in the Marcellus Shale

By J. Daniel Arthur, PE (NAFE 908M)

Abstract

The Marcellus Shale is one of the largest natural gas fields in the world and has been the site of a massive natural gas development effort involving hundreds of oil and gas companies. With the onslaught of the "shale revolution," developers moved into states like Pennsylvania and began drilling/completing natural gas wells by the hundreds. This development occurred so rapidly that attention to issues such as wellbore natural gas intrusion was not initially given the priority it demanded in all cases. This led to instances of alleged natural gas migration and impacts to groundwater supplies in several areas of the region. Although there has been an onslaught of evaluations geared toward the study of groundwater contamination, the author has researched the natural gas wells themselves. Based on thousands of wellbore integrity studies in the Marcellus and other worldwide shale regions, this paper will summarize the forensic processes, analysis methods, and approaches used in assessing wellbore integrity as part of a natural gas migration investigation. The paper will also present details that pertain to remedial alternatives and approaches to wells requiring attention.

Keywords

Natural gas migration, wellbore natural gas intrusion, well integrity, annular pressure, shut-in pressure test, venting rate test, temperature/audio log, remedial cement squeeze

Introduction

Oil and natural gas development in the Appalachian Basin area began in 1859 with the discovery of oil in the Drake Well in Titusville, PA (Owen and Dott 1975). The Marcellus Shale is a Middle Devonian-age black shale that occurs at depths ranging between 4,000 and 8,500 feet in portions of Maryland, New York, Ohio, Pennsylvania, and West Virginia (Grant 2010). Initial unconventional development of the Marcellus Shale began in 2004 with Range Resources drilling and completing the first Marcellus horizontal well in Washington County, PA (Ventura 2013). Since 2008, Pennsylvania's natural gas production from the Marcellus Shale has increased exponentially as a result of the utilization of the unconventional drilling and completion techniques developed within the Barnett Shale in Texas (PA DEP 2013). With the advancement of this drilling and completion technology, the new shale plays (like the Marcellus) are now able to be commercially developed.

Consequently, with the rapid influx of new development of the Marcellus came an increase in alleged incidents of gas migration and groundwater contamination. State regulatory agencies and the oil and gas industry have continued to work together to address defective cementing and well integrity issues through aggressive remedial or other alternative actions to ensure regulatory compliance. Through involvement in these efforts and the completion of thousands of wellbore integrity studies, the author has developed a comprehensive methodology and forensic process for the assessment of well integrity relating to alleged gas migration incidents. The process is based on a holistic approach that does not rely on any single assessment tool but evaluates the overall well integrity through a litany of tests, methods, and analytical reviews. This holistic approach has been designed to facilitate the determination of well integrity and potential relationship with alleged gas migration incidents.

Initial Stray Natural Gas Migration Incidents

Historically, there have been stray natural gas migration incidents associated with oil and gas development in the Appalachian Basin, but neither documentation of such incidents nor regulatory authority to address them was in place until the mid-1980s — when the rise in oil and natural gas prices spurred conventional oil and gas development in the Appalachian Basin area. Perhaps the first widely publicized stray natural gas

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migration incident in the Appalachian Basin occurred in December of 2007 when an explosion occurred in a home in Bainbridge Township of Geauga County, Ohio (ODNR 2008). This incident was a result of an annular overpressurization issue associated with a conventional oil and natural gas well, which led to natural gas migration into the aquifers and a number of water wells in the area (Tomastik and Bair 2010). In the ensuing weeks after the incident, 26 residential water wells were disconnected, temporary water supplies were installed, and, by 2010, all of these residences were connected to a public water line (Bair et al. 2010).

Complaints and allegations of environmental impacts coincided with the early development of the Marcellus Shale and are still the subject of discussion, compliance actions, and litigation. Between 1987 and 2011, the Pennsylvania Department of Environmental Protection (PA DEP) investigated 119 stray natural gas incidents related to oil and gas activities, of which 16 were alleged to be related to Marcellus Shale wells, with the first alleged Marcellus Shale incident occurring in 2008 (Moody 2011). Perhaps the most widely publicized alleged stray natural gas migration incident in the United States occurred in 2009 in Dimock, PA. The documentary *Gasland*, which premiered on HBO on June 21, 2010, begins and ends in Dimock, a rural area of Susquehanna County where supposedly several dozen residential homes were impacted by stray natural gas migration into domestic water wells (Gilliland 2010). *Gasland*, which also alleges stray natural gas migration associated with unconventional shale development in Colorado, Texas, Utah, and Wyoming, drew national and worldwide attention to hydraulic fracturing, or "fracking," and unconventional shale development.

Regulatory and Industry Development to Address Stray Gas Migration

After the initial boom in Marcellus Shale development in Pennsylvania — and the alleged stray natural gas migration cases associated with this development — the oil and gas industry adapted by updating its well construction and cementing practices. Designing a well drilling plan and a casing/cementing program requires an understanding of the local geology in order to prepare proper well construction and well control measures for expected subsurface conditions. However, it can be difficult to develop a thorough understanding of the local geology in a new location where there may be few historical wells or where no wells have been drilled (GWPC and ALL 2009). Such was the case in northeastern Pennsylvania where a limited number of oil and gas wells had been drilled prior to the development of the Marcellus Shale in that area (Zampogna et al. 2012). Therefore, a conservative well design that includes multiple casing strings and cementing plans with proper cement type, additives, and placement to ensure isolation of formation gases and fluids is warranted (**Figure 1**).

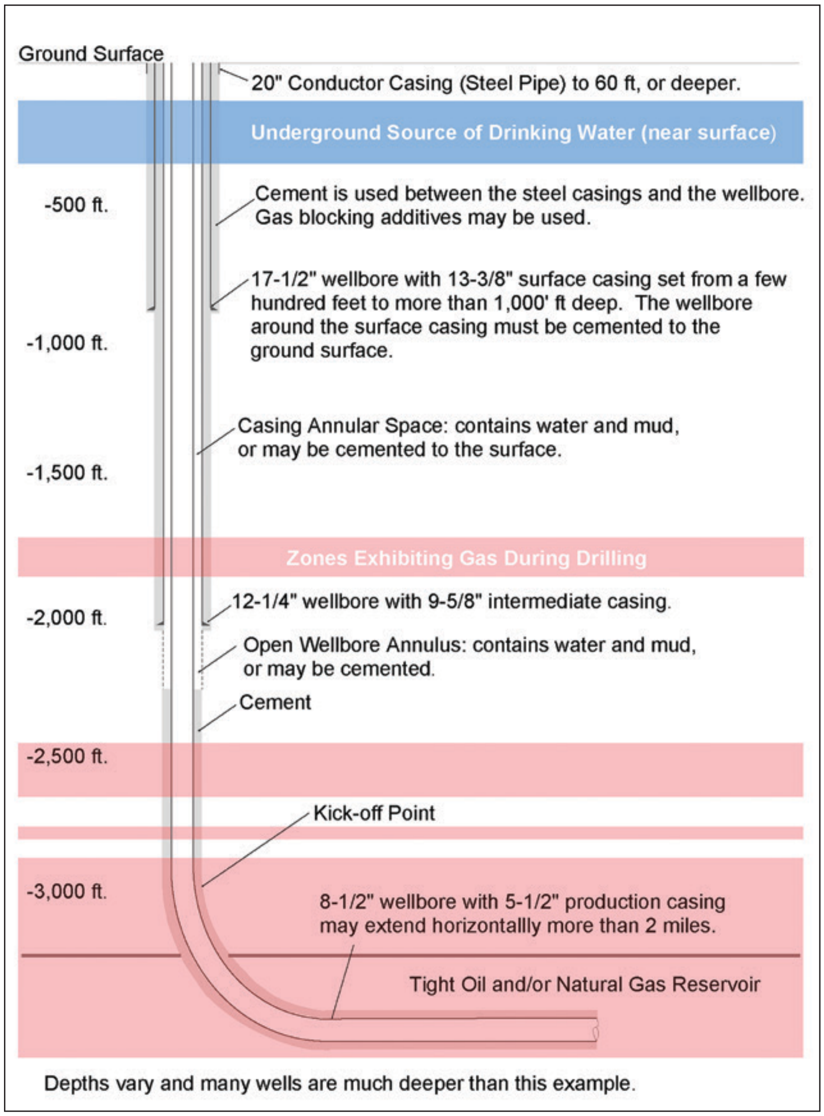

Figure 1
Sample well construction diagram.

Assessment of Well Integrity for Gas Migration Investigations

A critical component of any natural gas migration investigation is the evaluation and assessment of well integrity at adjacent oil and natural gas wells. For this paper, well integrity can simply be defined as a lack of significant leakage within the well and wellbore. Both internal integrity (e.g., casing, tubing, packers, etc.) and external integrity (e.g., cement, mud, annular fluids, etc.) must be considered and evaluated to identify potential concerns relating to the gas migration investigation that may require remedial measures.

Well integrity evaluation is based on a variety of industry standard tests and logs that have been refined for the holistic approach presented in this paper. Based on more than a thousand wellbore integrity studies, this holistic approach has been designed to facilitate the determination of well integrity and potential relationship with alleged gas migration incidents. The holistic approach does not rely on any single tool, but evaluates overall well integrity using an assortment of tests. While any one test may indicate a potential concern, the compilation of tests in the evaluation approach is intended to refine and identify evidence that the oil or gas well may be a potential source of the alleged gas migration incident. The holistic well integrity assessment process includes the following:

- Timeline analysis,
- Well casing and cementing review,
- Well logging,
- Well integrity testing,
- Geologic and gas migration pathway review, and
- Additional considerations for gas migration investigations.

Again, no single finding alone is sufficient; rather, when evaluation methods are used in concert, a proper assessment of well integrity can be made. The holistic approach and forensic processes used to assess well integrity are discussed in the following sections.

A. Timeline analysis

The initial evaluation for each well includes a review of the operator's daily drilling and well activity logs to determine where the oil or gas well was in the development process, and what, if any, activity was ongoing at the well at the time of the alleged gas migration incident. Completion of a timeline analysis is a critical step in the evaluation process to identify and evaluate potential correlations between the timing of the alleged gas migration incident and activity at the oil or gas well (e.g., drilling, completion, workover, etc.).

B. Well casing and cementing review

Review of the operators' drilling and well completion activities, including well casing and cementing records, is vital for assessing well integrity and related wellbore gas intrusion (Arthur et al. 2012). Records provided by the operator include:

- Cementing details, including: cement slurry design, fluid density, cement additives, cement volume, etc.,
- Cement bond logs used to evaluate bonding to the casing and to the formation, and
- Formation integrity test (FIT) results and leak-off test (LOT) results, if available.

C. Well logging

Cement evaluation logs are reviewed as part of the holistic well evaluation process. These logs (e.g., cement bond logs, radial cement bond logs, segmented bond log, Ultrasonic Imager tool, etc.) are utilized to locate cemented sections in the wellbore and to evaluate the quality of the cement bonding in those zones (Bigelow 1985). Temperature and audio logs are invaluable tools in assessing wellbore methane intrusion and can be utilized to identify and characterize gas flow occurring in the wellbore.

D. Well integrity testing

Multiple internal and external well integrity testing methods, including visual inspections, infrared camera videography, methane monitoring, shut-in pressure tests, annular vent rate tests, production casing build-up/leak-off tests, pressure differential tests, and pressure trend analysis, are available to assist in the assessment of well integrity.

E. Geologic and gas migration pathway review

In any stray natural gas investigation, all potential sources of stray gas must be identified and evaluated. Initially, a thorough geologic review and evaluation of potential gas sources and migration pathways are undertaken in the gas migration investigation. If available, all open-hole geophysical logs and mud logs are evaluated with particular attention paid to the occurrence of gas shows above the intended production zone. The identification of shallow gas-bearing zones is integral to evaluating wellbore methane intrusion. Gas migrates along pressure gradients from areas of high to low pressure. Gas may move up or down an elevation gradient and can travel for long distances (up to miles away) from the source. Potential gas sources and pathways include, but are not limited to, the following:

- Shallow gas-bearing zones
- Coal seams and underground coal mines
- Legacy oil and gas wells
- Natural occurrence of gas in aquifers

F. Additional considerations for gas migration investigations

As noted, other investigations are conducted in addition to the well integrity tests performed on the oil and gas wells themselves. These other tests include sampling water wells for laboratory analyses of the presence of hydrocarbons and other geochemical parameters (including isotopic analysis). Although these other investigations are separate from the well integrity assessment, their findings can help refine the assessment of well integrity by potentially identifying or excluding potential sources of natural gas.

Advanced Well Integrity Methodology

In cases where the potential for natural gas migration or loss of well integrity are suspected, a variety of assessments are performed to characterize downhole conditions within a wellbore. These assessments include a number of tests that are critical components of the gas migration investigation and provide data to determine regulatory compliance, evaluate wellbore natural gas intrusion, and determine the efficacy of remedial efforts. Generally, these tests are repeated during the well evaluation and remediation efforts in order to establish trends and demonstrate progress.

A. Shut-in pressure build-up testing

Shut-in pressure tests are used to quantify and characterize pressure build-up rates in the annular spaces being tested. Annular pressures can be attributed to a variety of causes, including well component leaks, thermal flux upon initiation of production, shallow hydrocarbon-producing formations, and other shallow overpressure formations (API 2006). A shut-in pressure test consists of closing the valve on the annulus being tested and allowing the annular pressure to build over the duration of the test. The data recorded during the test allows for construction of a curve, which provides a graphical representation of the pressure over time. The results can then be interpreted to assess the nature of the pressure within the annulus.

1. Instrument selection

The selection of transducers with appropriate sensitivity ranges is important to ensure accuracy. To prevent damaging the transducers, the instruments must be capable of tolerating the annular pressure observed during periodic monitoring. However, the instruments should not have an upper range that far exceeds the observed annular pressure. Otherwise, accuracy may be compromised.

2. Shut-in pressure build-up analysis

Plotting multiple shut-in pressure build-up test curves from an individual annular space on a single chart allows for trend analysis to evaluate changes over time. Characteristic shut-in pressure build-up curves have been observed during the evaluation of thousands of tests. Continuous monitoring of pressure data and identification of build-up curve signatures has allowed for a more robust analysis of annular pressure (**Figure 2**).

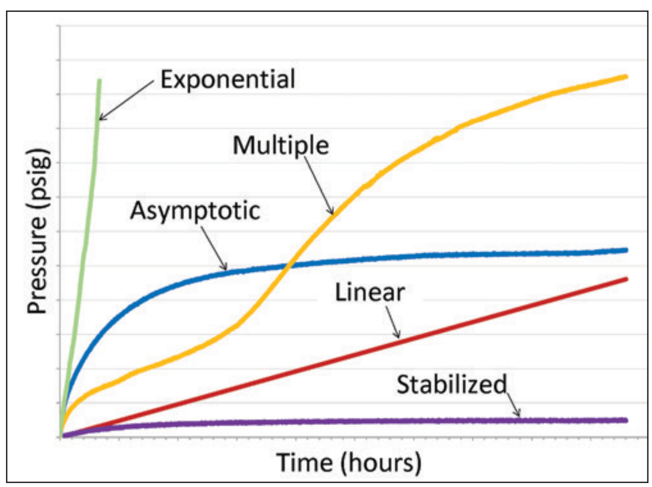

Figure 2
Signature shut-in pressure build-up curves.

While conducting shut-in pressure tests, testing errors and anomalies are sometimes encountered. Such errors can include transducer and data logger malfunctions, improperly functioning or clogged well setups, or changes in pressure due to environmental factors such as barometric pressure, surface temperatures, and internal wellbore pressures based on the fluid level in the well.

Similar to the pressure build-up signatures that have been identified, a series of signatures that identifies specific errors and anomalies based on their build-up curves has been defined by the author (**Figure 3**).

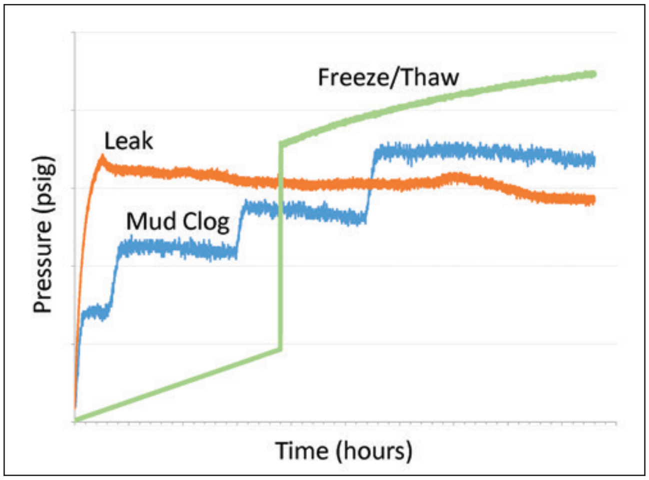

Figure 3
Signature curves of erroneous data.

The identification of these signature curves is instrumental when characterizing a well's annular pressure and confirming the quality of test results.

3. Evaluation of pressure trends

The evaluation of trends requires the repeated performance of tests over time. Shut-in pressure build-up curves can be plotted using several methods, including chronological (with a trend line or a timeline) and elapsed time. When plotting shut-in pressure build-up curves in chronological format, the x-axis is in chronological order (date and time of day). Typically, the chronological plot uses end of test data (e.g., the pressure after 72 hours from several tests). For comparative analysis, it is critical that pressures used are collected at a consistent interval (e.g., 24 hours, 48 hours, etc.). When plotting shut-in pressure build-up curves in elapsed-time format, the x-axis is in elapsed time and includes all data points from each test.

B. Vent rate testing

Vent rate tests are performed to quantify the volume of natural gas that may be present in the casing or annulus of a well. In conjunction with shut-in pressure build-up tests, they help to identify and characterize wellbore methane gas intrusion and are a key component in the assessment of well integrity.

1. Instrument selection

The orifice well tester and the critical flow prover are considered to be "primary elements" of the test assembly, and they require a method of measuring pressure on the upstream side of the flow line — the "secondary element." Due to the generally low pressures encountered at casing vents, testing is conducted using a U-tube manometer, with vent line pressure at one end and atmospheric pressure at the other. If a flow rate is less than the reportable limit for the instrument being used, qualitative testing using either a balloon test or bubble test may be conducted.

The balloon test consists of allowing a small balloon (4 to 6 inches) to inflate for 10 minutes or until the balloon is fully upright. Photographic documentation of the balloon, such as that shown in **Figure 4,** is taken at the completion of the 10-minute interval or when the balloon is determined to be inflated to an upright position. If the balloon is upright before the end of the 10 minutes, the test duration is recorded, and the condition of the balloon (minimal inflation, partial inflation, or upright inflation) is logged with the photographic documentation.

Figure 4
Photographs of different balloon test results (e.g., minimal inflation, partial inflation and upright inflation).

2. Vent rate analysis

Vent rate test results are analyzed in conjunction with other tests, specifically shut-in pressure build-up tests, to help identify and characterize wellbore natural gas intrusion. The test provides a measurement of the volume of gas that may be present in the annular spaces. Volumetric analysis of venting rates can be used to evaluate the connection between a well and the alleged natural gas migration incident.

3. Bubbling cellar assessment

Wells may exhibit "bubbling cellars" when rising gas reaches standing water in the cellar of the wellhead. Observation and measurement of the size and frequency of the bubbles may be used to estimate the relative volume of natural gas emanating from the well.

It is also useful to remove the standing water from the well cellars to screen the well using an infrared camera. Infrared video may be used to demonstrate conditions at the well to regulators. When used properly, infrared video can show whether gas is streaming at a high rate or wafting at a low rate (**Figure 5**).

C. Temperature and audio logs

Temperature and Audio (T/A) geophysical logs can be used to identify and characterize flow within a wellbore, guide remedial corrective action (if needed), and evaluate the effectiveness of the remedial corrective action after they have been completed. A discussion of individual log types is provided below with details on how the logs can be used to support the well integrity evaluation effort.

1. Audio logging

By utilizing audio logs during the well evaluation, operators can determine when flow is occurring, where the flow is originating, and where the flow is terminated. For example, if flow has been identified by increased amplitude over ambient noise originating at depths above the top of production casing cement and continuing to surface, it can be deduced that natural gas is entering the wellbore, traveling upward through the annular space and venting at the surface (**Figure 6**).

An example of greater concern would be flow identified by increased amplitude over ambient noise at depth, continuing upward, and dissipating at some depth below the base of the next outer casing string (**Figure 7**). This scenario potentially suggests that natural gas flow is entering the wellbore and exiting at some other depth. Corrective actions should generally be pursued in this scenario.

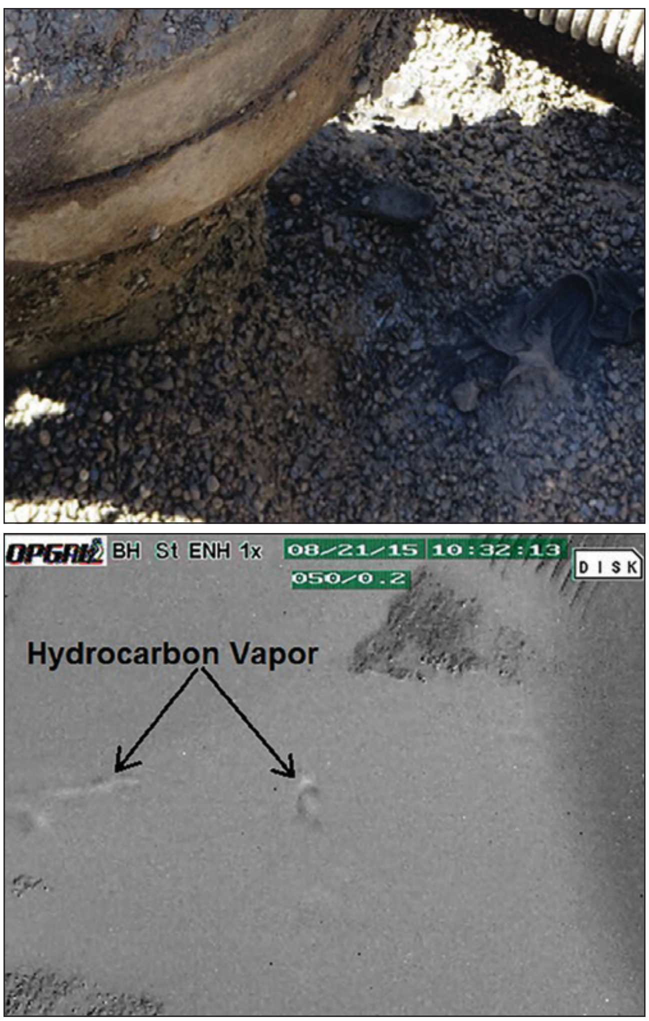

Figure 5
Photographs of a cellar in visible light (top) and in infrared (bottom).

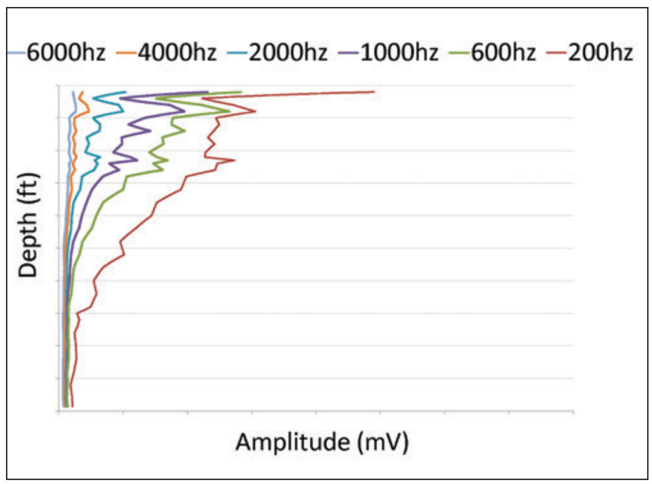

Figure 6
Sample audio log indicating venting at the surface.

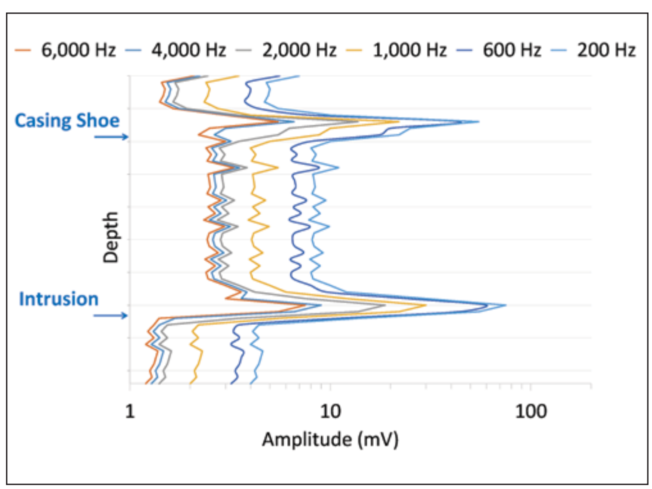

Figure 7
Example audio log indicating intrusion and shallow migration.

2. Temperature logging

The intent of conducting temperature logging is to identify depths at which deviations from the geothermal gradient occur, as deviations may indicate natural gas or fluid movement within the wellbore. These deviations are typically small, with some as little as 1°F. It should be noted that changes in the temperature gradient may also be unrelated to fluid or gas entering the wellbore. Natural variations in the static geothermal gradient may relate to lithologic changes. Geothermal gradient changes associated with lithology can be seen when logging above the Marcellus Shale. These formations consist of alternating beds of shales and sandstones with varying water retention capacities that can influence thermal conductivity. Changes in stratigraphy must be considered as an additional influence on temperature gradients and thus must be accounted for when interpreting temperature logs.

3. Quality control

The standardized logging procedures described below provide the most accurate well integrity analysis. A two-pass logging procedure, with quality control efforts, ensures the wells are prepared to be logged. It is important to ensure that noise from within the production casing is eliminated so that the analysis of the other annuli is optimized. The described T/A logging procedures establish a uniform testing protocol and a comprehensive reporting process. This process includes preparing the well, making sure the temperature passes are performed first, ensuring that the audio logs are properly reviewed for quality control and quality assurances, and analyzing any noise anomalies with greater detail. Quality assurance improvements that are implemented throughout the well evaluation process include the following:

- **Well preparation**: Prior to completing a T/A log, the well must be properly prepared in order to ensure quality of logging results. The tubing must be removed, the wellbore must be 100% filled with fluid, and the well should be allowed to stabilize for a minimum of 12 to 24 hours. The temperature log is always performed on the down-pass to ensure the logging activity has no influence on the wellbore temperature. After the temperature log is completed, fluid level is noted, and, if necessary, freshwater is added prior to completing the audio log on the up-pass.

- **Well configuration**: When running T/A logs for well integrity analysis, it is beneficial to run duplicate logs. The first pass should be done with the production casing closed and casing annuli open. The second pass should be done with the production casing open and casing annuli closed. This opposing well configuration can be used to further evaluate whether or not flow, if identified, was exiting the wellbore. The second log should be completed after allowing the well to re-stabilize and generally occurs the following day.

- **Logging practices**: Standardized logging practices ensure consistent results. The temperature log should be completed on the down-pass with a consistent speed of approximately 30 feet per minute. The audio log should be completed on the up-pass, stopping at stationary intervals approximately every 250 feet, allowing the noise to stabilize for a minute, and recording the ambient noise. Additional stationary intervals should be completed above, adjacent to, and below the intermediate casing shoe, perforations, and any anomalies identified on the temperature log.

D. Cement evaluation logs

Cement evaluation is a vital step in the assessment of well integrity for gas migration investigations. In conjunction with a review of casing and cementing details, the completion and analysis of cement evaluation logs provide insight into the presence of cement behind the casing and the level of cement bond to the casing and formation (Bigelow 1985) as well as cement integrity conditions (e.g., micro-annulus, channeling, compromised cement, etc.) (Schlumberger 1989). A variety of cement evaluation logs are available to assist with the assessment of casing and cement integrity. Select examples of cement evaluation logs are provided below.

- Cement bond log (CBL)
- Radial cement bond log (RCBL)
- Segmented bond tool (SBT)
- USI Ultrasonic Imager Tool (USIT)

Well Integrity Remediation Methods and Alternatives

If remedial action is indicated by cased-hole geophysical logging, well integrity testing, and holistic assessment, remedial action options exist. The development of these remedial methods is based on extensive research and actual field application using various procedures and products. Each remedial option has distinct advantages as well as challenges and concerns. All options should be fully evaluated when selecting the appropriate remedial method.

A. Casing perforation and squeeze remediation

A commonly utilized remedial method involves perforating the well casing and squeezing cement through the casing into the wellbore annulus. Perforations and squeeze intervals are selected based on the findings from the holistic well evaluations performed on the well. Specifically, understanding and accurately interpreting cement evaluation log(s) and T/A logs are critical for a cement squeeze to be successful. In some wells, multiple perforation intervals may be required to address wellbore natural gas intrusion adequately. When multiple perforation intervals are anticipated, the deeper intervals are squeezed first to address the potential of shallow flow being reduced by sealing off deeper natural gas flow. This methodology will also limit the occurrence of unnecessary perforations above the expected squeeze interval.

B. Alternatives to remedial methods

Alternatives to perforating and squeezing are available and should be considered when evaluating remedial options. Perforating and squeezing may not be necessary if wellbore natural gas intrusion can be controlled at the surface. Remedial alternatives can include continuous, long-term pressure monitoring, plumbing casing strings to sales lines of the production operation, and/or connecting the casing strings with annular pressure issues to a high-pressure separator with a pressure relief valve for controlled venting and blow down. Additionally, internal well integrity concerns (e.g., casing leaks) can often be controlled through the use of packers to isolate the leak and a fluid-filled tubing annulus to prevent migration of natural gas through the leak.

Sample Case History

In response to Pennsylvania landowner complaints about deleterious changes in water quality, a well integrity evaluation (following the holistic approach presented in this paper) was performed on a nearby gas well. Well integrity analysis began with preparation of the well timeline using available well records and test data. Records indicated that the construction, drilling, and completion of the subject natural gas well preceded the methane and turbidity reported in the subject water supply wells by 17 to 25 months. The subject water supply wells were within one mile of the natural gas well. Review of casing and cementing records along with analysis of cement evaluation logs for the subject gas well indicated evidence of poor cement bonding and/or a lack of apparent cement in the wellbore (behind the production casing) in excess of 1,000 feet below the intermediate casing shoe. Additionally, there was evidence of micro annuli behind the production casing, deeper in the well. Well integrity testing of the subject gas well included T/A logging, shut-in pressure build-up testing, and vent-rate flow testing. Review of integrity tests results revealed the following:

- Initial T/A logging indicated the entry of natural gas into the annular space behind the production casing.
- Shut-in annular pressure behind the production casing of the subject gas well built-up to more than 600 pounds per square inch gauge (psig).
- Vent-rate flow tests completed on the annular space outside the production casing indicated flows on the order of 0.166 to 0.335 thousand cubic feet per day (Mcf/day).
- Eighty gas vapor and dissolved gas samples were analyzed for molecular and geochemical (including isotopic) composition. Water samples were also collected from the drinking water wells for geochemical analysis. Fifty of the gas and isotopic samples were collected from three private water supplies, and 30 of the gas and isotopic samples were collected from gas wells. Analysis included cation-anion balance (CAB), water type (trilinear analysis) and reduction-oxidation potential (redox), in order to estimate the effect of microbial populations on the groundwater as well as the dissolved methane. This geochemical analysis provides an indicator whether the gas is being recharged in the aquifer from its source.

Based on the results of mechanical integrity tests, the subject gas well was selected for remedial action to reduce the flow of natural gas in the wellbore outside of the production casing. Remedial efforts included the perforation of the 5½-inch production casing and remedial cementing behind the production casing.

Post-remediation T/A logging of the subject gas well indicated that the remedial actions reduced natural gas migration in the annular space behind the production casing. Post-remediation shut-in pressure build-up testing indicated a 60% reduction in shut-in pressures as well as a declining trend in pressures. This decline indicates that the source is reduced, and the gas is depleting. Further, the shut-in pressure build-up curves indicated that with successive periods of controlled venting, shut-in build-up pressures will continue to decrease. Over successive months, shut-in build-up pressures were further reduced by 75%. These results suggest that natural gas that remained in proximity to the subject natural gas well was above the Marcellus and may have been artifact pressures on a depleting trend (**Figure 8**).

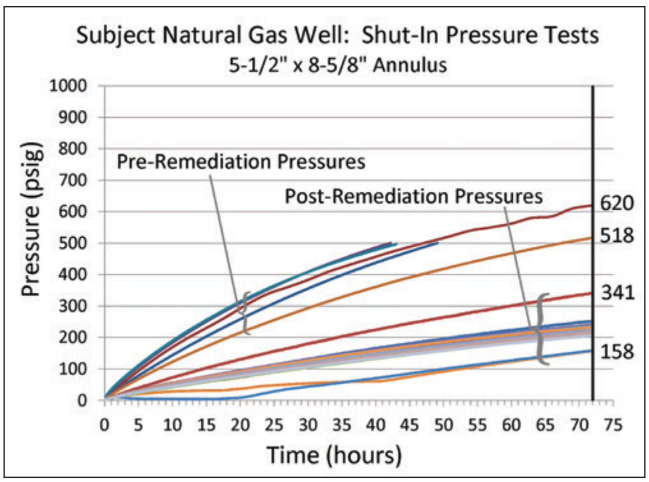

Figure 8

Graph of decreasing shut-in pressures after remediation.

Changes in the isotopic composition of dissolved methane in the water supply wells indicated increasing oxidation, suggesting the source of methane in the residential water well had been eliminated. The results of the well integrity analysis of the subject gas well indicate the following:

- Natural gas found in the subject water supply wells was similar in composition to the natural gas found at the subject natural gas well.

- Three neighboring gas wells did not appear to contribute natural gas to the subject water supply wells.

- The concentrations of dissolved methane gas at the subject water supply wells appeared to be depleting.

- Changes in isotopic composition of methane at the water supply wells indicated that the dissolved methane in the groundwater was not being replenished.

- Natural gas in the wellbore of the subject gas well, above the production zone, appears to be depleting.

Remedial actions performed at the subject gas well appeared to have reduced gas migration. The results of numerous well integrity tests indicated that natural gas in the wellbore of the subject gas well, above the production zone, was depleting — and the occurrence of natural gas in the subject water wells was decreasing. No further remedial action was recommended for this well.

Conclusion

With the rapid development of the Marcellus Shale, an increase in alleged natural gas migration incidents has been observed in several areas of the region. Although studies of groundwater contamination relating to the alleged incidents have been well documented, studies of the oil and natural gas wells themselves have not. As presented herein, the assessment of well integrity for natural gas migration investigations requires a holistic approach and a detailed evaluation process. The presented well evaluation process has been developed and refined through the completion of more than a thousand wellbore integrity studies. A multitude of well integrity tests and evaluation methods are available, each with unique challenges. While any one test may indicate a potential concern, no single finding alone is sufficient; rather, when evaluation methods are used in concert, a proper assessment of well integrity can be made. Additionally, when completed properly, an assessment of well integrity will help identify potential concerns relating to the natural gas migration investigation that may require remedial measures.

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Effects of Evidence Spoliation on Forensic Engineering Analysis of Alleged Brake Servicing Defects

By John Leffler, PE (NAFE 709S)

Abstract

A forensic case involved an allegation of defective minivan brake repairs. On a wet two-lane road, the minivan left the road while stopping, and impacted a telephone pole. The plaintiff driver's complaints implied a dragging brake, and the plaintiff's expert reported a bent lower caliper bolt. This forensic investigation involved instrumented exemplar analysis of the effects on caliper drag that could be caused by a bent caliper bolt. The investigation methodology was chosen (in part) based on significant evidence spoliation on the part of the plaintiff's expert. This paper will also discuss the effects of the spoliation and resulting limitations on the scope of the analysis.

Keywords

Brake, caliper, spoliation, forensic engineering

Introduction

In November of 2008, the plaintiff was driving a "loaner" pre-owned 1999 Plymouth Voyager minivan provided by a vehicle reseller while the plaintiff's car was being serviced. On the second day of the plaintiff's use of the minivan, the plaintiff was driving in rainy daylight on a straight two-lane road with a posted 45-mph speed limit. When approaching a vehicle waiting to turn left into a driveway, the minivan left the road — the plaintiff recalled only that she applied the brakes when approaching the stopped car. The minivan went onto the right shoulder and across a residential lawn, rotating about 80 degrees clockwise about a vertical axis, eventually stopping when the driver's door impacted a telephone pole. The plaintiff and a passenger were injured (**Figure 1**).

Figure 1
Impact damage to minivan.

The plaintiff stated in her deposition that upon receiving the "loaner" minivan from the dealership, she noticed that brake application caused the vehicle to pull to the right at speeds under 35 mph. She testified that she brought the condition to the attention of the reseller and that the service manager told her the minivan had recently had brake work done — and that the problem would go away with use. The plaintiff testified that she left the dealership and continued to experience pulling to the right (to varying degrees) upon brake application, though the vehicle tracked straight otherwise. She also reported that the brake pedal went close to the floor during operation.

Discovery documents revealed that the minivan indeed had new front discs and front pads installed just prior to the plaintiff's use of the vehicle. The service manager had no recollection of being alerted to the pulling condition by the plaintiff.

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The dealership's insurance company hired an expert to inspect the vehicle prior to receiving notice of pending litigation. That expert inspected in January 2009 and reported no causative problems. During this inspection, the wheels and rear brake drums were removed. According to this expert's report, due to vehicle damage, the brake pedal was not operated. The wheels and drums were replaced following the inspection.

The plaintiff hired an expert to inspect the vehicle, and he conducted inspections in August and September of 2011. According to his deposition testimony, in his first inspection, he did not find any notable issues with the brakes. He was also able to depress the brake pedal and found that the vehicle had "full pedal," which typically means that the brake pedal was not noticeably soft nor would the pedal slowly sink under sustained foot pressure. The plaintiff's expert's testimony went on to say that he was instructed (by his retaining attorney) to do another inspection and disassemble components in order to try and find problems. His second inspection was conducted alone, without participation by (or notice to) other potentially involved parties. During this second inspection, he removed the front brake calipers, disconnected the hydraulic brake hoses to the calipers, and took custody of these parts. During the removal of the right front caliper, the plaintiff's expert reported discovering that the passenger's side (right) lower front brake caliper bolt was bent.

The plaintiff's expert alleged that the incident was due to this bent lower caliper bolt causing brake pulling upon application. The subject minivan utilized single-piston sliding front brake calipers that have two bolts (**Figure 2**). In such designs, the caliper piston is inboard and (when actuated) presses the inboard brake pad against the disc. This piston force simultaneously causes the caliper to slide axially along lubricated cylindrical "slider" bushings (**Figure 3**), in turn causing the outboard features of the caliper to pull the outboard brake pad against the disc. The upper and lower caliper bolts locate and retain these lubricated cylindrical bushings. Over time, improperly maintained sliding caliper assemblies may bind or drag if the caliper itself cannot slide freely on the lubricated cylindrical bushings. Additionally, since the piston's force application is offset from the cylindrical bushing axes, a bending load is imparted to the cylindrical bushing/caliper interface. The bushings often (including on this minivan) have a rubber "bellows" type boot around them to reduce the ingress of contaminants into the bushing grease. It can be seen from **Figures 2** and **3** that if one of the caliper bolts were significantly bent, it could causing binding or dragging of the caliper in use.

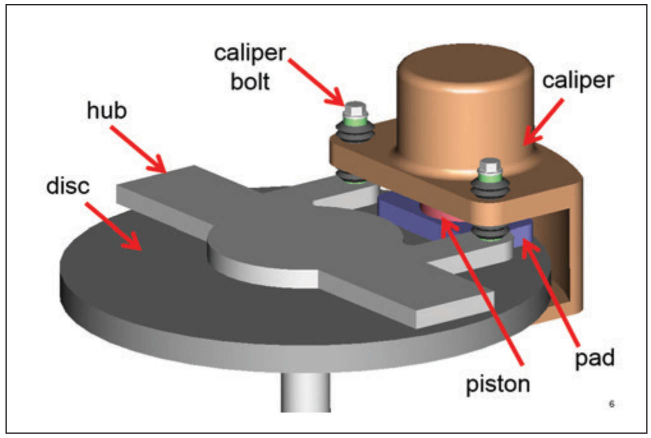

Figure 2
Simplified representation of sliding brake caliper.

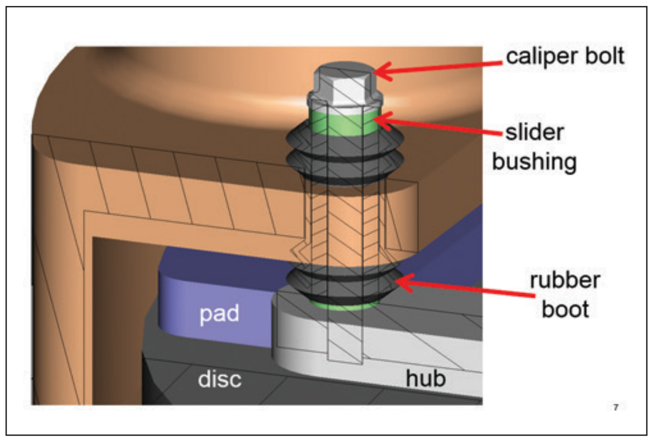

Figure 3
Close-up of caliper bolt area.

The plaintiff's expert alleged that the lower caliper bolt had been bent by the vehicle dealership when it was replacing the front brake discs and pads. This was based on his experimenting with an exemplar steering knuckle, brake disc and caliper wherein after removing one of the two caliper bolts the caliper could be rotated (about the other bolt) sufficiently "out of the way" to replace the brake disc. In doing this, it would be possible to bend the remaining caliper bolt during the manipulation of the caliper and brake disc — this is what the plaintiff's expert alleged the dealership had done. Of interest was that the plaintiff's expert based this allegation on his experimentation with the steering knuckle, disc and caliper from a Chevrolet Cavalier sedan. He did not try this on Plymouth Voyager (or equivalent Dodge or Chrysler) minivan components.

Recalling, the testimony by the plaintiff was that the brake pedal would go nearly to the floor in use. The plaintiff's expert claimed the bent caliper bolt caused this condition because the brake caliper dragged and heated up the brake fluid, which "thinned out the viscosity" of the brake fluid.

It is noted that the analysis conducted in this case was focused on addressing the assertions of the plaintiff's expert. The spoliation of evidence by the plaintiff's expert eliminated the ability to conclusively determine the cause of the incident, so potential mechanical factors that might have otherwise been evaluated were not, in fact, evaluated. Additionally, the extensive incident-related damage to the vehicle and accumulation of corrosion while sitting on the salvage lot further reduced the ability to investigate operational factors that might otherwise have been of interest.

Preliminary Analysis

In a scenario where a vehicle pulls to the left or right under braking, it can be due to problems in the braking system, suspension, or tire pressures. There was no record of the tire pressures either before or after the incident, and — due to the vehicle damage — it would have been difficult to evaluate any contribution of loose suspension joints, alignment issues, etc. The plaintiff's expert focused on the brakes (specifically, the front brakes).

Potential causes of brake pulling

1. Brakes pulling to one side can be caused by air or vapor in the hydraulic brake lines. With vehicle brakes, a specific depression of the brake pedal will result in a specific brake force response, due to the fact that hydraulic fluid is incompressible. Air or vapor in a hydraulic system, however, is compressible, and brake pedal motion is "lost" in first compressing the air/vapor before significant brake force response occurs at the disc brake caliper or drum. This condition of air/vapor in brake lines is commonly known to cause reduced brake performance and a potentially "low pedal" that must be depressed further than normal for a given brake response — both of these are conditions reported by the plaintiff. If one side of the braking system is working significantly better than the other side, the vehicle will pull in the direction of the stronger brake. Once air/vapor accumulates in the brake lines, it may migrate to areas where it has a greater or lesser effect on braking performance. The plaintiff's expert, in disconnecting the front brake lines, eliminated the ability to determine if air/vapor accumulation was a factor in the incident.

   a. Causes of air in brake lines include leaks, low brake fluid reservoir level, and failure to bleed the system after disconnecting brake lines for servicing. Vapor in the brake lines is due to overheating of the brake fluid. Water vapor can also accumulate in brake lines due to the hygroscopic nature of many types of brake fluid (which contain alcohol); the absorbed water vaporizes at a lower temperature than the brake fluid. Addressing these individually:

      i. Neither the insurance company's expert nor the plaintiff's expert had noted any brake fluid leaks or a low brake fluid reservoir level.

      ii. It was possible that the brake lines had been disconnected by the dealership during servicing, which could have introduced air, but there was no testimony indicating this had been done. Manufacturers typically recommend bleeding fluid out of the brake system during pad replacement (when resetting the caliper piston), but typically this is done simply by opening the caliper bleed screw. Another method often used during pad replacement is to simply reset the caliper piston and let the brake fluid backflow into the reservoir — this does not involve opening the brake lines to air ingress. As an exemplar inspection was planned, one task was to check to see if disconnecting the front brake lines was necessary in order to change the brake pads and brake discs.

      iii. Excessive heat can build in the brakes with extended hard use or due to the driver "riding" the brakes; this is often manifested by bluing and fine cracking of the disc surface, as well as an "ashen" appearance to the outside of the caliper. Neither of these conditions was noticed in the two inspections, though the brake discs had been recently replaced. Excessive heat can also result from a dragging caliper that does not fully release.

b. The plaintiff's expert's assertion that the low brake pedal was caused by hot and less-viscous brake fluid was judged irrelevant to the analysis. Viscous or less-viscous fluid is still incompressible, and there are no studies showing any pattern of less-viscous brake fluid affecting pedal height. Brake fluid viscosity is an issue in the valving of antilock brake system (ABS) modules, but this vehicle did not have ABS.

2. Brakes pulling to one side can also be caused by a binding/dragging caliper or, for rear drum brakes, a sticking wheel cylinder. In these scenarios, the brake actuator does not move freely due to mechanical interference caused by corrosion, usage of mismatched components, improper assembly and poor workmanship, or deformed components.

a. Inspection of the subject caliper components did not reveal undue corrosion overall. The passenger's side (right) front caliper was the primary focus as it was this caliper that had the bent lower bolt (see **Figures 4** through **7**). Note that regardless of where a bending load would have been applied along the bolt head or the slider bushing, the bending would manifest itself at the "weak point" of the threads, due to the stiffening support provided by the slider bushing. The lower slider bushing's boot was damaged, but the surface of the bushing did not show any corrosion. Note that by design the bushing is completely "suspended" within the rubber boot, and does not contact the caliper casting directly. Of interest, **Figure 8** shows an impact/wiping deformation area observed on the inboard end of the bent slider bushing; the most likely cause was judged to be that a floor jack was improperly placed on the bushing following manual retraction of the rubber boot. But such an action would be inconsistent with typical or effective shop practices. Regardless, the cause or time frame of this deformation remains unknown.

b. There was no evidence that mismatched components were used in this area of the subject minivan.

Figure 5
Lower slider bushing and boot.

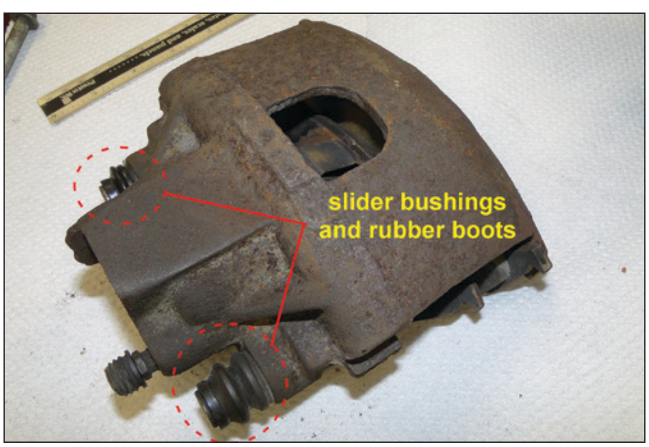

Figure 4
Right caliper.

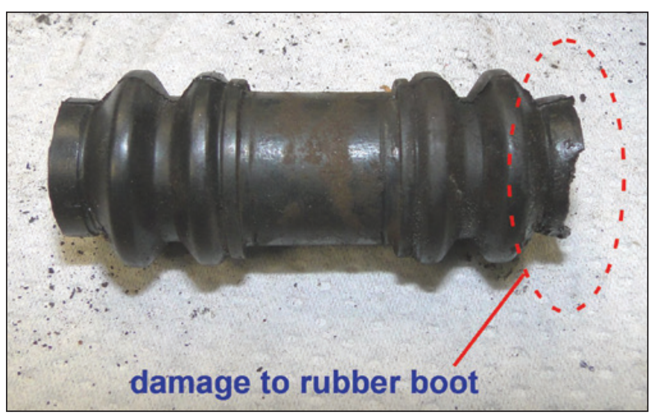

Figure 6
Damage to lower slider's rubber boot.

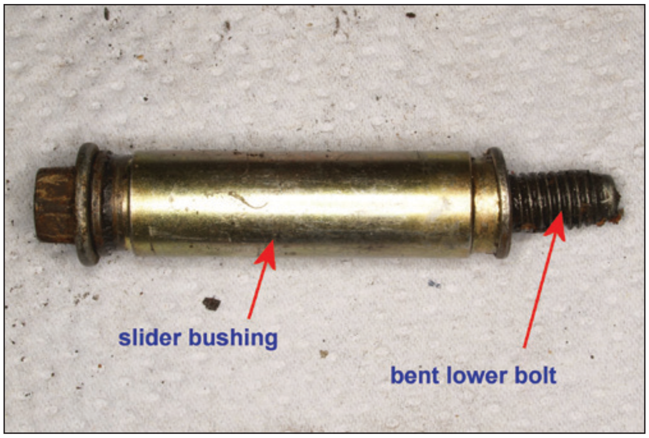

Figure 7
Lower slider bushing and bent bolt.

Figure 8
Impact/wiping marks on inboard end of slider bushing.

c. The question of improper assembly and poor workmanship could pertain to the question of how the subject lower caliper bolt became bent. One of the plaintiff's expert's allegations was that the bolt was bent by undue forcing of the caliper during service. It was decided that the exemplar minivan would be used to analyze this.

d. The subject lower bolt also could have been deformed by some external force application unrelated to the dealership's servicing. For example, the vehicle had been stored at an auction yard for years following the incident. This auction yard (like many) moves vehicles around through the use of large wheel loaders equipped with long forks that the drivers basically shove under the vehicles to pick them up. **Figure 9** shows (on an exemplar minivan) how the lower caliper bolt could have been readily contacted by fork tips; additionally, there was a fresh scrape mark on the front surface of the right front lower control arm (below and behind the lower caliper bolt) in photographs taken by the dealership's expert two months after the incident. Consistent with this scenario, it is also of note that not only the lower caliper bolt was deformed, but the face of that bolt's slider bushing (that contacts the suspension upright) also showed deformation consistent with a bending force being applied to the bolt (or bushing) while it was in place on the vehicle (**Figure 10**). It is not conclusively known, however, what the rotational orientation was of the bend in the bolt (and slider bushing) preceding their removal by the plaintiff's expert, as he had taken few photographs of the components during disassembly. Low-resolution zoomed-in portions of the few digital images taken by the plaintiff's expert appeared to show that the bolt was bent vertically up, but this was not conclusive.

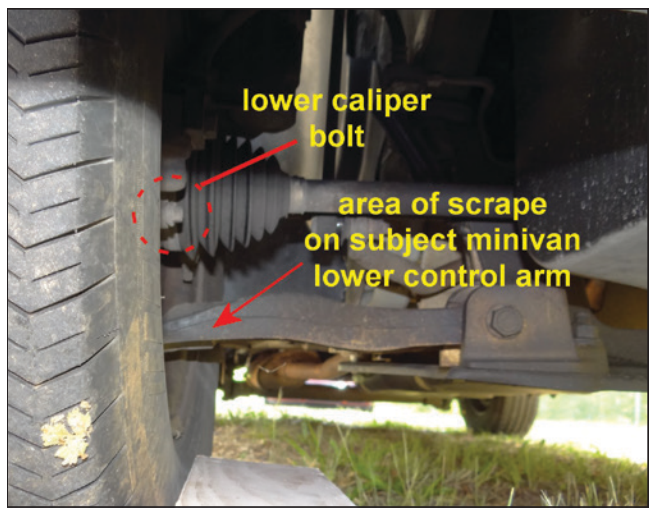

Figure 9
Accessibility of lower caliper bolt to fork tips (exemplar).

Figure 10
Deformed end of lower slider bushing.

Test Configuration

There were three hypotheses tested in this investigation:

1. It may have been necessary to remove the brake line from the caliper in order to replace the pads and brake disc during servicing.

2. It may have been possible to attempt to remove the brake disc with only the top caliper bolt removed (in servicing), which could, in turn, have led to bending of the lower caliper bolt.

3. The bent lower caliper bolt could have caused the caliper to stick or drag in use.

   a. A binding/dragging caliper could have caused brake overheating and hot brake fluid vapor buildup in the brake lines.

   b. A binding/dragging caliper could have caused brake pulling.

The testing plan for these hypotheses involved:

1. Evaluating the ability to replace the brake pads and disc without disconnecting the brake line.

2. Evaluating the ability to remove the brake pads and disc with only the top caliper bolt removed.

3. Testing the effect of the bent caliper bolt on brake force response through instrumented measurement of brake pedal application/release force + timing versus caliper actuation/release force + timing.

   a. This analysis involved depressing/releasing the brake pedal to see what the actuation/release response of the brake caliper would be. It was decided that obtaining repeatable data would require standardizing the speed and force of depressing/releasing the pedal, and pneumatics were chosen for this purpose. Though brakes will actuate without power assist, the subject vehicle had vacuum-assisted power brakes (as expected), so it was decided that the testing should involve a functioning power brake booster in the exemplar test vehicle.

   b. Two types of sensors were chosen for use in this force analysis:

      i. The application/release of brake pedal force was expected to be a "rapid" event, with impact spikes and other significant accelerations and decelerations occurring in less than 0.1 seconds. For this reason, it was decided to use a 500-pound capacity piezoelectric force transducer between the pneumatic brake pedal actuator and the brake pedal. This type of force transducer can capture data at a high sampling rate, but experiences rapid decay in its signal. Therefore, it was judged better suited to short-duration applications such as this (**Figure 11**).

Figure 11
Pneumatic brake pedal actuator/sensor apparatus.

      ii. The measurement of brake caliper piston response (through output force) was expected to be a "slower" event, potentially greater than 0.1 seconds, given that it was lagging/dragging of the caliper response that was being measured. For this reason, it was determined that a piezoelectric force transducer would not be appropriate due to signal decay. A 5,000-pound capacity strain-gauge type load cell was used for this application. These types of sensors are less compatible with high sampling rates, but are better at tracking force changes over time. These sensors took the place of the outboard brake pads and were mounted to a large washer and indexing rod that fit within the cylindrical recess of the composite caliper piston. The thickness of the installed assembly was approximately .06 inches thinner than a new brake pad (see **Figures 12** through **15**). Through this apparatus, the inherent self-retracting behavior of the caliper piston seal was not affected.

c. A calculation error led to the decision to use the 5,000-pound capacity load cell; it would have been better to use a 20,000-pound capacity cell due to the force multiplication that the exemplar vehicle's power brake system produced. As it was, pneumatic brake pedal force application was limited to 25 pounds in order to avoid overloading the 5,000-pound load cell. Time constraints precluded re-doing the test with a higher capacity load cell. It was decided that (due to the small operational deflections inherent in caliper application) dragging/lagging of the caliper response would likely happen at these lower application forces as well. During testing, the running engine's vacuum was periodically checked to ensure that it remained within factory specifications.

d. The pneumatic system utilized a large air reservoir so that repeated brake pedal actuation would not cause a significant drop in cylinder input pressure. A lever-actuated pneumatic valve was used to apply the pedal actuation force.

e. The actual force magnitudes measured by the sensors were judged less important than the consistency and rapidity of response of

Figure 12
Mounted strain gauge.

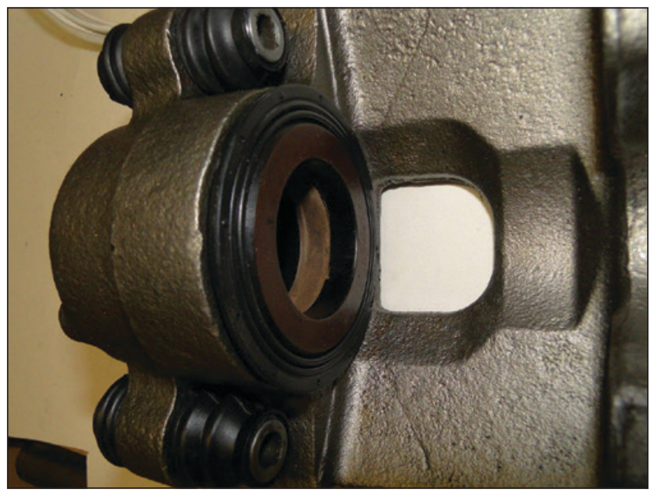

Figure 13
Exemplar caliper showing composite piston.

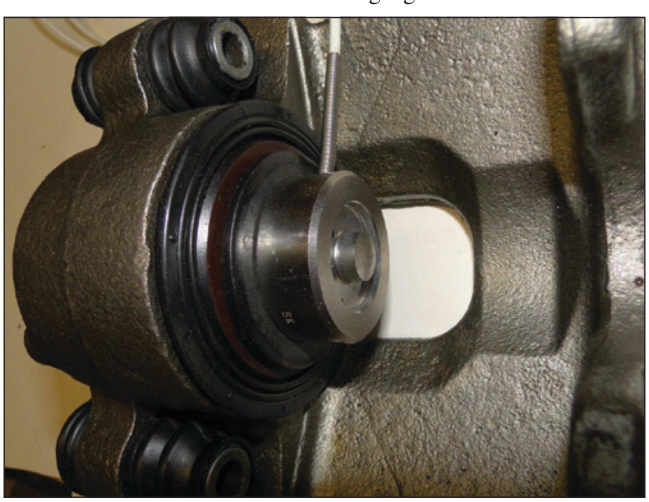

Figure 14
Strain gauge installed in caliper.

Figure 15
Instrumented caliper mounted on exemplar vehicle.

the brake caliper piston to the brake pedal actuation and release. This was to be evaluated for a baseline configuration, and then for a configuration where the lower caliper bolt was manually bent by the author.

Test Results

1. It was not necessary or beneficial to remove the hydraulic brake lines from the front calipers in order to change the pads and disc. As such, it is not reasonable to expect that the dealership would have done so and introduced air into the hydraulic system.

2. It was not possible to remove the brake disc without unbolting both caliper bolts and removing the caliper. This counters the assertion of the plaintiff's expert that the lower caliper bolt was bent during the brake servicing by the dealership's attempts to remove the disc without removing the caliper.

3. The baseline evaluation provided usable data, showing a consistent force response of the caliper piston to repetitive pedal input. The sampling frequency was 1,000 Hz. Once the baseline was obtained, the head of each lower caliper bolt was bent vertically up to a total bend of approximately 6 degrees. The bolt was bent first through the use of a bar clamp and then (when the bar clamp proved inadequate) by lifting the vehicle (in effect) by raising a floor jack under the caliper bolt (**Figures 16** and **17**).

4. The data is summarized in **Figure 18**. Pedal input force is in the top charts, at both application (top left) and pedal release (top right). The "baseline" tests were before the caliper bolts were bent, and five data sets were taken. The caliper piston output force is shown at application (bottom left) and release (bottom right).

5. Observing the data, some comments can be made:

   a. Pedal application: Apart from the spike at initial pedal application (time ~ 0), when the plunger impacted the sensor, the pedal application took about 0.4 seconds, so perhaps a strain gauge sensor would have worked in this part of the apparatus. The decay of the piezoelectric sensor signal is apparent starting at about 0.42 seconds. The applied force did vary somewhat, even when the initial "bias" of the system (before t = 0) is taken into consideration. But this did not seem to translate into corresponding variability in the caliper output.

   b. Pedal release: The force dropoff at pedal release appeared to have a consistent plot profile. Again, there were minor differences in the before/after force, even considering the bias.

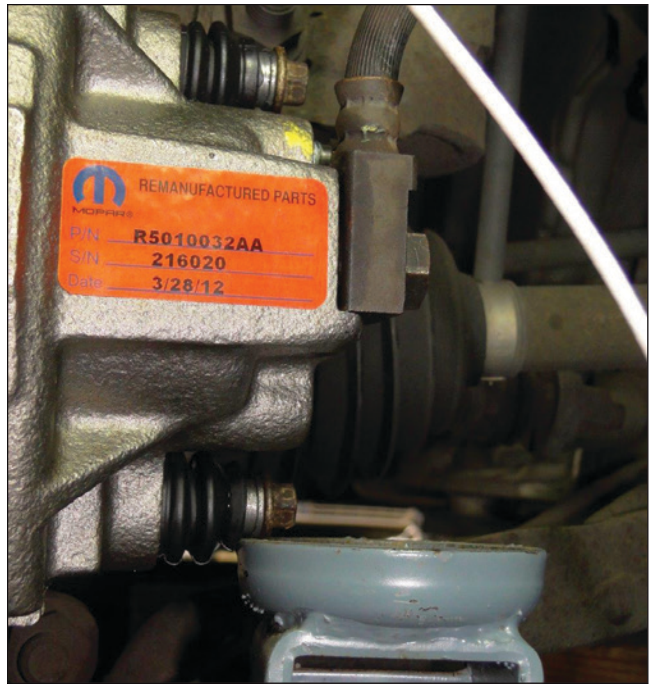

Figure 16
Bending bolt with jack.

Figure 17
Measuring amount of bend.

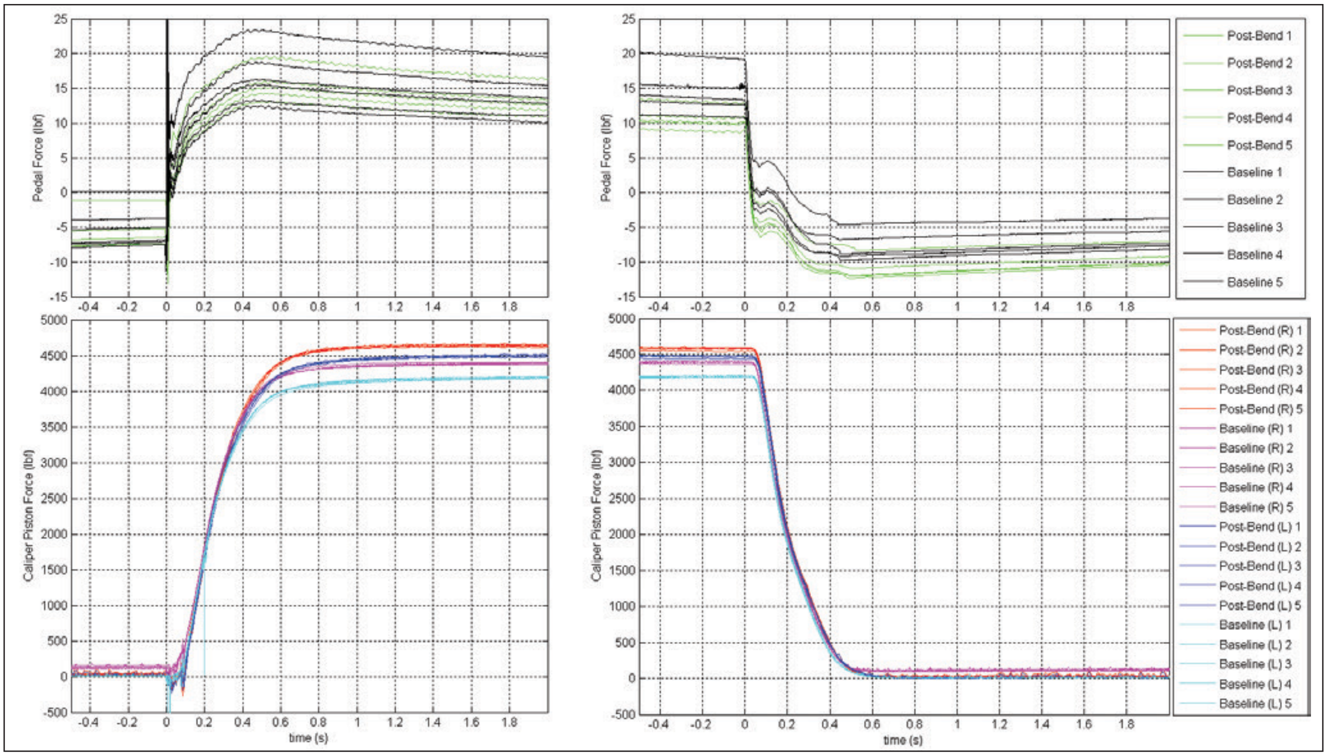

Figure 18
Test data summary plot.

c. Caliper response – application: The right side baseline and bent-bolt response curves were closer together than the left side, but in both cases there was more caliper force with the bent bolt than without. Each group of five traces appeared to be fairly consistent, despite minor variations in the pedal input force. And the force onset profile appears quite similar for all four sets of five traces.

d. Caliper response – release: In all cases, the caliper force release took no more than 0.03-0.04 seconds to occur. The "gentle" ramp down of forces after 0.04 seconds could be due to a combination of the sensor response and the elasticity of the caliper assembly. And in each trace, the force eventually goes to ~0 after 0.6 seconds.

e. Overall conclusions from this testing:

   i. The consistency of profile with each of the different plot traces appears to show that the apparatus and method provide usable results.

   ii. The bent bolt did not cause a significant comparative lag in either caliper force onset (upon pedal application) or release.

   iii. There did not appear to be residual caliper force (i.e., brake drag) due to the bent bolt, such that would cause overheating of the brakes and vaporization of the brake fluid.

Conclusions

Reviewing the plaintiff expert's assertions again, which were: 1) the dealership had bent the lower caliper bolt during servicing; 2) the bent bolt caused a low brake pedal; and 3) the bent bolt caused brake drag and pulling upon application, this investigation disproved those assertions at a general level — through the use of exemplars. However, because the plaintiff's expert unnecessarily disassembled the subject vehicle's brake components and opened up the hydraulic system, it is not possible to conclusively determine the cause of the subject vehicle's bent bolt, the effect it would have on the subject vehicle, or the potential contribution of air/vapor that might have been in the hydraulic lines. As such, it is not possible to conclusively determine the cause of the subject incident.

The author wishes to thank Erich Schlender, PE, for his invaluable assistance in this forensic analysis.

Forensic Engineering Analysis: Biomechanics is an Engineering Discipline

By William E. Lee III, PhD, PE (NAFE 655S)

Abstract

Forensic engineers with expertise in the field of biomechanics are frequently retained to conduct a biomechanical analysis of some injury-related incident. This may involve the areas of injury event reconstruction, what forces may have been involved, how the person responded to these forces, and whether injury mechanisms consistent with the claimed injuries were (or were not) established during the incident. It is the view of some engineering biomechanics experts that the presentation of injury mechanism-related opinions is based on biomechanics (a subject of engineering) and is not intended to serve as an opinion regarding injury causation (i.e., was the claimant injured as a result of the described incident). Attorneys have challenged the ability of forensic engineering biomechanics experts to offer injury mechanism-related opinions (and often the other associated areas described above) based on a theory that "biomechanics" is not a subject of engineering, but rather a subject of medicine, and, in turn, the engineering expert should not be allowed to present such opinions. This paper explores the validity of this claim, focusing on the academic evidence. More specifically, academic programs within the United States in both the areas of engineering and medicine were examined to find evidence of formal classes in the area of biomechanics, dedicated biomechanics research activities, current textbooks and references (focusing on author affiliation), and other academic-related activities.

Keywords

Biomechanics, injury analysis, biomedical engineering, forensic engineering

Introduction

Engineers with expertise in biomedical engineering (with a focus on biomechanics) are often retained by attorneys to provide analysis and render opinions in the area of injury biomechanics. Biomedical engineering is the engineering-based discipline at the interface of engineering mechanics, dynamics, materials, modeling/analysis, and relevant areas of clinical and research medicine. Biomechanics is a major sub-discipline of biomedical engineering that employs these areas to focused problems, such as: the understanding of how the body moves, the forces involved, and how the body responds to forces; mechanical behavior of various tissues such as bone under various loading scenarios (up to injury); orthopedics, including the behavior of joints and associated structures and the design of orthopedic implants; and occupational biomechanics and ergonomics. Injury biomechanics is a focused area of biomechanics that examines how the body or tissues react to load scenarios that are associated with injury. Injury biomechanics may be used to understand how a given injury may or may not have occurred in a given situation. Injury biomechanics is also employed in areas such as automotive design and safety engineering to prevent injuries from occurring.

Figure 1 presents a list of typical areas where a biomechanical analysis might be conducted. Typically, an individual makes an injury claim as the result of a specific event, such as a vehicular collision, slip and fall, falling object, etc. Forensic engineering experts are retained to provide opinions on what types of forces might have been experienced by the claimant, what types of injury mechanisms might have been established, etc. Often, a separate engineering expert is retained to formally reconstruct the injury-related event; however, some engineering experts can evaluate both the reconstruction phase and the biomechanics phase of the analysis. It should be noted that any of the parties involved in the litigation process can retain such expertise; often biomechanics experts are retained by both plaintiffs and defendants in civil matters. From an ethical viewpoint, a given biomechanics expert's opinion should be independent of which party retained the expert.

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Acceleration/deceleration injuries
- Vehicular collisions
- Single vehicle incidents
- Slip/trip-and-falls
- Elevator incidents
- Head/neck (or other body areas) acceleration/deceleration

Blunt trauma
- Vehicular collisions
- Pedestrian-vehicle incidents
- Falling objects
- Fall from height
- Slip/trip-and-falls
- Sports/recreation incidents
- Battery incidents

Other areas
- Seat belt issues
- Air bag issues
- Helmet issues
- Repetitive motions
- Medical malpractice
- Product liability

Figure 1
Examples of injury-related events where a biomechanics opinion may be presented.

During the litigation process, many attorneys will try to challenge the qualifications, methodology, and opinions of biomechanics experts, often basing their challenge on rules of evidence, such as the *Frye* or *Daubert* standards. **Figure 2** presents examples of the types of statements opposing counsel may weave into a legal argument in an attempt to exclude/limit/strike a biomechanics expert. This paper focuses on one specific type of challenge: that biomechanics (in general) and often injury biomechanics (specifically) are disciplines of medicine and not engineering. Therefore, only an MD, DO (Doctor of Osteopathic Medicine), or occasionally a DC (Doctor of Chiropractic) can offer any such opinions. Stated alternately, it is asserted that an engineer in a medically related engineering discipline (e.g., biomedical engineering) is not qualified to offer biomechanics-related analysis and opinions because biomechanics is not recognized as an engineering discipline but rather a discipline of medical science. It should be noted that "medical opinions" do include: was the claimant injured; was the diagnosis appropriate; was the treatment appropriate (including any physical or rehabilitation therapy, drug prescription, surgical interventions, etc.), was there permanent impairment, future health possible trajectories, etc. Engineering experts do not normally address such areas, recognizing them as "medical opinions." However, the author contends that the argument — engineers cannot offer biomechanics opinions because "biomechanics" is a medical subject (not an engineering one) — is invalid.

- Dr. X is rendering medical causation opinions. Since Dr. X is not an MD, he/she is not qualified to render such opinions.
- Opinions related to biomechanical mechanism of injury can only be offered by an MD, since mechanisms of injury is a subject of medicine and not of engineering.
- Dr. X cannot offer opinions related to biomechanics since he/she did not examine or otherwise treat the patient.
- Dr. X is not qualified to read medical records that document the claimed injuries; therefore, his/her opinions related to biomechanics should not be allowed.
- Dr. X cannot cite any peer-reviewed literature that documents his/her methodology related to his/her biomechanical analysis. Therefore, Dr. X's opinions should not be allowed.
- Dr. X's "methodology" is not generally accepted by his/her scientific community and is, in fact, based on "junk science." As such, it does not rise to the standards of either *Frye* or *Daubert*.
- Dr. X cannot cite a peer-reviewed article where a person of the plaintiff's age/height/weight and general physical condition was included as a subject in any studies. Therefore, Dr. X's "biomechanical" opinions are pure speculation and should not be allowed.
- Dr. X was not a witness to the collision, so he/she cannot say anything that is reliable regarding how the plaintiff moved in regard to the rear-end impact.
- Dr. X's references to Activities of Daily Living to supposedly assist the jury in understanding what 1 *g*, 2 *g*, 3 *g*, etc., mean is just a back-door way of arguing medical causation and therefore should not be allowed.
- Dr. X failed to agree with the plaintiff's treaters who clearly document that the plaintiff's injuries were caused by this accident. Obviously, the plaintiff's treaters are in the best position to opine that the plaintiff's injuries are a direct result of this accident.

Figure 2
Examples of phrases cited in various motions to exclude/limit/strike biomechanics experts.

It is important to note that there is a difference between "medical causation" and "biomechanical causation." Medical causation refers to whether a specific event did or did not cause a specific claimed injury from a clinical point of view. This may be especially problematic regarding soft tissue injuries. Often, the medical causation claim is based on the patient's self-reported history (for example, "I was fine before the event") or by a diagnosis of exclusion. As such, this is usually subjective information and not particularly "objective-scientific." The claim may also be based on the treating physician's clinical knowledge of the nature of the injury in question (for example, many subjects in rear-end collisions experience whiplash). Objective findings may indicate that an injury event may have occurred in the past, but when the event actually occurred may be difficult or impossible to determine. Indeed, physicians may often commit the *post hoc ergo propter hoc* logical fallacy (i.e., where one concludes that one event followed by another is sufficient evidence to conclude a causal relationship between the two). The American Medical Association guidelines[1] regarding injury causation present the methodology that should be followed in determining causation, and it states that causation opinions should not be based solely on the subjective history as provided by the patient. Complicating the issue, physicians may be providing opinions in cases where the treatment and diagnostics were performed under a letter of protection or similar agreement; the physician may have a vested interest in the outcome of the case. In contrast, "biomechanical causation" indicates whether the temporal events relative to the claimed injury, associated movements/forces, and potential mechanisms of injury are consistent with the claimed injury. Medical causation is based more on clinical knowledge, and biomechanical causation is based on engineering mechanics, physics, etc.

A related problem regarding who is qualified to render biomechanics opinions is often encountered in litigation where a physician renders what are clearly biomechanical opinions. For example, the physician may opine that forces were insufficient to cause the injury of interest or simply that the explanation of how the injury occurred is not tenable. This is a significant problem in the area of physical child abuse where pediatric physicians offer "biomechanical" opinions in areas such as short falls and acceleration-deceleration injuries ("shaken baby syndrome"). Physicians who also hold engineering degrees may be qualified to render biomechanical opinions. However, most physicians have undergraduate degrees in the life sciences with minimal physics. Therefore, such physicians' ability to offer opinions regarding forces, loading behavior, mechanical failure, etc., is often justifiably suspect.

Evidence to support the claim that biomechanics is, in fact, grounded in engineering will be presented from the following sources: 1) an analysis of engineering academic programs in this country wherein biomechanics and related subjects are taught; 2) an analysis of "injury biomechanics" as curricula in the United States medical academic programs; 3) an analysis of established research entities in the area of injury biomechanics; 4) an analysis of the literature in injury biomechanics (coauthor status, affiliations, etc.) and subject areas addressed and methodologies; and 5) other relevant information. The results of this investigation will clearly show that biomechanics and the focus area of injury biomechanics are well grounded in engineering and, in fact, are not addressed in medical school curricula.

Analysis

The Accreditation Board for Engineering and Technology (ABET) website[2], *The Online Guide to Engineering School*[3], and other resources such as the Biomedical Engineering Society (BMES) website[4] were included to identify engineering programs in biomedical engineering, bioengineering, or other disciplines that might include biomechanics (for example, mechanical engineering). The Association of American Medical Colleges (AAMC) website[5] was consulted to identify Doctor of Medicine (MD) programs. The American Association of Colleges of Osteopathic Medicine (AACOM) website[6] was consulted to identify Doctor of Osteopathic Medicine (DO) programs. The Council on Chiropractic Education (CCE) website[7] was used to identify programs leading to the Doctor of Chiropractic (DC) degree.

For engineering and medical sciences programs, as identified via the above resources, each program was examined for the offering of permanent courses in biomechanics, including general biomechanics and more specialized classes, such as soft tissue biomechanics, orthopedics biomechanics, injury biomechanics, research methods in biomechanics, etc. Classes such as "special topics," "independent study," "directed research," etc., were not considered. In addition, general or survey classes (for example, "Introduction to Biomedical Engineering") were not considered. For the engineering programs, the analysis focused on bioengineering (BioE) and biomedical engineering (BME) programs; when an institution offered one or both of these, the associated mechanical engineering (ME) program was also investigated. Each surveyed program and institution were also probed for a biomechanics-related area being a designated area of emphasis as well as the existence of a defined research group/laboratory/etc.

For textbooks related to biomechanics, the Amazon and Barnes & Noble websites were searched along with a broader Google search. When an in-print text was identified, the author(s), affiliation, and credentials (as available) were noted. In addition, a Google search was conducted to identify research groups, laboratories, institutes, etc., with a focus on biomechanics. The latter search was performed to identify possible research entities that were more broadly defined, possibly spanning several academic units or perhaps not directly affiliated with an academic institution. When possible, the types of individuals associated with the research entity (MD, PhD, discipline, etc.) were noted.

Results

According to the Accreditation Board for Engineering and Technology website, there were 612 institutions in this country with accredited engineering programs (3,002 total departments/programs) as of the 2013-2014 accreditation cycle. Of these programs, there were 167 schools with programs in bioengineering or biomedical engineering, of which there were 92 ABET-accredited BS programs in BioE or BME (as of 2015). It is important to note that ABET only accredits undergraduate engineering programs. Many BioE/BME programs offer only graduate degrees, although there is a growing trend to establish Bachelors BME programs. The Association of American Medical Colleges identifies 145 accredited medical schools in this country; the same programs were identified in the Liaison Committee on Medical Education website. The American Association of Colleges of Osteopathic Medicine identifies 31 accredited colleges of osteopathic medicine in this country (44 teaching locations in 29 states). According to the Council on Chiropractic Education, there are 15 accredited programs (at 18 locations) in this country.

Figure 3 summarizes the results of the survey of accredited academic programs in engineering and the medical sciences. Of the 167 programs surveyed in engineering per the protocol outlined above, 155 (92.8%) included at least one course in biomechanics. More than one biomechanics course was offered at 91 (54.5%) of the 167 programs. Beyond the basic biomechanics courses, many programs offer additional courses such as orthopedic biomechanics (12 programs), soft tissue biomechanics (22 programs), and biomechanics research methods (9 programs). Specific examples of courses beyond a basic biomechanics course include:

- Movement biomechanics, and rehabilitation (Case Western Reserve University)
- Structure, mechanics, and adaptation of bone (Columbia University)
- Musculoskeletal biomechanics 1, 2 (Marquette University)
- Advanced musculoskeletal biomechanics (Columbia University)
- Experimental biomechanics (Drexel University)
- Introduction to orthopedic biomechanics (Johns Hopkins University – Mechanical Engineering)
- Orthopedic biomechanics (several programs)
- Tissue mechanics (Georgia Institute of Technology)
- Biomechanics of the spine (Marquette University)
- Soft tissue biomechanics (Stanford University)
- Fracture mechanics (University of Alabama – Birmingham)
- Ergonomics of occupational injuries (University of Iowa)

Degree offered	Programs Surveyed	Programs offering biomechanics course(s)	Programs where biomechanics is an identified area of emphasis
BME/BioE/ME	167	(at least one) 155 (more than one) 91	138
MD	145	0	0
DO	31	0	0
DC	15	0	0

Figure 3
Summary of the survey of academic programs in engineering and medical sciences.

- Impact biomechanics (Virginia Polytechnic Institute – Mechanical Engineering and Wayne State University)
- Experimental methods in impact biomechanics (Wayne State University)

Wayne State University offers a graduate certificate in injury biomechanics within its BME program. Stanford University offers a B.S. biomechanical engineering program (only such degree program in this country). The University of Texas Mechanical Engineering department offers a "biomechanical engineering" program (the awarded degree is in mechanical engineering).

Several programs offer a biomechanics concentration or track within the broader BME/BioE graduate program, including:

- Yale University
- University of Pittsburgh
- University of Michigan
- University of Iowa
- University of Illinois at Urbana-Champaign
- University of Akron
- Temple University
- Rensselaer Polytechnic Institute
- New Jersey Institute of Technology
- Marquette University
- Case Western Reserve University
- Drexel University
- Johns Hopkins University (mechanical engineering)

Concentrations or tracks usually refer to a collection of required and elective courses that students may select, reflecting on their desire to focus on the sub-area or sub-discipline while pursuing the broader degree.

As part of the academic infrastructure, many BME/BioE programs have a dedicated research group and an associated laboratory. These entities tend to be more multidisciplinary in nature, often including both engineers and physicians. Examples of such defined entities that are based in engineering include:

- Injury and Orthopaedics Biomechanics Laboratory (Duke University)
- Orthopaedic Biomechanics Laboratory (Michigan State University)
- Orthopaedic Biomechanics research group (Purdue University)
- Injury Biomechanics Laboratory (University of Pennsylvania)
- Biomechanics Research Laboratory (University of Southern California)
- Applied Biomechanics Laboratory (University of Washington)
- Center for Injury Biomechanics (joint program between Virginia Tech and Wake Forest)
- Orthopedic Biomechanics Laboratory (University of Iowa)
- Biomechanics Research Laboratory (University of Illinois at Chicago – Mechanical Engineering)
- Neuromuscular Biomechanics Laboratory (Stanford University)
- Soft Tissue Biomechanics Laboratory (University of Arizona)
- UW Neuromuscular Biomechanics Laboratory (University of Wisconsin-Madison – Mechanical Engineering)
- Laboratory for Neuroengineering (includes the Neural Injury Biomechanics and Repair Laboratory) — joint program between Georgia Tech and Emory University

While not a formal laboratory, the impact biomechanics group at Wayne State University includes several BME faculty members. The Injury/Impact Biomechanics Laboratory at University of Michigan is housed within the Transportation Research Institute. In addition to the engineering-based entities, some research entities may be based in a medical school or health sciences complex. For example, the Spinal Column Biomechanics Laboratory at Johns Hopkins University is based within the medical school, but engineering faculty plays a significant role. Also, the Injury Biomechanics Research Center at Ohio State University is housed within the College of Medicine but is staffed (and directed by) engineering PhDs. The Center for Injury Biomechanics at Wake Forest

University is based within the School of Medicine but is a part of the Virginia Tech-Wake Forest University School of Biomedical Engineering and Sciences.

No biomechanics courses were identified for any of the MD, DO, or DC programs. To be more specific, there was no evidence that any biomechanics courses were required as part of the academic requirements (or as elective courses) for any of these degrees.

Figure 4 presents examples of textbooks (currently in print) in basic/general biomechanics and also in injury biomechanics. As included in the information, almost all of the authors/editors are PhD scientists/engineers; only a few are MDs.

Many engineering technical societies have divisions or sections that focus on biomechanics. For example, the annual meeting of the Biomedical Engineering Society (BMES) has a biomechanics track as one of its major areas of focus. This usually includes specific sections on injury biomechanics. This is also true of the American Society of Mechanical Engineers. The American Academy of Forensic Sciences (AAFS) includes a forensic engineering sciences division. Many of the presentations and publications focus on injury biomechanics and are authored by engineers. The Society of Automotive Engineers (SAE) publishes many significant papers in the area of injury biomechanics. The National Academy of Engineering (NAE) and the National Academy of Forensic Engineers (NAFE) routinely publish the works of engineering biomechanists.

Other societies may be broader in membership in terms of their academic disciplines, but still include a significant engineering presence. For example, the Association for the Advancement of Automotive Medicine (AAAM) publishes many papers on injury biomechanics authored by engineering investigators. The European Society of Biomechanics also involves many engineering contributors.

An inspection of the peer-reviewed literature in a wide variety of journals readily indicates a strong

Basic/general biomechanics

Basic Biomechanics of the Musculoskeletal system
4th edition, Lippincott Williams & Wilkins, 2012
M. Nordin (PhD Medical Science);
V. H. Frankel (MD, PhD)

Basic Orthopaedic Biomechanics and Mechano-Biology
3rd edition, Lippincott Williams & Wilkins, 2004
V. C. Mow (PhD) and R. Huiskes (PhD)

Biomechanics: Mechanical Properties of Living Tissues
2nd edition, Springer-Verlag, 1993
Y. C. Fung (PhD)

Biomechanics of the Musculo-Skeletal System
3rd edition, Wiley, 2003
B. Nigg (D.Sc.) and W. Herzog (PhD)

Biomechanics: Principles and Applications
2nd edition, CRC Press, 2008
D. R. Peterson (PhD) and J.D. Bronzino (PhD)

Fundamentals of Biomechanics
2nd edition, Springer, 2007
D. Knudson (PhD)

Fundamentals of Orthopaedic Biomechanics
Williams & Wilkins, 1994
A.H. Burstein (PhD) and T.M. Wright (PhD)

Tissue mechanics
Springer, 2007
S. C. Cowin (PhD) and S. B. Doty (PhD)

Injury biomechanics

Accidental Injury: Biomechanics and Prevention
3rd edition, Springer, 2014
N. Yoganandan (PhD) and A. M. Nahum(MD)

Biomechanics of Impact Injury and Injury Tolerances of the Head-Neck Complex
Society of Automotive Engineers, 1993
S. H. Backaitis (Principle Engineer, NHTSA)

Biomechanics of the Upper Limbs: Mechanics, Modeling, and Musculoskeletal Injuries
2nd edition, CRC Press, 2011
A. Freivalds (PhD)

Biomechanics of Musculoskeletal Injury
2nd edition, Human Kinetics, 2008
W. C. Whiting (PhD) and R. F. Zernicke (PhD)

Trauma Biomechanics: Accidental Injury in Traffic and Sports
3rd edition, Springer, 2010
K. U. Schmitt (PD Dr), P. F. Nieder (Dr),
M. H. Muser (Dr Med), and F. Walz

Figure 4
Examples of basic/general biomechanics textbooks and textbooks focusing on injury biomechanics.
In all cases, the highest degree of the author/editor is indicated.

presence of engineering investigators who focus on injury biomechanics. This includes both technical-focused journals and more medical journals.

As a final observation, it should be noted that federally funded research into injury biomechanics has significant engineering involvement. A number of engineering research centers were identified above; these collectively receive significant federal funding to accomplish their research missions that focus on biomechanics, specifically (in most cases) injury biomechanics. Other federally funded organizations that have an aspect of injury biomechanics (and therefore significant engineering participation) include the National Highway Traffic Safety Administration (NHTSA), the National Transportation Safety Board (NTSB), and the Consumer Product Safety Commission (CPSC). Other federal groups provide research funding for engineering biomechanics as part of their mission, including the Department of Veterans Affairs (VA), National Institutes of Health (NIH), and the National Science Foundation (NSF).

Discussion

As noted above, 92.3% of engineering programs have at least one defined course in biomechanics. All programs have one or more "survey" classes at both the undergraduate (when offered) and graduate level, including biomechanics as a core subject within the explored sub-disciplines. For example, *Introduction to Biomedical Engineering*[8] has a dedicated chapter on biomechanics. Similarly, *Biomedical Engineering Fundamentals*[9] includes a biomechanics chapter. Most BME programs also include biomaterials as a core subject — a field that overlaps and complements biomechanics.

Because of accreditation, programs in all the health degrees (MD, DO, and DC) are standardized, showing little variability in curricular issues, particularly in the first two years of study. The emphasis is clearly on the preparation of students to enter clinical practice. This may involve additional residency and other postgraduate training. Many MD programs and some DO programs offer interested students the possibility of pursuing MS and PhD degrees in a variety of subject areas, often including biomedical engineering. These degrees may be in parallel to their basic degree or postgraduate work. Most students do not seek this option. For example, according to the AAMC website for 2014-2015, there were 18,704 MD graduates, but only 616 MD/PhD graduates. As a result of such programs, there are a limited number of health care professionals who have pursued advanced topics in biomedical engineering (including biomechanics). Most MD/PhD students opt for doctoral studies in a medical science.

It should be noted that "biomechanics" is included as a subject area with osteopathic programs. For example, the biomechanics of movement is a common topic in broader classes. Also, courses in adjustment and manipulation will often touch on biomechanics. This is also true of many chiropractic programs. For example, the *Textbook of Clinical Chiropractic: a Specific Biomechanical Approach*[10] is used in many programs. In general, there is comparatively little emphasis on the original injury mechanisms and the broader biomechanical behavior at the tissue and functional unit level.

Historically, a few of the pioneer programs in BME came up through electrical engineering. More recently, BME programs may develop within other engineering disciplines, including chemical engineering and mechanical engineering. In general, the EE-influenced departments tend to have less emphases in biomechanics than those that came up through other engineering disciplines or alternately developed more recently as freestanding departments/programs with no historical departmental affiliations.

No biomechanics courses were identified for any of the MD, DO, or DC programs. This is not surprising when one considers that these are degrees designed to prepare students for the clinical environment. As a result, the ability to render biomechanics opinions by holders of these degrees (in the absence of any other degrees in engineering) is limited. Furthermore, the typical pre-professional curriculum (for example, a typical pre-med degree) has a minimum of physics courses (usually one year) and calculus (usually one year). Thus, a physician's ability to understand and perform basic analyses using statics, dynamics, behavior of materials under load, and the other tools of biomechanics are also limited. As noted in the introduction, a common claim of many attorneys is that any sort of biomechanics-related opinion is best provided by a physician. Schneck[11] observes:

> *In defense of the medical establishment, let me add quickly that clinicians are concerned more with the diagnosis and treatment than*

with causation. Thus, they tend to justify their opinions in a rather cavalier fashion – not by hard, objective quantified evidence on which to base a conclusion "to a reasonable degree of scientific certainty," but by soft, subjective, qualitative conjecturing that goes something like this: "look, patient says he (or she) was fine prior to the incident in question, and I have not really dug deep enough or hard enough to assume otherwise, so I arbitrarily take his (or her) word for it."

Again, typical health care professionals basically have minimal to no training in the biomechanics area as part of their professional training (including pre-professional academic pursuits). Two potential exceptions to this would be a student who earned a BS (or higher) degree in a relevant engineering discipline as their pre-professional degree(s) or physicians who earned advanced engineering degrees either in parallel to their professional training or post-graduate work.

One area of supporting evidence not included in this analysis is the biomechanics-related peer-reviewed literature. This is voluminous. Journal articles on any topic of biomechanics are easily located. In the preponderance of these articles, the authors are affiliated with some BME/BioE/ME department or program. It should be noted that older articles (for biomechanics, "older" means pre-1970), many of the authors would have been affiliated with traditional engineering departments, since BME/BioE was just starting to emerge as a freestanding program or department in the 1970s. The Biomedical Engineering Society was founded in 1968, reflecting the emergence of this engineering discipline during the latter half of the 20th century. The first accredited BS programs in BME occurred in 1972 (Duke University and Rensselaer Polytechnic Institute)[12].

More recently, the term "forensic biomechanics" has come into use (the term "forensic engineer" has been around for a longer time). This term acknowledges that engineering biomechanics has become a part of the litigation process in situations involving potential or demonstrated injury. Schneck[11] observes:

What, then, is "forensic biomechanics"? This term is relatively new to the legal industry, but gaining in popularity as the general field of biomechanics grows and matures. Stated simply, forensic biomechanics applies biomechanical knowledge to answer certain questions of civil and criminal law … Biomechanics, then, involves the application of the science of mechanics to biological things, including the human body. Among numerous diverse activities, biomechanical engineers deal with subjects such as the body's response to sub-gravity environment; vehicular impacts; work—and sports-related stresses and strains … Our judicial system must recognize that the forensic biomechanical engineer – not the treating physician, not an ergonomist, not any other type of "expert" – is the one most qualified to tender legal opinions as to causation in civil and criminal matters when the cause of a medical affliction clearly involves biomechanical issues.

The information presented above clearly indicates that biomechanics is a subject area well-established within the field of engineering. Biomechanics research groups and laboratories are found throughout the engineering environment. To say that biomechanics is *not* a matter of engineering but rather one of medicine is simply uninformed and erroneous.

Regarding the protocol of how to conduct a biomechanical analysis, this has been addressed in detail in many peer-reviewed publications (for example, Lee[13] summarizes other protocol references). As practiced by biomedical engineering experts throughout the country, the general protocol regarding the analysis of a claimed injury-causing event (regardless of the retaining party) involves:

- body motions in response to applied forces (the physics of the event may be determined by a separate expert).
- the determination of any associated forces (including magnitude, direction, and area of the body affected).
- the establishing of (or lack of) any injury mechanisms for injuries of the type claimed.
- the extent to which any applied forces may exceed relevant injury thresholds. In many situations, it may also be useful to cite the forces associated with so-called Activities of Daily Living[14].

Recent Florida courtroom decisions have supported the viewpoint that biomedical engineering expert opinions regarding injury biomechanics assist the trier of fact. From the recent ruling in *Council v. State* [15], excluding the testimony of a biomedical engineer/biomechanics expert is an abuse of discretion. The boundaries of a trial court's discretion to admit or exclude evidence are confined by Florida's evidence code and controlling case law [16]. Court decisions have established that: 1) a fundamental cornerstone for analysis is that all relevant evidence is admissible, except as provided by law[17] and 2) relevant evidence may be inadmissible where its probative value is outweighed by the danger of unfair prejudice[18]. Florida courts have held that if relevant evidence is not unfairly prejudicial, the trial court has no discretion or authority to exclude it[19]. In summary, the decision in *Council v State* provides controlling Florida case law to support the conclusion that the proffered testimony of a biomedical engineer/biomechanics expert may be relevant to the issues of causation, including the disputed issues concerning velocity and the directionality of forces involved in an accident. If a trial court elects to discount and discard the authority of the *Council* case, the appeals court has been clear that excluding a biomedical engineer/biomechanics expert is an abuse of discretion.

Conclusion

The ability of a forensic biomedical engineer to offer opinions related to biomechanical issues (specifically including injury biomechanics) is well-grounded within the engineering discipline. Contrary to the beliefs of many (including non-engineers and attorneys), biomechanics is not the exclusive turf of medical sciences. Just because one holds a traditional MD, DO, or DC degree, he or she is not automatically qualified to render biomechanics opinions. In fact, biomechanics is a subject that is virtually absent from the pre-health care professional academic curriculum. On the other hand, biomechanics is an academic subject routinely included in the engineering curriculum, both at the undergraduate and graduate program levels. The foundations upon which biomechanics are based, including statics, dynamics, materials science, modeling, and knowledge of human tissue anatomy/behavior is well-integrated within biomedical engineering education and research. Most health care professionals were exposed to minimal physics and associated mathematics in their undergraduate training; it is basically not significantly relevant to their future clinical careers. Research groups and laboratories focusing on biomechanics are found throughout engineering programs and beyond (for example, aspects of automotive and consumer product safety). Relevant literature (journal articles, books, etc.) is dominated by engineering investigators and practitioners. To say biomechanics is *not* a matter of engineering (but rather one of medicine) is unsupportable.

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16. *Angrand v Key,* 657 So. 2d 1146, 1148 (Fla. 1995).
17. *Council v State,* 98 So. 3d at 117 (Fla. 1st DCA 2012).
18. Section 90.402, Fla. Stat. (2014).
19. Section 90.403, Florida Statues (2014).

Forensic Engineering Tools and Analysis of Heavy Vehicle Event Data Recorders (HVEDRs)

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Abstract

Since the 1990s, domestic passenger vehicles have been equipped with increasingly more sophisticated supplemental restraint system event data recorders (EDRs) that have become more commonplace in collision analysis. Many collision analysts are aware that most heavy commercial vehicles are likewise equipped with heavy vehicle event data recorders (HVEDRs) that may trigger during a hard braking or sudden deceleration event — or when the driver activates a signal to trigger an event to the system. Some heavy commercial vehicle engine manufacturers even provide an additional record of the last stop of the vehicle. Unfortunately, there are no uniform standards as to the information recorded or even the triggering criteria for an event regarding heavy commercial vehicles. HVEDR records oftentimes provide valuable information that assists the forensic engineer in analyzing collision or failure events. This paper provides the forensic engineer with HVEDR engine manufacturer download coverage and tools needed (as of the presentation of this paper), and explores anomalies in event recording that the forensic engineer should be aware may exist. A case study pertaining to an HVEDR record of a commercial vehicle having a peculiar recording anomaly is presented. This paper outlines the process of how the anomaly was resolved and the process of plotting the sequence of events for courtroom presentation.

Keywords

Forensic engineering, HVEDR, ECM, Caterpillar Electronic Technician, DDDL, DDEC Reports, Cummins PowerSpec, Cummins Insite, International ServiceMaxx, Paccar DAVIE, Volvo PTT/VCADS, Mack/Volvo V-MACK IV, commercial vehicle reconstruction

Background

As vehicles equipped with event data recorders (EDRs) become more ubiquitous, the forensic engineer must stay abreast of current developments within the applicable technology. Heavy vehicles (Class 3-8), as defined within this paper, contain a special subset of heavy vehicle event data recorders (HVEDRs), which lack the standardization prevalent within passenger vehicle EDRs. In general, the EDR function in passenger vehicles is contained within the electronic modules of the supplemental restraint system (airbags, seatbelt pre-tensioners, etc.), excluding certain Ford vehicles. In heavy vehicles, the HVEDR function is contained within one or more modules designed for operating the vehicle's drivetrain and emissions system, which are not specifically designed for collision sensing.

Heavy vehicles are equipped with standardized communication networks; the SAE J1708/J1587 is a serial network (low speed), or the SAE J1939 is a controller area network (CAN) (high speed and data). These communication networks connect to the diagnostic port (in-cab Deutsch connector) where a forensic engineer can access the vehicle's communication network and thereby image any event-related data stored on the vehicle. The in-cab Deutsch connector on most heavy trucks is usually located under the dashboard. However, there are exceptions, such as in certain Kenworth tractors, which have the in-cab Deutsch connector located near the driver's side door jamb behind the driver's seat.

Electronic control units (ECUs) for operating a heavy vehicle's drivetrain first became prevalent in the 1990s. Mainly spurred by emissions regulations, ECU technology has grown rapidly from its initial primitive form into the advanced computer controls equipped on newer vehicles. The manufacturers quickly determined that ECU modules could do more than just store the operating parameters of an engine and the vehicle. ECU units could record event data related to vehicle

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diagnostic faults, hard or quick stops, and the last or most recent stop of the vehicle — all useful data for analyzing mechanical operations and issues. In this paper, the term "ECU" will refer to systems with multiple electronic control units storing event-related data, and engine control module or "ECM" will refer to systems where only one module need be accessed for a complete download of event-related data.

Methods for Imaging HVEDR Data

Imaging HVEDR stored data is facilitated through one of four methods:

- On-vehicle, in-cab Deutsch connector with adapter.
- Surrogate vehicle connection.
- Benchtop download using a simulator harness.
- Benchtop download without simulator harness.

The first and preferred method using the in-cab Deutsch connector and adapter facilitates imaging the data while all ECUs and sensors are still attached to the vehicle and accessed through the vehicle's communication network. On-vehicle imaging entails attaching an RP-2010A-compliant communications adapter to the vehicle's diagnostic data port (Deutsch connector). There are multiple RP 2010A adapters available — some are manufacturer-specific and may not work well for connecting to all manufacturers' ECUs, whereas some aftermarket systems are universal. The recommended communication adapters by vehicle manufacturer are as follows:

- Detroit Diesel, Mercedes, and Paccar; RP-2010A Nexiq USB-Link adapter.
- Caterpillar; the CAT communication Adapter 3.
- Cummins; the INLINE 7.
- Volvo; either the Movimento or the Volvo Link.

Although imaging the ECU on-vehicle is the preferred method, in certain situations it may not be feasible or desirable. Imaging ECUs on the vehicle requires that the ignition be turned to the "ON" position, either by using the vehicle's key, if available, or by bypassing the ignition lock cylinder.

The second method of imaging a heavy vehicle ECU(s) is by using a surrogate vehicle, which must have an identical configuration to eliminate the potential for generating new faults that were not present or recorded by the damaged vehicle's ECU(s). Prior to swapping the ECU(s), the surrogate vehicle should be checked for active faults. If no fault codes are present, the ECU(s) from the damaged vehicle are swapped out and connected through the communication cables of the surrogate vehicle so that the ECU(s) can be interrogated by communication through the surrogate vehicle's in-cab Deutsch connector when imaging the damaged vehicle's ECU(s).

The third preferable download methodology consists of a benchtop download of the ECU(s) using either a simulator harness or a programming harness. A simulator harness has sensors or resistors that "trick" the ECU(s) into sensing a connection with a vehicle communication system during interrogation, and therefore prevents setting new fault code and possibly fault snapshots. The simulator harness must also be configured to match the vehicle the subject ECU(s) was removed from to avoid generating new fault codes during the imaging process of the interrogated ECU(s). Simulator harnesses can be costly and are time consuming to construct.

The final and least-preferred option is completing a bench download of the ECU(s) using a programming harness. A programming harness allows the user to connect to the ECU(s), but does not simulate any of the engine or vehicle sensors. Using a programming harness to interrogate the ECU(s) will generate new fault codes. To minimize setting new fault codes while imaging an ECU with a programming harness, the programming harness can be plugged into the "chassis" connector on an ECU while leaving the "motor" connector attached to all of the wiring for the motor (**Figure 1**), thus eliminating most, but not all, faults. However, circumstances may dictate that a benchtop download without a simulator harness may be the only method available for imaging HVEDR data.

Caterpillar

Since 1994, Caterpillar has equipped heavy- and medium-duty engines with an ECM accessible while using Caterpillar Electronic Technician (CAT ET). Starting in 1995, most Caterpillar ECMs recorded vehicle snapshots. Caterpillar stopped manufacturing over-the-road engines in 2009. Engines offered in new Caterpillar vocational trucks are manufactured

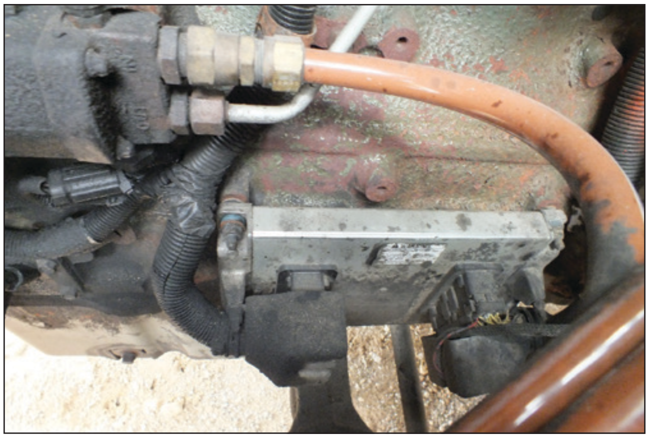

Figure 1
ECM chassis and motor connectors DDEC V.

by Navistar, which are accessible using Navistar ServiceMAXX software. A single ECM generally located on the left side of the engine block manages most downloadable Caterpillar engines (**Figure 2**). Caterpillar engines have three generations of ECMs with accessible HVEDR data; ADEM II, ADEM 2000/III, and ADEM IV.

Figure 2
Typical Caterpillar ECM location.

All three CAT ADEM generations have *Quick Stop* recording capabilities, but, by default, all CAT engines manufactured prior to January 2007 had the *Quick Stop* function turned off at the factory[1]. However, a technician could activate the *Quick Stop* function using CAT ET software, and some fleets running Caterpillar engines enabled the *Quick Stop* function on pre-2007 CAT engine-equipped vehicles. After January 2007, the *Quick Stop* function was defaulted as "ON" from the factory. Caterpillar *Quick Stop Records* record 44 seconds of data prior to the trigger point and 15 seconds after the trigger point at a 1 Hz frequency (one data point per second). The factory-default *Quick Stop* trigger on post 2007 is unknown, as Caterpillar's literature cites a rate of 0 miles-per-hour-per-second (mphps), which has been found to be incorrect[2]. The *Quick Stop* trigger on all Caterpillar ECMs can be user defined. Caterpillar *Quick Stop* data records consist of the vehicle's speed, accelerator pedal position, clutch pedal position, service brake pedal position, engine speed (RPM), cruise control status, and more.

Aside from recording *Quick Stops,* Caterpillar ECMs record diagnostic snapshots, triggered snapshots, and engine parameters. Both the diagnostic snapshots and the triggered snapshots record 9.12 seconds prior to the fault/trigger and 3.36 seconds after at 2.083 Hz (one data point per 0.48 seconds). The vehicle operator can trigger a snapshot record by toggling the cruise control set/resume switch on and off on a Caterpillar-equipped heavy road vehicle with ECM software post-dating November 2005.

In order for a Caterpillar ECM to write a complete *Quick Stop* record, the vehicle must maintain adequate battery voltage for 15 seconds after trigger activation. This indicates that if a power interruption occurs during a collision event, a *Quick Stop* record cannot be extracted using CAT ET. Synercom Technologies' TruckCRPT software has had some success in obtaining and decoding partially written *Quick Stop* records due to a power loss during the event[3].

Several known data irregularities exist within data extracted from Caterpillar ECMs, most of which are related to the date stamping of reports and snapshots. Several Society of Automotive Engineers (SAE) papers outline the specifics of Caterpillar ECM recording irregularities[2,4,5]. Another significant irregularity the forensic engineer must be aware of when examining data from a Caterpillar ECM is that all ADEM 2000, ADEM III, and ADEM IV EPA07 modules reported a 1 Hz recording rate on both *Quick Stops* and *Diagnostic Snapshots,* which, in reality, were gathered for the record at 2 Hz and 2.08 Hz, respectively. A software update for the ADEM IV EPA07 corrected this issue. To date, the recording rate anomaly remains a concern for engines equipped with the ADEM 2000, ADEM II "Bridge" module and the ADEM IV MXS/NXS ECMs[2]. Forensic engineers should be aware that the data obtained from an affected module will require adjustment to the proper time intervals between data points when using the information for a time and distance analysis of a particular recorded event.

Cummins

Cummins produces one of the most widely used engines in heavy over-the-road vehicles. In 2002, Cummins first equipped its engines with an ECM having the necessary hardware to record event-related data, but not the necessary firmware to access the data from the module. The early 2002 through 2005 Cummins ECMs recorded event-related data only after the ECM software was updated with firmware released in 2005. ECMs produced by Cummins in late 2004 or early 2005 shipped with the updated firmware, allowing for the recording of event-related data without software updates[1]. The specific ECMs requiring a re-flash in order to record EDR data and the production dates where the updated firmware was implemented in specific ECMs are beyond the scope of this paper. However, the information is covered during most in-depth training classes on HVEDRs.

Vehicles equipped with Cummins engines store event-related data on a single ECM, which is generally located on the left side of the engine (**Figure 3**). To access the complete event-related data, the forensics engineer uses two software applications: Cummins Insite and Cummins PowerSpec. Cummins Insite is a technician-level program that allows for the access of engine and vehicle parameters, in-depth fault information, audit trails, and other information. Cummins PowerSpec allows the forensic engineer to access most of the "event-related" data recorded by the ECM, including *Sudden Deceleration Reports*, vehicle trip information, fault codes, feature settings, data plate, and maintenance monitor data. Cummins PowerSpec is generally not utilized by technicians, and most dealerships and/or technicians will not have the software or even know of its existence. Without Cummins PowerSpec, the event-related data cannot be imaged.

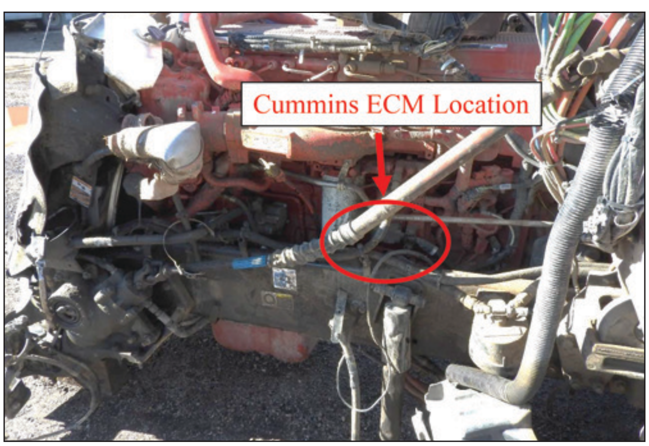

Figure 3
Typical Cummins ECM location.

Cummins ECMs built after the firmware upgrade — and ECMs from 2002 to 2005 with updated firmware — can record up to three *Sudden Deceleration Records,* which are accessed using Cummins PowerSpec and contain data for 59 seconds prior to the trigger and 15 seconds after the trigger, reported at a 1 Hz sampling rate. To trigger a *Sudden Deceleration*, the vehicle must slow at a default rate of 9 mphps (≈0.41*g*) or greater. *Sudden Deceleration Records* report vehicle speed, engine speed (RPM), throttle position, engine load, brake status, clutch status, cruise control status, and Malfunction Indicator Lamp (MIL) status at a reporting rate of 1 Hz. A few words of caution with Cummins *Sudden Deceleration Records*:

- *Sudden Deceleration Records* are recorded on volatile memory and then written to non-volatile memory at vehicle key-off. This means if a power interruption occurs during the collision, the *Sudden Deceleration Record* will not be recoded. Fault code snapshots, on the other hand, are recorded to non-volatile memory as they occur and may be correlated to a collision[5].

- Certain Cummins ECMs have a calibration error where the *Sudden Deceleration Record* is recorded at 5 Hz (0.2 second intervals), but reported at 1 Hz (1 second intervals)[6]. To account for this calibration issue, the forensics engineer must adjust the recorded data from the *Sudden Deceleration Record* of an affected ECM so that reported data intervals are spaced at 0.2 seconds from the trigger point, effectively compressing the data fivefold[6].

One notable difference with Cummins ECMs compared with other engine manufacturers is that setting a fault snapshot requires a fault to be active, go inactive, and then go active once more. This implies that the forensic engineer performing a Cummins ECM benchtop download with just a reprogramming harness should not generate any new fault code snapshots if the imaging is completed in a forensically sound manner (i.e., properly trained methods)[1].

Cummins equipped vehicles may also be fitted with Cummins RoadRelay, which is an in-dash trip and driver computer. RoadRelay 3, 4, and 5 are downloadable by the forensic engineer and can store *Panic Stops*. RoadRelay 3 requires special software (Cummins InRoads) while RoadRelay 4 and 5 can be imaged using Cummins PowerSpec. *Panic Stop* records on a RoadRelay 4 and 5 contain 59 seconds of pre-trigger data and 15 seconds of post-trigger data recorded at 1 Hz. The trigger threshold for a *Panic Stop* is a deceleration rate of 9 mphps (≈0.41*g*) — the same as a *Sudden Deceleration Record*. On a RoadRelay 3, the *Panic Stop* record reports 45 seconds prior to the trigger and 15 seconds post-trigger. The trigger threshold on a RoadRelay 3 is user programmable.

Figure 4
Cummins Road Relay.

Detroit Diesel

Detroit Diesel has been manufacturing ECUs with hardware to store event-related data since 1994. It currently has six generations of ECU-equipped engines capable of recording event-related data. Each generation of ECU has differences between the recorded data. The six generations of recording ECUs are DDEC III, DDEC IV, DDEC V, DDEC VI, DDEC 10, and GHG14. In 1997/1998, Detroit Diesel released a software update, allowing DDEC III ECUs to record data. However, the recorded data did not include *Hard Brake* records or *Last Stop* records. The functionality to record *Hard Brake* and *Last Stop* records was first introduced with the DDEC IV in 1998, and continues on to the latest generation of ECUs[1]. DDEC III, IV, and V are all single ECU systems, whereas DDEC VI consists of two modules, DDEC 10 consists of three modules, and GHG14 is either a three- or four-module system, depending on transmission configuration (manual vs automatic transmission).

To image data contained in a Detroit Diesel ECU, the forensic engineer must use two software suites: two versions of Detroit Diesel Diagnostic Link (DDDL), depending upon the ECU being interrogated, and Detroit Diesel Electronic Controls Reports (DDEC Reports). DDEC Reports accesses most of the incident-related data, but both pieces of software must be used to obtain a complete image of a Detroit Diesel ECU.

Detroit Diesel's one module ECUs have the module located on the left side of the engine block. The two-module ECUs consist of a Motor Control Module (MCM) and a Common Powertrain Controller (CPC). The MCM is located on the left side of the engine block and contains most of the engine parameters. The CPC is located in the tractor cab and contains most of the event-related data. The location of the CPC varies by tractor make and model, but is most often centered in the cab behind the dashboard. The three module Detroit Diesel ECUs consist of the MCM, CPC, and after-treatment control module (ACM) located on the underside of the tractor, most often by the diesel exhaust fluid (DEF) tank. The ACM retains data mainly related to the engine exhaust after-treatment. On four module ECUs, in addition to the three previously discussed modules, a Transmission Control Module (TCM01T) controls the Detroit Diesel automatic transmission when equipped.

A *Hard Brake* record recorded by a Detroit Diesel ECU consists of 60 seconds of data prior to the trigger and 15 seconds of data past the trigger, reported at 1 Hz. The trigger for Detroit Diesel ECUs is factory set at a speed drop of 7 mphps (≈0.32*g*), with a technician-changeable trigger. To trigger a *Hard Brake* event, the vehicle must be traveling a minimum of 10 mph prior to the speed drop, and the speed drop cannot be followed or proceeded by a speed gain of 4 mphps (≈0.18*g*) or greater[1]. Detroit Diesel ECUs can store up to two *Hard Brake* events and a single *Last Stop* record, reflecting the most previous operation of the vehicle. *Last Stop* records report 1 minute and 44 seconds prior to the vehicle's speed dropping to zero and 15 seconds thereafter. In order to trigger a *Last Stop* record, the vehicle must travel at a speed greater than 1.5 mph with the engine speed greater than 0 RPM. Then, the vehicle's speed must drop to 0 mph or the ignition turned off. Lastly, the vehicle must remain stopped for a minimum of 15 seconds[5].

Detroit Diesel ECUs record diagnostic snapshots that contain one minute of data prior to the diagnostic fault code becoming active at a 0.2 Hz (1 record every 5 seconds) interval. A note to the forensics engineer: If an ECU is imaged using a programming harness only, a high probability exists that new diagnostic snapshots will be written that will overwrite those previously existing. But, even if active fault codes exist on the vehicle after an event, no new diagnostic snapshots should be written if the forensic engineer images the ECUs directly through the in-cab Deutsch connector.

Another commonly useful data set obtained from Detroit Diesel ECUs is the *Daily Engine Usage* reports, which provide the following detail: drive time, idle time, and off time for the last 30 days. The data imaged can be useful when checked against a driver's logs and when investigating potential hours-of-service violations.

Testing demonstrates that in order for a DDEC IV or V ECU to write a *Hard Brake* record, the vehicle must have continuous power for at least 20 seconds and a key-off condition prior to the vehicle losing power. The DDEC VI generation of ECUs requires only a key-off condition prior to the vehicle losing power to write a *Hard Brake* event. On DDEC VI, X and GHG14 ECUs, the *Last Stop* is written immediately after the trigger event[5].

Similar to Cummins RoadRelay, Detroit Diesel offered the ProDriver computer. ProDriver can contain up to 5 *Hard Brake* records and a *Last Stop* record. For a *Hard Brake* event, ProDriver reports 90 seconds prior to and 30 seconds after a trigger event. The driver can manually trigger a snapshot for ProDriver by pressing a button. When a Snapshot is manually triggered, a record of the 2 minutes prior to activation of the snapshot button will be recorded[1]. ProDriver was discontinued in 2010, and is not widely equipped on vehicles.

Figure 5
Detroit Diesel ProDriver.

International/Navistar

Many International engines have accessible event-related data since 2010 and downloadable parameter data since 2007. The downloadable parameter data in pre-2007 International engines includes diagnostic trouble codes, vehicle events, and engine and vehicle parameters. Generally, the single ECM on International engines is located on the left side of the engine block. Starting in 2010, newly built International MaxxForce engines started to record event-related data. Access to these engines is made possible using International's ServiceMaxx software.

International MaxxForce engines that have the ability to record event-related data can record up to two *Hard Accel/Decel* records and up to two *Last Stop* records. *Hard Accel/Decel* records are triggered when the vehicle either accelerates or decelerates at a user-programmable rate. A *Hard Accel/Decel* record will store 105 seconds of data at 1 Hz prior to the trigger, a snapshot of engine and vehicle parameter at the time of the trigger, and 15 seconds after the trigger. *Last Stop* records are recorded once the vehicle comes to a stop and the engine is shut off — or the vehicle comes to a stop and idles for at least 2 minutes. A *Last Stop* record contains the same amount of data as a *Hard Accel/Decel* record at the same recording frequency of 1 Hz.

International engines can record diagnostic snapshots when fault codes are set. These snapshots contain data from a single point in time and do not record a time series of the data surrounding the trigger. International engines can also contain vehicle activity reports, vehicle event reports, diagnostic trouble codes, parameters, and vehicle information[1].

Mack

Starting in 1998, vehicles equipped with Mack engines can contain event-related data. However, the software necessary to access the data in a forensically sound manner is available only to Mack/Volvo-authorized providers. Three options exist for the forensic engineer to obtain the EDR data on a Mack-equipped vehicle. The first option is to have the Mack/Volvo-authorized provider directly download data from the vehicle. The second option requires the Mack/Volvo-authorized provider to use a surrogate vehicle with the ECUs swapped. The third is to remove the ECUs and send them to the authorized provider to attempt a benchtop download. More information on authorized providers and costs for data downloads can be found at www.hvedr.com.

Mack uses a two-ECU or three-ECU system — each consisting of a Vehicle Electronic Control Unit (VECU) and an Engine Electronic Control Unit (EECU) — and the three-ECU system having the addition of an Instrument Cluster ECU in 2006 and later

Mack trucks. The EECU is located on the left side of the engine block, whereas the VECU is located within the cab, generally near the passenger-side kick panel. The Instrument Cluster ECU is usually integrated into the instrument cluster, and the entire instrument cluster must be removed and sent to the authorized provider for a benchtop download (**Figure 6**).

Figure 6
Mack/Volvo instrument cluster ECU.

Mack ECUs either contain two deceleration-triggered events or one deceleration-triggered event and one last stop event, depending on the software revision. Most Mack engines built from 1998 to 2007 record 15.8 seconds of data prior to the trigger for either a deceleration event or a last stop event, and 16 seconds after the trigger event at a reported interval of 5 Hz (one data point per 0.2 seconds). These same modules require a default 10 mphps speed increase or drop (±0.46*g*) and a change in engine speed of 50 rpm/second to set a deceleration trigger event, although the speed change is user programmable. In order to set a last stop event, a Mack-equipped vehicle must have traveled faster than 45 mph prior to coming to a stop, and the parking brake must be set prior to the vehicle's ignition key being switched to the off position.

Starting in 2006, Mack released V-MACK IV to replace the earlier V-MACK III. V-Mack IV-equipped vehicles record 60 seconds of data prior to a deceleration triggered event and 30 seconds after, reported at 4 Hz (0.25 data points per second). The factory default for the deceleration trigger was changed to 10 mphps, but is user programmable. The last stop triggered events on a V-MACK IV records 90 seconds prior to the vehicle coming to a stop, reported at 4 Hz (0.25 second intervals) [1].

Mack ECUs can also record diagnostic snapshots when a fault code is first detected, which contains data from a single point in time. Mack ECUs also contain vehicle and engine parameters and various other information that may be useful to the forensic engineer.

Mercedes

Mercedes engines appeared in North American heavy vehicles from 2000 to 2010, and record essentially the same information as Detroit Diesel engines of the same vintage. Mercedes ECUs are accessed using the same software as Detroit Diesel engines; specifically, DDDL and DDEC Reports. From 2000 to 2006, Mercedes engines contained a two-module ECU system, consisting of a *Pumpe Liene Dusse* (PLD) located on the left side of the engine block and the Vehicle Control Unit (VCU) located in the cab of the tractor (**Figure 7**). After 2006, Mercedes engines switched to Detroit Diesel's DDEC VI ECU system.

One notable feature of pre-2007 Mercedes ECUs is that a *Last Stop* record is set when the engine rpm drops to 0, regardless of the vehicle's speed[5]. An equally

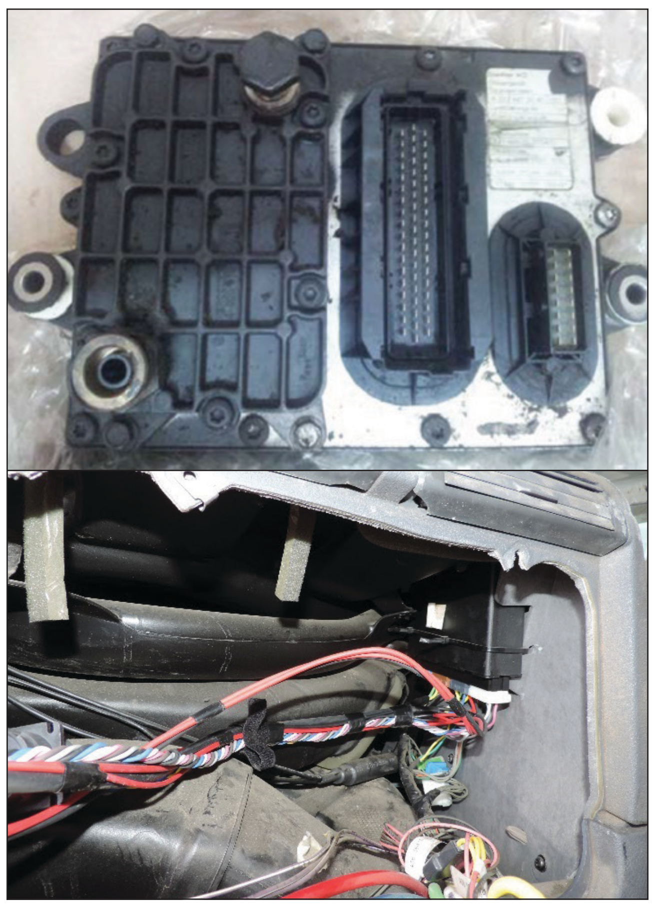

Figure 7
Mercedes ECUs.

notable difference between the data from Mercedes ECUs and Detroit Diesel ECUs is that Mercedes data does not contain an audit trail to monitor changes to the ECU's programming. A word of caution to the forensic engineer: Testing has found that if active faults are present on pre-2007 vehicles with Mercedes ECUs, accessing the modules through the Deutsch connector will result in the diagnostic records being overwritten[7].

Paccar

Paccar, the parent company of Kenworth, Peterbilt, DAF, and other vehicle manufacturers, started producing its own branded engines for the North American market in 2008. These engines (branded "PX" and "MX" series engines) are increasingly more common. The PX branded engines are manufactured by Cummins and contain Cummins ECUs. Accessing Paccar PX engines for imaging uses the same methods and contains the same data elements as outlined in the previous Cummins section of this paper.

The Paccar MX-13 engine was introduced into the North American market in 2013 and contains event-related data that the forensic engineer can access using Paccar's Software DAVIE4. A few notes: DAVIE4 requires an active Internet connection to properly function, and accessing Paccar MX engine parameters requires the use of the dealer-only software Paccar Engine Pro[1].

Paccar ECUs containing event-related data in Paccar MX series engines are the Paccar Multi-Control Injection (PMCI), the Emissions After-Treatment System (EAS), and the Cab Electronic Control Unit (CECU). The PMCI is located on the left side of the engine block (**Figure 8**), the EAS is generally located near the DEF tank under the cab, and the CECU is typically mounted in the dash within the interior of the tractor.

Paccar MX-13 engines can record *Fast Stops,* diagnostic trouble code freeze frames, trip data, and more. A *Fast Stop* record contains 5 seconds of data prior to the trigger for the *Fast Stop* and 5 seconds after the *Fast Stop* at 4 Hz (0.25 second intervals). Paccar ECUs store the last 3 *Fast Stops*, with the oldest of the three records overwritten by subsequent events. The recording of *Fast Stops* can be disabled by a technician by changing the factory default trigger. The default trigger to set a *Fast Stop* Record is 11.2 mphps (≈0.51*g*), but is user programmable[8].

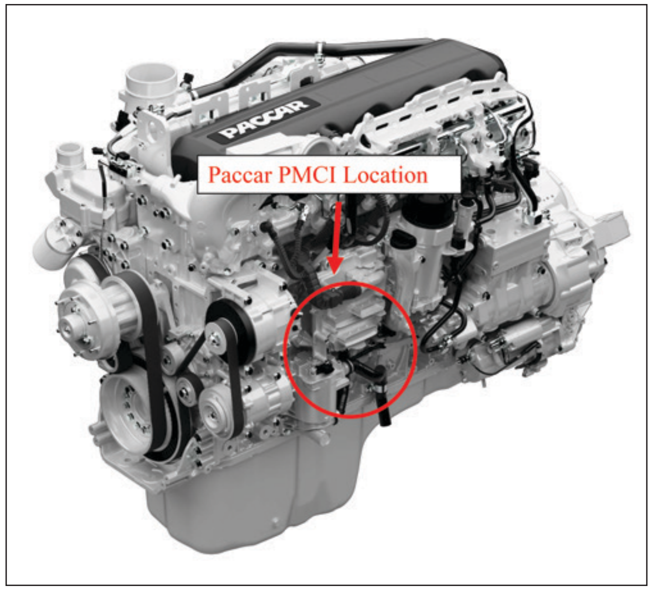

Figure 8
Typical Paccar PMCI location
(image courtesy of www.ccjdigital.com).

Paccar ECUs can store snapshots, which can be operator activated by toggling the cruise control "Resume" switch followed by the cruise control "Set" switch. Paccar ECUs can store up to three snapshots, each containing 10 seconds of pre-trigger and 5 seconds of post-trigger data at 2 Hz (0.5 second intervals). Certain diagnostic trouble codes, generally critical faults, can also trigger a snapshot report.

Diagnostic freeze frames most often contain only one data point in time when the diagnostic trouble code became active, but some diagnostic codes will trigger multiple freeze frame data sets surrounding when the diagnostic code became active. This data will encompass 5 seconds prior to the diagnostic code becoming active, the time of the diagnostic codes and the 4 seconds after the diagnostic codes — all at 1 Hz.

Volvo

From 2002 to 2010, Volvo heavy vehicle engines recorded *Freeze Frames* surrounding diagnostic trouble codes. The data surrounding a fault code consists of two data points prior to the fault, a data point at the time of the fault, and two data points after the fault code. The two data points recorded prior to the fault are spaced 30 seconds apart, but, due to the way Volvo stores data, the timing of the closest data point could be anywhere from 0 seconds prior to the fault to 30 seconds prior to the fault[1]. In order to image Volvo ECUs from 2002 to 2010, the forensic engineer must use the

Pro Tech Tool/Volvo Computer Aided Diagnostic System (Volvo PTT/VCADS). Starting in 2010, Volvo switched over to the same ECU controls as Mack engines. Although this enabled the recording of deceleration events and last stop records, the recorded data can only be imaged by Mack/Volvo-authorized service providers. The data on the post 2010 Volvo is the same as the data contained on the same vintage Mack ECUs and outlined in a previous section of this paper.

Volvo heavy vehicles may be equipped with supplemental restraint systems (SRS) that may have limited event-related data stored on the SRS ECU. An SRS ECU in a Volvo heavy vehicle must be sent to the manufacturer for retrieval of an event-related acceleration pulse.

Case Study

The following case study revolves around the analysis of *Sudden Stop* data imaged from a 2005 Kenworth T2000 equipped with a Caterpillar C15 heavy-duty diesel engine having a Caterpillar ADEM IV HVEDR. The Kenworth tractor/semi-trailer experienced a loss of control during a sudden heavy rain storm weather event in southern Wyoming. The collision event involved three tractor/semi-trailer units, and was initiated by the loss-of-control event for the Kenworth. The Kenworth semi-trailer came to rest along the inside median, partially blocking the inside traffic lane of the roadway. The right rear of the Kenworth's semi-trailer was subsequently sideswiped by a 2007 Peterbilt tractor pulling a loaded livestock semi-trailer and traveling in the inside traffic lane in the same direction as the Kenworth. The Peterbilt came to rest in the outside traffic lane approximately 50 feet beyond the final rest position of the Kenworth. After an extended time period, a 2004 Volvo tractor/semi-trailer entered the collision area while traveling in the outside traffic lane and collided with the rear of the stopped livestock semi-trailer of the Peterbilt, resulting in catastrophic damage to both the Volvo tractor and Peterbilt semi-trailer.

The authors were called upon to document the roadway evidence and post-collision condition of the Kenworth and Volvo within a two-week period following the collision date. The Peterbilt and its livestock semi-trailer were no longer available for inspection. The scene evidence was recorded using a total station survey as well as a high-resolution custom aerial of the scene flown specifically for this incident. The Kenworth was documented, the airbrake system was inspected to include push-rod adjustments and brake shoe/drum conditions, and the HVEDR was accessed and imaged for further analysis.

The Kenworth was traveling within the inside (left) traffic lane of a stretch of four-lane-two-way interstate highway having a 75-mph posted regulatory speed limit and a brushed concrete surface. The roadway section was on the downgrade side of an extended crest vertical curve of approximately -3%. The roadway geometry also consisted of an approximate 2,000-foot radius horizontal curve to the left at the centerline of the travel lanes for the Kenworth's travel direction, having an approximate 7% super-elevation toward the outside edge of the roadway. **Figure 9** provides a diagram of the collision scene, documented evidence, and final rest locations of the three tractor/semi-trailer combinations.

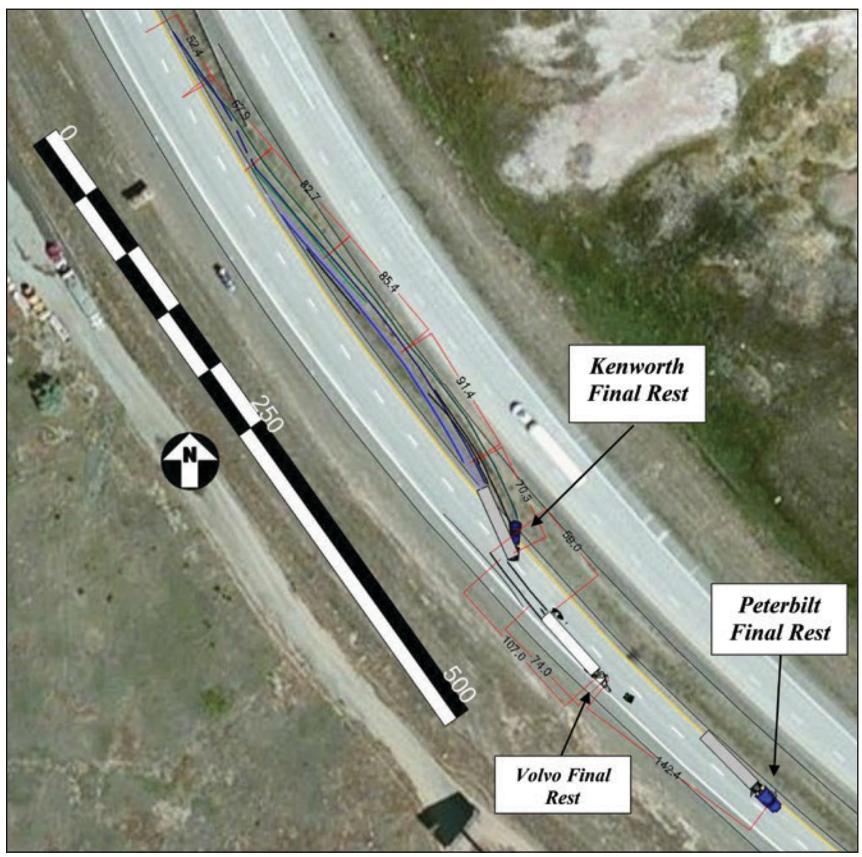

Figure 9
Collision scene evidence.

Emergency personnel cut the power supply cables from the service batteries of the Kenworth. However, the authors were able to provide power to the vehicle using a high-amperage jump box connected to the main power terminals located on the driver's side firewall inside the engine compartment, as shown in **Figure 10**. The Kenworth Caterpillar engine was equipped with an ADEM IV generation Caterpillar HVEDR, located on the driver's side of the engine block at frame rail height, also shown in **Figure 10**.

Figure 10
Power supplied through main power terminal; location of HVEDR.

The Kenworth's HVEDR was accessed using the preferred direct download method through the in-cab Deutsch Connector while using Caterpillar Electronic Technician software. Vehicle speed limit and cruise control settings, as well as trip parameters extracted from the download of the ADEM IV, provide the governed maximum speed limit, high cruise control speed limit, and *Quick Stop* trigger rate settings for the Kenworth, which is also shown in **Figure 11**.

The *Quick Stop* trigger rate for the Kenworth was set at a speed drop of 9 mph/second or greater for recording a *Quick Stop* event. During the loss-of-control event for the Kenworth, the driver had applied braking, and the event produced a speed loss of the vehicle with sufficient magnitude to trigger a *Quick Stop* occurrence consistent with the incident date and adjusted ECM clock time. The *Quick Stop* record indicates the cruise control system was active until service brake application at the record's time entries between -7 and -6 seconds. The initial speed range for the Kenworth ranged from 73 mph to 76 mph prior to brake application, followed by a speed drop to 7 mph at time entry 0-seconds, and a subsequent increase in vehicle speed up to 38 mph before decreasing toward final stop. **Figure 12** illustrates the *Quick Stop* record as recorded for the event.

Vehicle Speed Parameters		
Vehicle Speed Calibration	27526 P/mile	1
Vehicle Speed Cal (J1939-Trans)	Unavailable	
Vehicle Speed Cal (J1939-ABS)	Unavailable	
Vehicle Speed Limit	75 mph	5
VSL Protection	1398 rpm	1
Tachometer Calibration	113.0 PPR	1
Soft Vehicle Speed Limit	Yes	1
Two Speed Axle - Low Speed Range Axle Ratio	Unavailable	
Nominal Axle Ratio - High Speed Range Axle Ratio	Unavailable	
Cruise Control Parameters		
Low Cruise Control Speed Set Limit	30 mph	7
High Cruise Control Speed Set Limit	75 mph	5
Fuel Correction Factor	0 %	0
Dash - Change Fuel Correction Factor	No	0
Dash - PM1 Reset	No	0
Dash - Fleet Trip Reset	No	0
Dash - State Selection	Yes	0
Theft Deterrent System Control	No	0
Theft Deterrent Password	****	
Quick Stop Rate	9 mph/s	2
Vehicle Overspeed Threshold	73 mph	1

Figure 11
Kenworth Caterpillar engine ADEM IV parameters.

Frame	Time		Engine Speed	Vehicle Speed	Cruise/Idle On-Off	Clutch Pedal	Service Brake	Accelerator Pedal	Cruise Mode
Unit	Seconds		rpm	mph				%	
Minimum Value			0	4				3	
Maximum Value			1630	76				85	
1	-44		1569	73	On	Off	Off	3	Active
2	-43		1567	73	On	Off	Off	3	Active
3	-42		1572	73	On	Off	Off	3	Active
4	-41		1565	73	On	Off	Off	3	Active
5	-40		1575	73	On	Off	Off	3	Active
6	-39		1571	73	On	Off	Off	3	Active
7	-38		1575	73	On	Off	Off	3	Active
8	-37		1577	74	On	Off	Off	3	Active
9	-36		1572	73	On	Off	Off	3	Active
10	-35		1578	74	On	Off	Off	3	Active
11	-34		1579	74	On	Off	Off	3	Active
12	-33		1584	74	On	Off	Off	3	Active
13	-32		1584	74	On	Off	Off	3	Active
14	-31		1581	74	On	Off	Off	3	Active
15	-30		1586	74	On	Off	Off	3	Active
16	-29		1591	74	On	Off	Off	3	Active
17	-28		1596	74	On	Off	Off	3	Active
18	-27		1594	74	On	Off	Off	3	Active
19	-26		1596	74	On	Off	Off	3	Active
20	-25		1597	75	On	Off	Off	3	Active
21	-24		1600	75	On	Off	Off	3	Active
22	-23		1605	75	On	Off	Off	3	Active
23	-22		1604	75	On	Off	Off	3	Active
24	-21		1609	75	On	Off	Off	3	Active
25	-20		1608	75	On	Off	Off	3	Active
26	-19		1607	75	On	Off	Off	3	Active
27	-18		1615	75	On	Off	Off	3	Active
28	-17		1616	75	On	Off	Off	3	Active
29	-16		1614	75	On	Off	Off	3	Active
30	-15		1615	75	On	Off	Off	3	Active
31	-14		1616	75	On	Off	Off	3	Active
32	-13		1618	75	On	Off	Off	3	Active
33	-12		1623	75	On	Off	Off	3	Active
34	-11		1624	76	On	Off	Off	3	Active
35	-10		1626	76	On	Off	Off	3	Active
36	-9		1630	76	On	Off	Off	3	Active
37	-8		1622	76	On	Off	Off	3	Active
38	-7		1611	75	On	Off	Off	3	Active
39	-6		1394	70	On	Off	On	3	Not Active
40	-5		1239	59	On	Off	On	3	Not Active
41	-4		1204	57	On	Off	On	3	Not Active
42	-3		1049	51	On	Off	On	3	Not Active
43	-2		807	40	On	Off	On	3	Not Active
44	-1		481	26	On	Off	On	3	Not Active
45	0		42	7	On	Off	On	3	Not Active
46	1		85	13	On	Off	Off	6	Not Active
47	2		34	19	On	Off	Off	6	Not Active
48	3		0	25	On	Off	Off	17	Not Active
49	4		0	32	On	Off	Off	18	Not Active
50	5		0	38	On	Off	Off	17	Not Active
51	6		0	36	On	Off	Off	23	Not Active
52	7		0	33	On	Off	Off	13	Not Active
53	8		0	27	On	Off	Off	12	Not Active
54	9		0	23	On	Off	Off	61	Not Active
55	10		0	19	On	Off	Off	85	Not Active
56	11		0	16	On	Off	Off	77	Not Active
57	12		0	11	On	Off	Off	74	Not Active
58	13		0	7	On	Off	Off	73	Not Active
59	14		0	5	On	Off	Off	73	Not Active
60	15		0	4	On	Off	Off	73	Not Active

Figure 12
Kenworth ADEM IV *Quick Stop* record.

The Kenworth was equipped with an ADEM IV generation ECM, which had a recording anomaly where each record was reported within the table shown in **Figure 12** as though at 1-second intervals (1Hz), when, in fact, the recordings were made every 0.5 seconds (2Hz). Accordingly, the data in **Figure 12** must be adjusted to reflect the recording anomaly in order to properly reflect the timing of the event for the Kenworth.

Additionally, in order to verify the *Quick Stop* record as related to the subject incident, the deceleration of the Kenworth and timing of the Kenworth's path after leaving the roadway were reconstructed using kinematic methods. The friction for the median and the wet roadway surface related to truck tires was obtained[9]. From the scaled diagram of the scene evidence, the incremental rotation and linear motion of the Kenworth to final rest were determined. Finally, the speeds and timing for each increment were calculated using kinematic methods as follows:

$$D3jk := \begin{pmatrix} 52.4 \\ 67.9 \\ 82.7 \\ 85.4 \\ 91.4 \\ 70.3 \end{pmatrix} \cdot ft \qquad \theta 3jk := \begin{pmatrix} 51.8 \\ 77.3 \\ 137.7 \\ 152.4 \\ 168.1 \\ 150.1 \\ 148.2 \end{pmatrix} \cdot deg$$

$\mu max := 0.50$ friction range of median (SAE830612 mud)

$$\Delta\theta 3_k := \frac{|\theta 3jk_k| + |\theta 3jk_{k+1}|}{2}$$

$\mu road := 0.50$ friction range of truck tire on wet concrete (SAE830612)

$$Vjk3max := \left[2 \cdot g \left[\sum_k \left(\mu max \cdot \sin\left(\Delta\theta 3_k\right) \cdot D3jk_k\right)\right]\right]^{\frac{1}{2}}$$

$Vjk3max = 62.0 \cdot mph$ speed at start of jackknife to rest

On-road rotation and braking:

$Dbrakeecm := 153 \cdot ft \quad \theta := \theta 3jk_0$

$$Vinitial := \sqrt{Vjk3max^2 + 2 \cdot g \cdot (\mu road \cdot \sin(\theta)) \cdot Dbrakeecm}$$

$Vinitial = 75.1 \cdot mph$

The kinematic analysis produced a confirmation for the Kenworth's initial speed at the start of braking.

Finally, the corrected HVEDR data (corrected to 2 Hz from the reported 1 Hz within the *Quick Stop* record) from the initiation of braking by the Kenworth until final rest was plotted and compared to the previous kinematic analysis results, as shown in **Figure 13**, **Figure 14,** and **Figure 15**.

The case example presented provides a basic outline of general procedures for a forensic analysis of HVEDR data:

- Plot a scale diagram of the roadway evidence, placing the heavy vehicle on the diagram at regular intervals.
- Calculate the deceleration of the heavy vehicle across the evidence area.
- Determine if the HVEDR for the subject vehicle has any data recording anomalies.
- Adjust for HVEDR recording anomalies.
- Graph the HVEDR data and/or calculated deceleration and compare to roadway evidence.
- Interpret the data for vehicle dynamics.

Findings and Final Observations

Having an HVEDR record should never be the substitute for engineering analysis. Independent calculations for determining the speed of a heavy vehicle should be completed to verify the speeds recorded in an HVEDR record whenever appropriate physical evidence from the collision event is available. A proper engineering analysis will assist the forensic engineer in determining if anomalies in the data record exist, as well as confirm whether or not the record is related to the subject incident.

Graphical representations of the HVEDR data provide a visual means of presenting the timing of an incident involving a heavy vehicle to a jury. When coupled with a detailed scene diagram that places the heavy vehicle (and other involved vehicles) on a scaled diagram of the scene, a clear and effective presentation of the collision timing is achieved.

Actual Time @2htz (seconds)	ECM time increm	ECM Time Value	distance	Velocity (fps)	Ave drag factor	Ave Calced Speed MPH	Brake Status	ECM Reported MPH	
12			0.0	0.0	0.294	0.0			Final rest
11.5	60	15	1.2	4.7		3.2	off	4	
11	59	14	4.7	9.5		6.5	off	5	
10.5	58	13	10.7	14.2		9.7	off	7	
10	57	12	18.9	18.9		12.9	off	11	
9.5	56	11	29.6	23.7		16.1	off	16	
9	55	10	42.6	28.4		19.4	off	19	
8.5	54	9	58.0	33.1		22.6	off	23	
8	53	8	75.8	37.9		25.8	off	27	
7.5	52	7	95.9	42.6		29.0	off	33	
7	51	6	118.4	47.3		32.3	off	36	
6.5	50	5	143.2	52.1		35.5	off	38	Strike median cables
6	49	4	170.4	56.8		38.7	off	32	
5.5	48	3	200.0	61.5		42.0	off	25	
5	47	2	232.0	66.3		45.2	off	19	
4.5	46	1	266.3	71.0		48.4	off	13	
4	45	0	303.0	75.8		51.6	on	7	Cab rotates to maximum angle
3.5	44	-1	342.1	80.5	Dist time 0.5	54.9	on	26	
3	43	-2	383.5	85.2	to 2 seconds	58.1	on	40	
2.5	42	-3	427.3	90.0		61.3	on	51	
2	41	-4	473.4	94.7	153.0	64.5	on	57	start jackknife on median
1.5	40	-5	522.0	99.4		67.8	on	59	
1	39	-6	572.9	104.2		71.0	on	70	
0.5	38	-7	626.4	110.0		75.0	off	75	In lane
0	37	-8	681.8	111.5		76	off	76	
-0.5	36	-9	737.5	111.5		76	off	76	
-1	35	-10	793.3	111.5		76	off	76	
-1.5	34	-11	849.0	111.5		76	off	76	
-2	33	-12	904.4	110.0		75	off	75	
-2.5	32	-13	959.4	110.0		75	off	75	
-3	31	-14	1014.4	110.0		75	off	75	
-3.5	30	-15	1069.4	110.0		75	off	75	

Figure 13
Corrected HVEDR data.

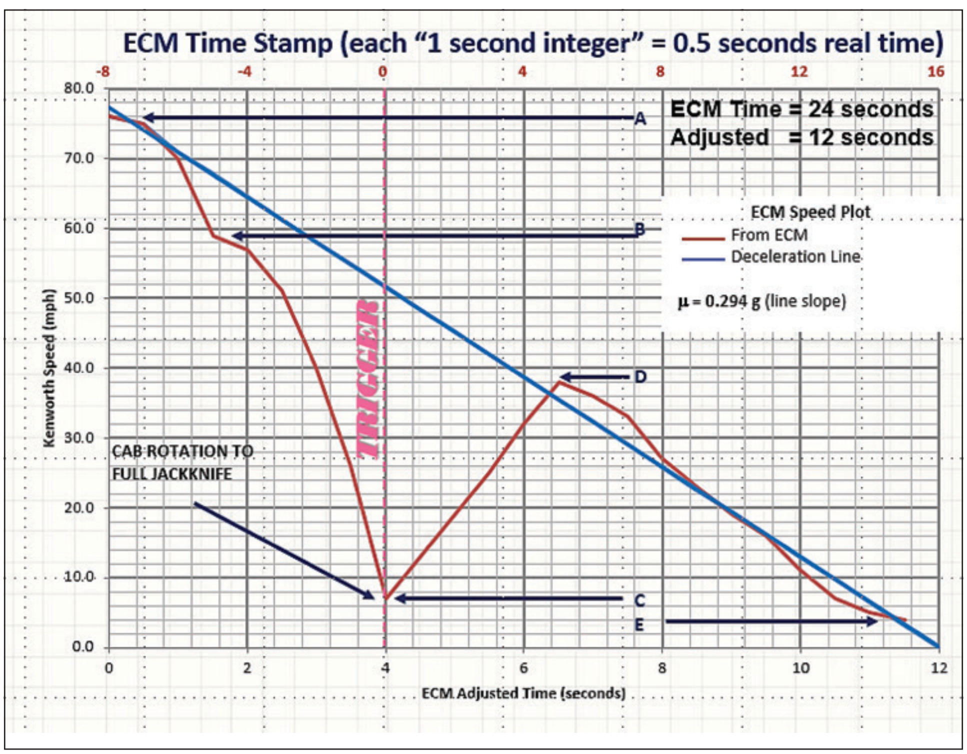

Figure 14
Graphical analysis of HVEDR data.

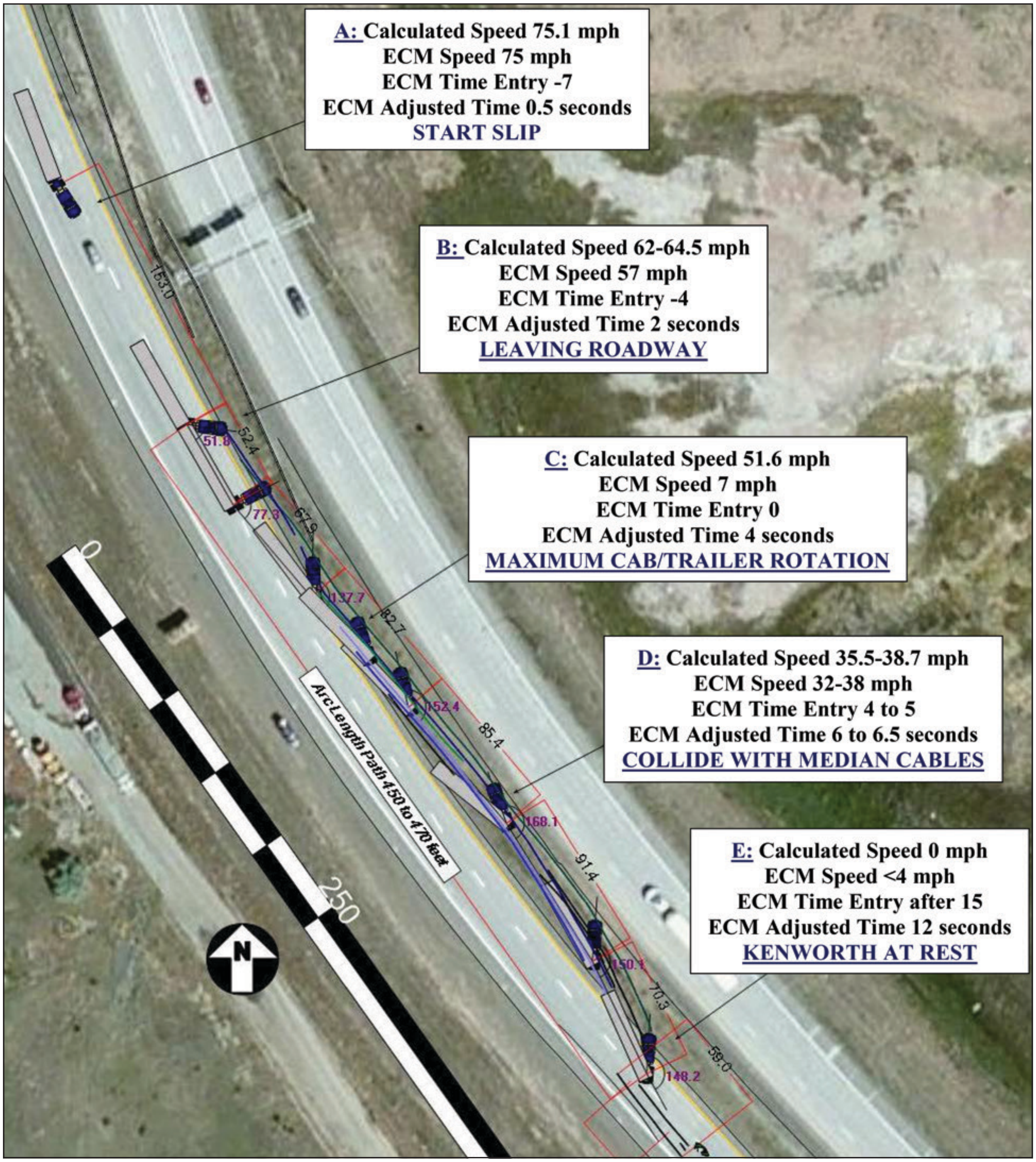

Figure 15
Diagram of Kenworth Dynamics.

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Appendix A

Possible EDR Data by Engine Manufacturer

Caterpillar

Years	ECM	Sudden Deceleration	Last Stop	Snapshots	eLog
1994	ADEM II	Not recorded	Not recorded	Not recorded	Not recorded
1995-2006	ADEM II & 2000/III	Can be recorded if programed	Not recorded	Diagnostic and user triggered	Not recorded
2007-2010	ADEM IV	Up to 2 recorded	Not recorded	Diagnostic and user triggered	Not recorded

Cummins

Years	Engine	Sudden Deceleration	Last Stop	Snapshots	eLog
1998-2001	IS-series	Not recorded	Not recorded	Not recorded	Not recorded
2002-2004	IS-series	Can be recorded if ECM updated	Not recorded	Diagnostic	Not recorded
2005+	IS-series	Up to 3 recorded. Trigger 9 mphps	Not recorded	Diagnostic	Not recorded

Detroit Diesel

Years	ECM	Sudden Deceleration	Last Stop	Snapshots	eLog
1997	DDEC III	Not recorded	Not recorded	Not recorded	Not recorded
1998-2006	DDEC IV & V	Up to 2 recorded Trigger 7 mphps	Recorded	Diagnostic last 3	Recorded
2007-2009	DDEC VI	Up to 2 recorded. Trigger 7 mphps	Recorded	Limited diagnostic	Recorded
2010+	DDEC 10, GHG 14	Up to 2 recorded. Trigger 7 mphps	Recorded	Diagnostic last 3	Recorded

International

Years	Engines	Sudden Deceleration	Last Stop	Snapshots	eLog
2010+	MaxxForce 11, 13, 15	Up to 2 recorded Trigger programmable	Recorded	Diagnostic	Not recorded

Appendix A

Continued

Mack

Years	ECM	Sudden Deceleration	Last Stop	Snapshots	eLog
1998-2007	V-MACK III	Up to 2 recorded Trigger 10 mphps	Can be recorded	Diagnostic	Not recorded
2006+	V-MACK IV	Up to 1 recorded Trigger 10 mphps	Recorded	Diagnostic	Not recorded

Mercedes

Years	Engines	Sudden Deceleration	Last Stop	Snapshots	eLog
2000-2006	MBE 900 & 4000	Up to 2 recorded Trigger 7 mphps	Recorded	Diagnostic Last 3	Recorded
2007-2010	MBE 900 & 4000	Up to 2 recorded Trigger 7 mphps	Recorded	Limited diagnostic	Recorded

Paccar

Years	Engines	Sudden Deceleration	Last Stop	Snapshots	eLog
2008+	PX-6,7,8,9	Up to 3 recorded Trigger 9 mphps	Not recorded	Diagnostic	Not recorded
2013+	MX-13	Up to 3 recorded Trigger 11.2 mphps	Recorded	Diagnostic and user triggered	Not recorded

Volvo

Years	Engines	Sudden Deceleration	Last Stop	Snapshots	eLog
2002-2010	D-11,12, 13,16	Not recorded	Not recorded	Diagnostic	Not recorded
2010+	D-11,12, 13,16	Up to 1 recorded Trigger 10 mphps	Recorded	Diagnostic	Not recorded

The Impact of the Lack of Marine and Rail Standards on the Transportation of Large Power Transformers

By David Gillingham, P. Eng. (NAFE 935A)

Abstract

Power transformers (>10MVA) are typically shipped from the factory by rail or marine cargo ship. In these harsh shipping environments, transformers are subjected to a variety of vibrational and impact forces. If these forces are too great, the transformers could be damaged, resulting in premature failure. There are few guidelines that describe best practices for monitoring, and, more importantly, mitigating such stresses when shipping transformers. Furthermore, manufacturers, railways, and marine shipping companies do not always have this information available, particularly for refurbished units. This paper discusses the impact this documentation drought may have for the affected parties.

Keywords

Transformer, rail, marine, shipping, vibration, impact, acceleration, pitch, yaw, roll

Introduction

With the aging of North America's power utility infrastructure, in conjunction with urban densification, a large percentage of generation, transmission, and distribution utilities (as well as industrial users) are purchasing large power transformers in ever-increasing numbers. But for many of these asset owners, the location of use for the transformer is many hundreds, if not thousands, of miles away from the manufacturing plant. Because of the weight or clearance restrictions on roadways, this often means transformers must travel to site by rail. Additionally, the manufacturing plant may be located overseas, which means that part of the transformer's journey is by marine vessel.

Transformer purchase specification documents provided to a manufacturer generally identify the specific electrical requirements that must be met, and usually include some form of reference to the external mechanical connections to the transformer, such as primary and secondary bus connections. However, the purchaser relies on the manufacturer to design and construct the internal components of the transformer. The challenge to the manufacturer lies with providing a transformer that is cost effective and suitable for the intended application, which would be easily facilitated if it could feasibly build the transformer on-site. However, the manufacturer must instead design and manufacture the transformer so that it will not only perform according to the end-user's specifications, but also withstand the various environmental conditions and mechanical forces it would be subjected to during transportation to the site.

Although it is essential in the course of designing and transporting power transformers to consider appropriate protective measures against environmental factors, such as weather and corrosive marine environments, these factors are outside the scope of this paper. Instead, it focuses on the various acceleration forces applied during transportation and the dynamic response of the transformers due to such forces.

The Transformer Market

According to data obtained from the United States International Trade Commission Interactive Tariff and Trade DataWeb[1], between 2010 and 2015, the United States imported nearly 1,200 large power transformers (>10MVA) per year, with an annual value totaling more than $1 billion, from around the globe, including North and South America. More than 500 of these units were imported from Europe and Asia alone, so the assumption could be made that nearly half of all imported

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power transformers were exposed to the marine shipping environment[*].

Similarly, in Canada, between the years 2011 and 2015, the import market for large power transformers averaged more than $180 million annually[2]. Although no specific data was available regarding the actual number of units, based on the import data for the United States, it could be estimated that approximately 200 units were imported annually from other countries — with approximately 40% from outside North and South America (where railcar or truck would be considered the primary method of transportation to site).

With the utility and large industrial electrical infrastructure in North America continuing to age, it is expected that the importation of large power transformers will continue to occur in the foreseeable future. Although it is difficult to obtain information regarding the percentage of power transformer damage claims where the failure can be directly attributed to transportation, it is the author's experience that this number is statistically significant — at least with respect to total loss value.

As will be discussed later in this paper, there are a number of standards and guidelines in place to guide manufacturers and shippers in the proper care and handling of a power transformer; however, it is the author's experience that the manufacturers do not generally adhere to the specifications contained in these documents. As a result, it becomes very difficult to accurately identify transformer failures that can be attributed directly to transportation. In addition, it is likely that these statistics will not change significantly in the future, unless the transformer industry makes a concerted effort to comply with (and maintain) these standards.

The Transportation Environment

The transportation environment for large power transformers is harsh, since it subjects transformers to forces that are not normally experienced during their operational life. These forces include vibration, impact, pitch and roll, and extreme weather conditions, all of which can be detrimental to the life of a transformer and must be accommodated for by the transformer manufacturer.

Figure 1 shows the primary acceleration forces that may act on a transformer during transportation[†].

Mode of Transportation	Forces	Event Triggers
Truck	Vibration Impact	During movement During onload / offload
Rail	Vibration Impact	During movement Switching activities During onload / offload
Marine	Vibration Surge, sway, and heave Pitch, yaw, and roll Impact	During movement During movement During movement During onload / offload

Figure 1
List of primary acceleration forces experienced during various modes of transport.

For reference purposes, **Figure 1** includes the acceleration forces experienced during truck transport. However, because most transformers larger than approximately 25MVA exceed the weight and size restrictions of standard transport trucks[‡], this paper focuses on the primary modes of transport for these larger transformers — namely railcar and marine vessel. Although similar forces are present in each of the different transportation environments, this paper will evaluate the rail and marine environments separately.

Although **Figure 1** includes impact forces during onload and offload to trucks and railcars, the risk of impact is significantly reduced from that on a marine vessel. This is primarily because of the open sides of trucks and railcars that provide full visibility for the crane operator. On the other hand, transformers are often placed in the holds of marine vessels, where they are at risk of impacting the sides of the hold. This risk is further increased where the crane operator does not have full visibility below decks and relies on the stevedores for guidance via radio communication and hand signals.

Rail Shipping: The Methods of Transport

Rail transportation of transformers occurs via one of three main methods. The choice of method is dependent on the size, and, more specifically, the clearance and weight of the equipment. These methods include:

* This assumption ignores the possibility that a certain percentage of these transformers may have been transported by aviation carrier — a method that is generally considered too expensive for large power transformers.

† Forces shown are expected during normal operating conditions. This table does not include abnormal conditions such as vehicular impact during transportation.

‡ Specialized trailers with multiple independent axles are often used to shuttle these large transformers between the railcar and the pad; however, their use on public access roads is generally restricted. In addition, their operating speed is slow enough to mitigate most of the detrimental acceleration forces.

1. Standard flatbed railcar
2. Low-ride flatbed railcar
3. Schnabel car

Only the smallest of power transformers will meet the clearances when loaded on a standard flatbed railcar. This is partly because there are often many low bridges along the track route; therefore, height restrictions can be quite severe. Midsize power transformers (up to ~90T) are usually loaded onto heavy capacity flatcars, which have lower loading decks and additional axles to handle the heavier loads. Transformers weighing more than 90T require special railcars known as Schnabel cars, which have multiple axles and use the transformer itself as part of the car. The two sections of the Schnabel car shown in **Figure 2** would be separated in the middle and the transformer inserted between the support arms.

The transformer must be protected against both vibration and impact when shipped by rail. Various vibrational forces are applied against the transformer while the train is rolling. The intensity of these vibrational forces is influenced by a number of factors, including track quality and bearing wear.

Impact forces normally peak during switching activities of the rolling stock. Switching activities can impose significant longitudinal forces on a transformer and its internal components.

Figure 2
Unloaded Schnabel car parked on a siding. The transformer would be inserted between the two support arms.

Marine Shipping: The Methods of Transport

Transportation of transformers by sea vessel usually involves a combination of transportation modalities, as the manufacturing plant and/or the final destination for the transformer may not necessarily be located close to a port. With this in mind, however, the primary focus of this paper with respect to marine transportation of transformers is from the time the transformer is craned onto the vessel until the time it is offloaded.

A transformer is most at risk of severe impact during the time of onload and offload, while suspended underneath the crane. This impact can be lateral (from hitting the vessel wall during maneuvering) or vertical (due to high-speed contact with the ground or vessel bottom when lowering). Impacts during onload and offload can be as high as 10*g*, particularly when maneuvering the transformer during high winds.

During vessel movement, the transformer will experience both high-frequency (vibrational) and low-frequency (roll/pitch/yaw) motions. The high-frequency mechanical forces on a marine vessel are caused by the operation of the engines and generators used to drive the vessel. Low-frequency forces are exerted as a result of the vessel's response to the movement of the ocean.

A Look at the Forces Involved

Whether shipping a transformer by rail or marine vessel, it must be protected against excessive vibration (high- and low-frequency) and impact. **Figure 3** provides data regarding the estimated acceleration forces that may be applied to a transformer during rail and marine shipments[3]:

Mode of Transport	Longitudinal	Lateral	Vertical
Rail (Combined Transport)	1.0*g*	0.5*g*	1.0*g*
Marine (Unrestricted)	0.4*g*	0.8*g*	1.0*g*

Figure 3
Estimated acceleration forces during transport.

It is important to note that there is also an inherent frequency associated with each of the acceleration forces described in **Figure 3**. It is not just the forces, but also the frequencies of these forces, that affect the transformer and its components. This frequency is related to the critical duration (or minimum event duration) below which damage will not occur. Critical duration is discussed later in this paper.

The Standards

Manufacturers can refer to a number of generic standards and guidelines when designing and manufacturing a transformer to be shipped by rail or marine vessel. The Association of American Railroads (AAR) publishes a number of guidelines, standards, and regulations pertaining to the safe transportation of various types of cargo by rail.

The International Maritime Organization (IMO) correspondingly publishes similar guidelines for safe transportation of cargo via marine vessel. Another organization, the American Bureau of Shipping (ABS), publishes similar rules, guides, and regulations; however, these pertain primarily to life safety and security of property in the context of ship design, construction, and operation.

The issue at hand is that the shipping industry created the noted standards. In 2010, the International Council on Large Electric Systems (CIGRÉ) started a Working Group (WG A2.42), comprised primarily of members representing the large multinational transformer manufacturers[4], to look into this matter. The mandate of this working group included the preparation of a brochure guide on transformer transportation, which would provide useful information to transformer manufacturers regarding the withstand forces and times that might be imposed on a transformer during various modes of transportation. According to the CIGRÉ website, this working group completed its mandate in 2012 with a presentation to the Study Committee A2 on Transformers. A search by the author found no evidence that the brochure was ever published.

The Institute of Electrical and Electronics Engineers (IEEE), which is an industry association (as opposed to an industry standards organization such as the International Electrotechnical Commission or the International Standards Organization), has an active standards development community, and regularly publishes standards relating to various issues within the electrical and electronics industry. With respect to the topic of this paper, the relevant published standard is C57.150-2012, *IEEE Guide for the Transportation of Transformers and Reactors Rated 10,000 kVA or Higher*[5]. This comprehensive document provides designers, manufacturers, and shippers with a number of items that should be considered when transporting a transformer. Although this is an important industry standard, manufacturers and shippers are not required to conform to the provisions in the document. Therefore, items will inevitably be ignored due to cost or other restrictions.

Finally, FM Global, one of the world's largest insurance and risk management providers, published *Property Loss Prevention Data Sheet 5-4 "Transformers"*[6]. This document provides guidance primarily to asset owners regarding loss mitigation techniques (from an insurance perspective) with respect to transformers. It includes a very short section on transportation of transformers, which states only to install multiple impact recorders and to perform Sweep Frequency Response Analysis[§] (SFRA) before and after shipping. The *Data Sheet* includes no other information that may help mitigate transportation losses.

The Data Problem

The challenge with investigating transportation damage of large power transformers depends upon the amount of test and monitoring data available from the time of factory acceptance testing until the incident. In many cases, the manufacturer only performs its standard battery of electrical tests during the factory acceptance procedure. These tests prove that the transformer will perform according to the specification requirements, but they do not provide any information as to the physical characteristics of the transformer's internal components.

In most cases, only one or two impact recorders are installed on the transformer to monitor transportation conditions. These can typically be configured in one of two ways:

1. Setpoint trigger, wherein data is recorded at levels above a specific value;

2. Regular sampling interval, where data is recorded at regularly timed intervals, regardless of the value.

Some of the more advanced impact recorders allow recording of both modes simultaneously, while others will maintain a temporary data buffer and log a certain amount of time on either side of a significant event. The premium models of impact recorders also contain a GPS receiver, and will provide real-time data monitoring and alarming during the entire voyage.

Both types of monitoring methods mentioned above have advantages and disadvantages. The first type — recording only significant events that are

§ The SFRA applies a low-voltage sine wave to each individual coil within a transformer. The sine wave is applied across a large spectrum of frequency — from a few Hertz to several MHz. Because the windings of a transformer coil are separated by a layer of paper insulation, each winding exhibits different resistive (R), inductive (L), and capacitive (C) properties, thereby creating a complex electrical filter that passes some frequencies and mitigates others. Each injected frequency, therefore, will generate its own response at the output of the coil, based on the electrical filtering characteristics of the windings.

greater than a setpoint value — will identify potentially significant impacts, but this data does not provide any indication about the amount or frequency of vibration experienced by the transformer during the rest of the voyage. The second recording method — regular sampling — may capture vibration levels and frequencies, but risks missing potentially significant impact events. This is why it is important to use an advanced model capable of hybrid data recording.

Impact recorders, if properly utilized, are sufficient for rail transport. They are also important for marine transport in two capacities. First, they are critical during the onload / offload phase, when the transformer is at higher risk of impact while being maneuvered by the crane. Secondly, an impact recorder capable of monitoring vibration is necessary to capture the high-frequency vibration exposure of the transformer during operation of the marine vessel.

A second key device is essential for monitoring the transformer while onboard a marine vessel: an inclinometer. Because impact recorders are sensitive only to high-frequency events (including impacts), they do not capture low-frequency events, such as the pitch, roll, and yaw experienced on a ship. These events can be just as detrimental to the coils of a transformer as an impact or vibration, and it is just as essential to capture these as well as impact events.

The Missing Test

One test that provides excellent information about the geometry of transformer coils is SFRA. When performed before shipping — and again after installation of the transformer — the two SFRA graphs can be superimposed. If the two curves line up, this is a good indication that the transformer windings did not incur physical damage during transportation. If a shift is observed between the two curves, then it becomes important to conduct further visual and electrical examinations in order to verify the operational integrity of the transformer.

The Investigation Challenge

The fragility of a transformer is determined by its weight, internal configuration and construction, and the presence of either permanent or temporary internal shipping braces. Because of the complexity of these devices, it is not possible to establish a "typical baseline" of resistance to impact and vibration through simple verifications, such as drop testing or shaker table analysis. Furthermore, theoretical analysis — even with the use of modern 3D software models — is difficult. The forensic engineer, therefore, must rely on the manufacturer's knowledge, experience, and historical data for similar transformers when evaluating the fragility (or alternatively the toughness) of a transformer.

Case Studies

There are many variables that can lead to transformer damage during transportation. This paper will present three case studies wherein the transformers were subjected to excessive forces:

1. Transformer #1 –
   Vibration damage during rail transport:
   The transformer was shipped by rail from the manufacturing plant to the customer's site in another province. Upon arrival at the customer's site, damage was observed on some of the transformer components, and an insurance claim was filed.

2. Transformer #2 –
   Impact/incline damage during marine transport:
   A newly refurbished transformer was shipped from the manufacturing plant by truck and then by marine vessel to Canada. During offload from the marine vessel, the surveyor observed the transformer strike the sidewall of the vessel hold.

3. Transformer #3 –
   Excessive vibration during rail transport:
   A new transformer was shipped by rail from the manufacturing plant to the customer's site in another province. Upon arrival at the customer's site, the manufacturer noted high levels of vibration were logged by the impact recorders, and commenced a transportation damage claim against the rail company.

Each case study will evaluate the forensic engineer's observations and the data that was available to the forensic engineer in the course of the investigation. The forensic engineer's analysis of the data and resulting conclusions will then be presented, along with the challenges encountered in the course of the subject investigation.

**Transformer #1 –
Vibration Damage During Rail Transport**

In this case, the subject transformer was shipped by rail to the customer's site. Upon arrival, the customer observed damage on the transformer and filed an insurance claim. The forensic engineer was mandated on behalf of the manufacturer. The shipper, whose liability was limited by the contract terms, did not assign an expert.

Upon arrival at site, the forensic engineer reviewed the impact recorder data, and determined that the unit had sustained a number of significant acceleration events. Further inspection by the engineer also revealed several damaged internal components.

When evaluating the potential effects of an acceleration force on a transformer, the forensic engineer must identify both the intensity of the applied force as well as the duration. Together, these values provide an indication of the energy content applied to the transformer during an event. Exceeding one value or the other may not necessarily cause damage to the transformer. However, if both values are exceeded during the same event, the forensic engineer should expect to find damage.

In this case, the transformer manufacturer had provided specific maximum acceleration intensity limits to the shipper. Also included in these limits were values of critical impact duration for the subject transformer. Mathematically, the relationship between intensity and duration is expressed as follows:

$$If\ t_e < t_c\ or\ a_e < a_c\ then\ damage\ will\ not\ occur.$$

$$If\ t_e > t_c\ AND\ a_e > a_c\ then\ expect\ to\ find\ damage.$$

$$where:$$

$$t_e\ is\ event\ duration\ (s)\ t_c\ is\ critical\ duration\ (s)$$

$$a_e\ is\ event\ acceleration\ \left(\frac{m}{s^2}\right)\ a_c\ is\ critical\ acceleration\ \left(\frac{m}{s^2}\right)$$

In the subject case, two identical impact recorders were installed on the transformer, both mounted next to each other on the top of the transformer tank, as shown in **Figure 4**.

Figure 5 shows the relationship between the recorded acceleration intensities and the critical duration values for each of the four significant events identified by the forensic engineer.

In the first event, Impact Recorder #1 (IR1) logged acceleration and duration values greater than the specified limits, while the same event logged by Impact

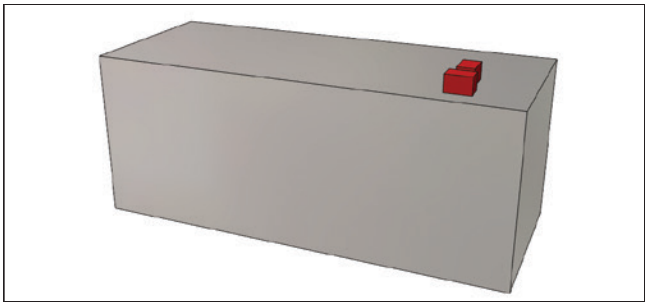

Figure 4
Transformer showing location of impact recorders.

Event	Acceleration Intensity	Duration
#1	IR1 $a_e > a_c$ IR2 $a_e < a_c$	IR1 $t_e > t_c$ IR2 $t_e < t_c$
#2	IR1 $a_e < a_c$ IR2 $a_e > a_c$	IR1 $t_e < t_c$ IR2 $t_e > t_c$
#3	IR1 $a_e < a_c$ IR2 $a_e > a_c$	IR1 $t_e < t_c$ IR2 $t_e < t_c$
#4	IR1 $a_e < a_c$ IR2 $a_e > a_c$	IR1 $t_e < t_c$ IR2 $t_e < t_c$

Figure 5
Actual event vs. critical value.

Recorder #2 (IR2) was below both limits. IR2 logged a second event as exceeding both critical values, while IR1 logged the same event below both values. Subsequently, IR2 logged two additional significant events that exceeded the critical acceleration, but the critical duration was too short. Because the critical duration of the last two events was below the threshold specified by the manufacturer, the forensic engineer deemed them not to have harmed the transformer. Instead, the focus of the investigation was placed on the circumstances surrounding the first two events.

Upon arrival at site — and due in part to the recorded impacts — a representative of the manufacturer undertook an internal inspection of the transformer**.

During this inspection, the representative discovered several pieces of pressboard that were loose or completely dislodged from their mounting locations. Additionally, he also found several internal securing bolts to be loose, in addition to a number of other cracked, broken, and abraded components within the transformer, including fragments of magnetic debris on the tank floor.

** The forensic engineer was not present during this examination and relied on notes and photos provided by the manufacturer's representative for this portion of the investigation.

The forensic engineer worked with the manufacturer to evaluate the cause of damage to the transformer. Based upon the limited data available, neither party could determine, with any accuracy, the root cause for any of the damage incurred to the internal components of the transformer. With this in mind, however, the following hypotheses were postulated:

- The recorded impacts, excessive vibration, or both, may have cracked the internal components;
- The magnetic debris most likely resulted from metal-on-metal contact that followed the breakage of another component and subsequent vibration of the metallic parts during the remainder of the journey;
- Vibration probably caused the pressboard to become displaced.

Because of the limited data available during this investigation, neither the forensic engineer nor the manufacturer's design engineers could determine a probable cause for the damage to this transformer. Although the impact recorder data provided evidence of significant acceleration events that exceeded the manufacturer's specifications, the forensic engineer had to rely on the manufacturer's information and design engineers' expertise with respect to the fragility of the transformer and the potential effects of the recorded shock events.

Since the impact recorders were mounted side by side, the logged data should have been similar between the two devices; however, the forensic engineer observed significant differences between the two data sets. Because the damage to the transformer was evident, the forensic engineer accepted the significant event data as valid, and did not perform any further verification on the data. A Nyquist analysis may have explained the differences between the two data sets and provided validation of the differing data; however, this would be a topic for a future research paper.

Because he was mandated on behalf of the manufacturer, the forensic engineer was able to work closely with the manufacturer's design engineers to properly understand the design parameters of the transformer. The fragility data (acceleration and critical duration limits) provided by the manufacturer greatly assisted the forensic engineer in determining the correlation between the impact events and the damage to the transformer components. Although the exact sequence of events could not be accurately identified (and may have only been possible with internal and external time-stamped video monitoring), the availability of vibration monitoring data and fragility data made this investigation as close to an ideal case as could reasonably be expected.

Transformer #2 –
Impact / Incline During Marine Transport

In this case, the subject transformer was shipped by truck and marine vessel to the customer's site. After it had been in service for some time, the owner noticed an issue with the transformer operation and filed an insurance claim. The forensic engineer was mandated on behalf of the manufacturer; another expert investigated the claim on behalf of the truck transport company. Marine surveyors were present during the onloading and offloading of the transformer from two separate marine vessels, and their reports were provided to the forensic engineers to aid in their investigations.

The subject transformer was an 88 MVA rectifier transformer that the European manufacturer had refurbished. After the refurbishment was completed, the manufacturer shipped the transformer by truck from the manufacturing facility to a shipping port, where it voyaged by ocean vessel to Canada. Upon arriving in Canada, the transformer was offloaded from the ocean vessel to continue its journey to the site.

Prior to leaving the manufacturing facility, the transformer was fitted with two impact recorders, as shown in **Figure 6**. The data logs from these impact recorders showed that this transformer experienced two significant impact events during its voyage. The first occurred on the truck after leaving the manufacturer — where it sustained damage to a bushing cover and grounding link cover that were situated on top of the transformer when it failed to meet the clearance under an overpass. A second incident occurred when

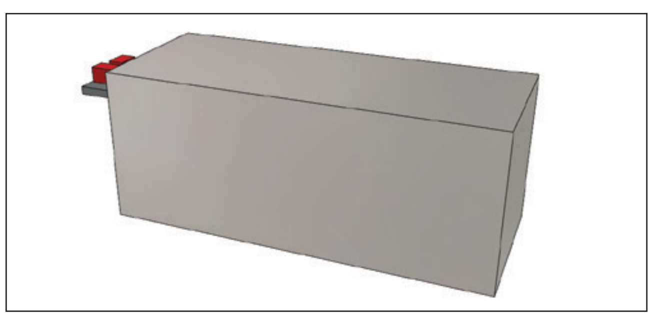

Figure 6
Transformer showing location of impact recorders.

the transformer impacted the side of the vessel during offloading, as shown in **Figure 7**. This impact event was observed and logged by the marine surveyor, whose report was used by the forensic engineer as evidence for his investigation.

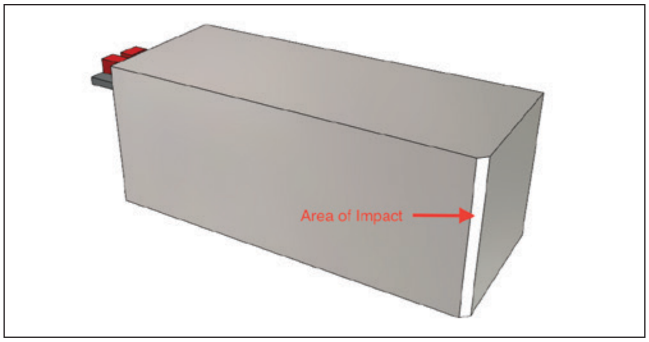

Figure 7
Transformer showing location of impact in white.

The forensic engineer reviewing the logs from the two impact recorders found two anomalous events. The first event, recorded while the transformer was on the truck, was an excessive impact in the vertical (z) axis. Only fractions of a *g* acceleration were recorded in the transverse and longitudinal (x and y) axes, likely due to the normal deceleration of the truck and the location of the impact recorders. The forensic engineer confirmed this event by correlating the impact recorder logs with the driver's logs.

The second event was an anomalous acceleration in the transverse (x) axis. Unfortunately, the impact recorder logs provided to the forensic engineer only indicated the acceleration in each direction; the duration of these events was not available. Therefore, the forensic engineer could not calculate or otherwise determine the energy content of the impacts associated with either event.

As discussed previously, the shipping industry has developed (most likely through empirical data) a set of values that comprise the maximum acceptable accelerations to which a transformer can be exposed without damage. As part of the investigation, the forensic engineer asked the manufacturer for information about the subject transformer; however, the manufacturer indicated that it "had no data regarding the maximum *g* force acceptable for that transformer." Instead, the manufacturer had relied on the industry standard high limit of 5 *g*. The implication, in this case, was that the manufacturer had not determined the maximum level of acceleration that the transformer could withstand, nor did it provide such information to the transporters.

As described in Section 8.3.2 of IEEE C57.150-2012, there are six degrees of motion that a transformer may experience when onboard a marine vessel. These fall into two categories: linear or axial motion, which includes surge (longitudinal), sway (lateral), heave (vertical), and rotational motion, which includes roll, pitch, and yaw. Impact recorders would normally be used to capture linear motion, while inclinometers would be necessary to capture rotational motion. Inclinometers were not attached to this transformer; therefore, the forensic engineer could not assess the intensity of low-frequency motion to which the transformer was exposed in the pitch (x), roll (y), or yaw (z) axes nor determine their possible effects on the transformer.

Following the commissioning and energization of the transformer, the owner observed internal gassing. Using an infrared imaging camera, they discovered a hot spot near one of the mounting feet for the core and coil assembly, as shown by the red spot in **Figure 8**. The owner conducted an internal inspection of the transformer tank and provided photographs to the forensic engineer. After analyzing the photographs, as well as construction drawings of the transformer core assembly, the forensic engineer subsequently determined that the core assembly had shifted within the tank, placing one of the three mounting feet too close to the tank wall. This physical shift changed the electrical dynamics of the transformer, which led to arcing activity between the core assembly and the tank wall.

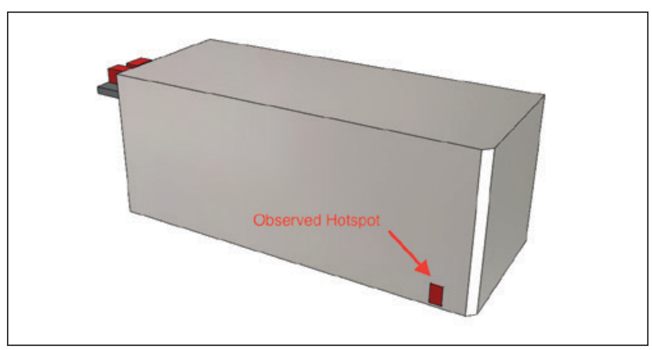

Figure 8
Transformer showing location of hot spot.

The manufacturing shop drawings of the transformer revealed that the core assembly was permanently attached to the tank lid. If constructed properly, this configuration ensured that the internal tolerances would have been very tight with respect to the resting location of the core assembly on the tank floor once the lid was installed. Based on this information, the forensic engineer determined that the probability of the core assembly being misaligned during insertion into the tank was very low — therefore, the misalignment at the base of the core assembly would have occurred during the transportation of the transformer.

Because the impact recorders were mounted near one top corner of the transformer— and the observed damage was to the opposite corner — it is reasonable to believe that they did not record significant accelerations during the offloading impact. The concept of angular velocity dictates that the closer the impact recorder is to the pivot point of the transformer, the smaller the acceleration it will log. It may have been possible to extrapolate the acceleration forces applied to the opposite end of the transformer during this event; however, a second set of impact recorders installed at the end closer to the impact would have logged a more accurate value of acceleration, as well as provided an additional data set for validation. Despite the logged acceleration values being within acceptable limits, based on the analysis of the marine surveyor's report and the events following the detection of the hot spot, the forensic engineer deemed it reasonable to believe that the transformer was damaged, at least in part, by the impact with the sidewall of the marine vessel.

Additionally, the lack of inclinometers installed on the transformer during the ocean voyage left a large data gap with respect to angles of inclination of the transformer. Due to the core assembly being mounted toward the top of the transformer, even a moderate angle of inclination might have caused the core assembly base to shift within the tank. Without this data, the forensic engineer could not determine if the misalignment of the core was a result of excessive inclination of the transformer during the ocean voyage.

Based on the previous example — and in light of the limited amount of data available from the voyage of the transformer — the forensic engineer could not identify a root cause of the core assembly displacement with a high degree of certainty. Notwithstanding, the following possible events led to the displacement of the core assembly from its original configuration:

- The core assembly shifted as the result of excessive angle of incline of the transformer during the ocean voyage;
- The core assembly shifted due to reduction of friction forces caused by high-frequency (engine) vibration during transport;
- The core assembly shifted during the impact sustained when the transformer contacted the ship wall during offloading.

Because the impact recorders were both mounted adjacently near a top corner of the transformer (which was close to the pivot point), the sensors recorded minimal levels of acceleration forces, which were applied transversally at the opposite end of the transformer when it impacted the sidewall of the ship. Furthermore, it is also possible that the core assembly could have slipped during movement of the ship in heavy seas.

In this case, the best evidence to indicate that the transformer had been damaged during transportation was the marine surveyor's observation of the transformer hitting the sidewall of the marine vessel during offloading. Because the impact recorders did not log an anomalous event due to their mounting location relative to the impact location, the data did not provide much assistance to the forensic engineer during his investigation, which was further hindered by the lack of transformer incline data.

Observations of the physical displacement of the transformer core assembly, along with the marine surveyor's report, provided enough evidence to the forensic engineer that the transformer had been damaged at some point during the voyage from the plant to the site. However, due to lack of data, he could not accurately identify whether the damage occurred on land, on the marine vessel, or during marine shore-handling operations.

Transformer #3 –
Vibration During Rail Transport

The subject transformer was a new 300 MVA substation transformer shipped by rail from the manufacturing plant, with a short road journey by multi-axle transport truck from the rail siding to the substation (approximately 3km away). Prior to offloading from the railcar, the manufacturer's representative visually inspected and observed no damage to the exterior of the transformer.

Prior to shipping from the factory, two impact recorders were mounted on the top of the transformer (one at each end, as shown in **Figure 9**), with a third mounted directly on the railcar; however, the location and orientation of this one was not known. Once the transformer railcar was parked on a siding near the substation — and before the transformer was offloaded to the multi-axle transport vehicle — the manufacturer's representative downloaded and reviewed the impact recorder data, noting high levels of vibration. However, none of the recorders logged any significant impacts. Because of the high levels of vibration recorded by the impact recorder, the manufacturer put the rail transporter on notice for potential damages to the transformer, pending an internal inspection and electrical testing. The forensic engineer was mandated directly by the rail transporter. A marine surveyor also attended the site investigation along with the manufacturer's technician.

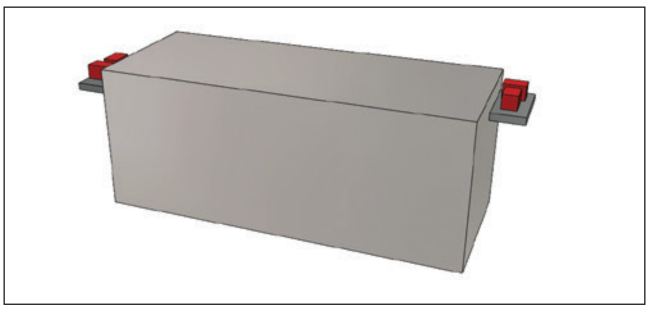

Figure 9
Transformer showing locations of impact recorders.

Due to space restrictions within the tank, only the high-voltage side (HV) of the transformer was accessible. From this side, the forensic engineer and manufacturer's representative conducted a visual inspection of the transformer core, the HV coils and taps, and the tertiary voltage (TV) windings. Because of these internal space restrictions and working at height regulations, only the manufacturer's representative could visually inspect the low-voltage (LV) windings, which was done by looking through an access hatch on top of the transformer.

During the internal inspection, the forensic engineer found all blocking and bracing to be in place and secure. Of particular note were the cushioning pads under the transformer core, which were of considerable interest due to the high levels of vibration recorded by the impact recorders. The forensic engineer noted that these were still in place under the core, and remained secured to the pins that extended out of the transformer core. The forensic engineer also found spacer blocks on the outside of the core sections were still in place and secure, and the cords used for securing internal components were still under tension and did not show signs of wear. Another key area susceptible to vibration damage was the insulation between the high-voltage windings; however, the forensic engineer did not observe any indications of abrasion, puncture, or cracking due to vibration.

Because the transformer was not completely assembled at the time of the examination, a limited number of electrical tests could be performed to confirm the operational state of the windings. In the case of this transformer, the manufacturer's representative conducted only an insulation resistance test, the results of which were consistent with the expected values for a new transformer. Based on the insulation resistance test, the manufacturer's representative determined that the coils were not damaged during transportation. The manufacturer did not indicate whether they performed an SFRA test on the transformer prior to it leaving the factory, but this test was not performed on-site.

In the case of this transformer, the core assembly was secured to the floor of the transformer, and appeared to be generally freestanding inside the tank, with some lateral bracing to maintain the stability of the top of the assembly. The forensic engineer determined that this was one of the main reasons the core assembly was able to withstand the high levels of vibration incurred during transportation.

Since neither the forensic engineer nor the manufacturer's representative observed damage to the internal transformer components — and the insulation resistance test results were acceptable — the transformer manufacturer closed the claim against the rail transporter. Because the manufacturer acted quickly in closing its claim against the rail transporter, it did not provide the impact recorder data to the forensic engineer, nor did the forensic engineer have an opportunity to determine if the manufacturer had calculated values for the fragility of the transformer.

Based on the internal examination and discussions with the manufacturer's representative, the forensic engineer determined that despite the high levels of vibration logged by the impact recorders, the transformer was not damaged during transport. The working hypothesis for this was that there was sufficient internal bracing and other protective measures, which reduced the fragility of the transformer so that it could withstand high levels of vibration.

As previously discussed, although the manufacturer indicated that significant levels of vibration were detected, they did not indicate which impact recorder logged the high levels of vibration, nor did they provide the actual data logs from the impact recorders. Although still an interesting case study in the capabilities of transformers to withstand significant levels of vibration, having the actual vibration data in hand would have provided hard evidence to support the theory that not all "significant events" recorded by impact recorders necessarily lead to transformer damage.

Conclusions

Because of the unique and complex nature of transformers, significant barriers exist to calculating the response of a given transformer to external stimuli within a reasonable degree of engineering certainty. Manufacturers rely on their experience and knowledge of transformer construction in order to design and manufacture the units to survive the journey to the customer's site. The author believes that many manufacturers rely on shippers to "handle with care," but do not necessarily understand the dynamic forces encountered during shipping, nor do they provide fragility values to the shippers. In many cases, this simply means that transformers are designed and constructed with large safety factors. There are software programs that can assist transformer manufacturers with modeling external forces; however, these programs do not provide all the answers, and still require significant experience and input from the design engineer.

Despite the availability of published standards pertaining to both design and shipping of large power transformers, transportation incidents regularly cause damage to the internal and external components of transformers. Sometimes the damage is the result of mishandling that impacts a transformer well above its withstand capability. Other times, the acceleration forces are below the acceptable thresholds, but due to other (often unknown) factors, the transformer still incurs damage.

When investigating transportation damage claims, the forensic engineer must obtain all available design, test, and monitoring data from the transformer manufacturer and shipping companies. It is in the best interest of the forensic engineer to examine the design, construction, and shipping conditions of the damaged transformer in order to develop a thorough comprehension of the fragility of the transformer and the forces that acted upon it to cause damage.

Until the holy grail of transformer modeling is discovered, manufacturers must rely on their knowledge, experience, and a bit of luck when shipping their transformers by rail or marine vessels. This knowledge and experience must continue to come from empirical data obtained from actual transformer transportation projects – those with and without significant events. The only way to obtain this data is to install as much monitoring equipment as is economically and technically feasible on the transformer – and the vehicle – and then analyze the data. This should be done in conjunction with SFRA tests before and after shipping so that even minor deviations in the transformer winding structure can be correlated with the transportation event data. As such, until the utility industry officially adopts a minimum standard of required testing, monitoring, and handling procedures for transformers, forensic investigators must rely on their own experience in finding the root cause hidden in the large data gap.

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Forensic Engineering Analysis of Fuel Usage and Thermostat Settings

By John Certuse, PE (NAFE 708F)

Abstract

According to the Insurance Institute, frozen pipes are one of the leading causes of building damage in the United States. In the forensic engineering analysis of building damage due to burst pipes, fuel tank runout or excessive thermostat setback are common causes of these losses — and may lead to a fuel provider being culpable for a late fuel delivery or the property owner being responsible due to excessively turning down thermostat settings. This paper will address the relationship between thermostat settings and fuel consumption. From a building's demonstrated fuel consumption and known thermostat settings, corresponding changes in thermostat settings and the resulting fuel consumption will be discussed. Department Of Energy adjustments for fuel savings in relation to thermostat setback will be discussed as well as a fuel usage study in an exemplar home. Forensic case examples utilizing this relationship will also be presented.

Keywords

Fuel usage, K factor, burn rate, fuel consumption, frozen pipes, heating degree day, HDD, base temperature

The Heating Degree Day

What is a degree day? In its simplest definition, a degree day is the measure of the need for heating or cooling. It is the average daily temperature above (for cooling) or below (for heating) a base temperature (which is usually 65°F).

The concept of the heating degree day (HDD) can be traced back to British Army Lieutenant General Sir Richard Strachey (1817–1908), who introduced the concept as a way of identifying the growing season for agricultural purposes (**Figure 1**). Terminology and calculation basics of HDD calculations today are still based upon his works from 1878. Although the HDD concept is the basis for fuel consumption prediction in buildings today, it is not unique to building energy analysis with the difference being in the choice of a *base temperature* and what one does with the resulting degree day total.

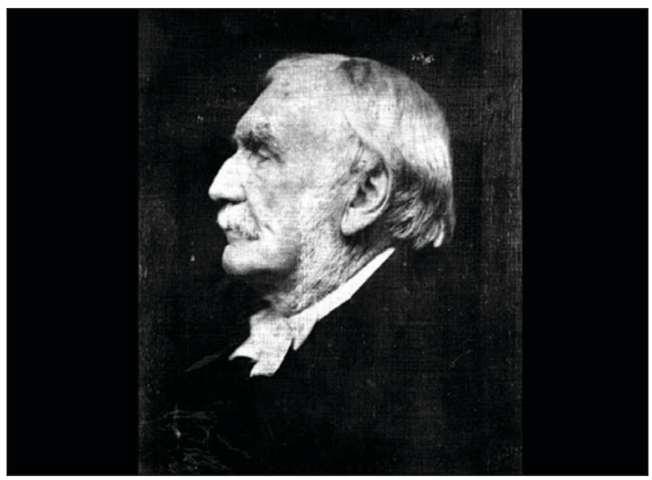

Figure 1
Lieutenant General Sir Richard Strachey (1817–1908).

The HDD procedure's transition from agricultural applications to the heating and fuel delivery industry is evident, as referenced in the *Handbook of Heating, Ventilation and Air Conditioning, HVAC Design Calculations*, which states that in the 1930s gas utility companies used the degree day method to predict gas consumption[1]. This publication also states that the oil embargo of 1973 and subsequent oil supply issues led to an increased awareness of the cost of energy to heat and cool buildings.

The definition of the HDD as "a unit of measurement of the average temperature deficiency during any specific interval of time and to be corrected by heating" was also presented in the 1936 heating technicians' publication *Oil Heating Handbook — The All Inclusive Guide for Every Man Who Designs, Installs, Sells or Uses Oil Heating Equipment*[2]. As such, historical documentation is present, detailing the relationship between the HDD and fuel consumption for the past 80 years.

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Calculation Methods of the Heating Degree Day

The HDD is a factor of the average temperature in a 24-hour period and the base temperature used for the application. The base temperature is defined as the balance point of the building at which the building's internally generated heat begins to counterbalance the loss of heat to the outside (see **Figures 2** and **3**). The opposite of this heat flow direction is true in cooling mode. In heating applications, this is typically 65°F. So, for example, a 24-hour period that has the average temperature of 20°F has a value of 45 HDDs when the HDD base temperature is 65°F.

HDD data can be calculated in specific field locations through a number of means; however, it is usually collected from reliable weather stations maintained by organizations such as the National Oceanic and Atmospheric Administration (NOAA) or the Federal Aviation Administration (FAA). There are also several Internet-based services that provide HDD data collection services as well as HDD-based computer programs used in the fuel delivery industry to schedule delivery of heating oil and propane to tank-based heating systems. There are varying capabilities of specific weather stations to provide data. This affects the accuracy of the heating degree day calculation. For example, given the following 24-hour temperature readings and a base temperature of 65°F, depending on the calculation method, slight variations in the resulting heating degree day exist.

1-12 Hours Average Hourly Temperature	30	30	31	31	30	29	28	28	29	29	30	32
13-24 Hours Average Hourly Temperature	36	37	40	43	43	44	39	39	38	37	32	31

(Daily Average) or Hi-Low Degree Day Calculation Method – (High-Low)/2

44+28/2 = 36°F

65-36 = 29 Heating Degree Days

Whereas if the total number of temperature readings were utilized:

816/24 = 34

65-34 = 31 Heating Degree Days

In reality, weather stations that have reliable 30 minute or hourly temperature readings are not the norm, and may rely upon other approximation methods to calculate HDDs. These methods typically use numerical integration, daily maximum and minimum, or daily average temperature readings.

Johnson Degree Day Calculation Method

In the event that compensations for wind speed and solar effects in heating degree calculations are desired, these variables are addressed by the measurement of daily temperatures by the Johnson degree day method. These measurements are taken locally utilizing black-colored containers exposed to both direct sunshine and wind. The accuracy of this method may not completely align itself to the specific building's performance, however, due to differences in the actual building's construction features and that of the collection box.

Weather and Fuel Usage Provides Specific Building Consumption Needs

Once a consistent HDD system is established, the integration of fuel consumption against cumulated HDDs provides fuel delivery companies a means to gauge the need for a fuel delivery ahead of time and schedule their deliveries accordingly (**Figure 2**).

Providers of fuel for tank-based systems routinely recognize a "reserve" minimum amount of fuel in a tank to ensure that unexpected slight increases in fuel consumption between deliveries do not result in a tank running out of fuel.

Fuel providers make note during wintertime heating conditions of how much fuel is consumed in regard to the cumulative HDDs between deliveries. Identification of how many HDDs are provided (to each building) per unit of fuel results in a unit known as the K factor (**Figure 3**). The reciprocal of this value, known as the burn rate, has units of gallons per HDD.

There are many commercial computerized programs available to the fuel delivery industry that make use of the relationship between fuel consumption and HDDs. As long as the temperature being maintained in a building remains constant, these values, which are typically tracked as HDD/gallon (K factor), remain consistent throughout winter months (**Figure 4**).

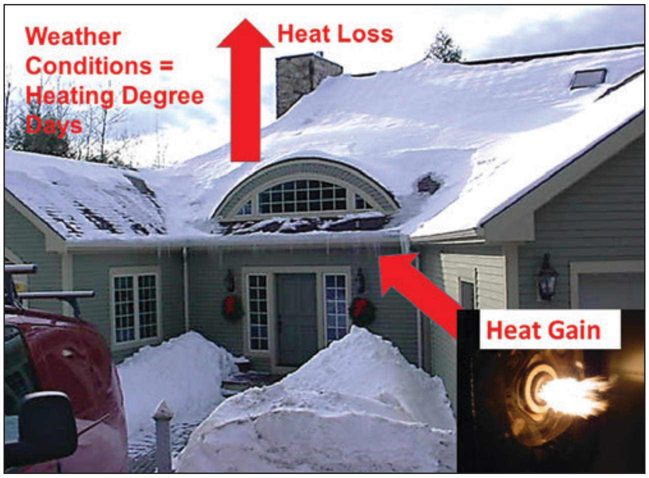


Figure 2
Heat loss and heat gain in a residential structure.

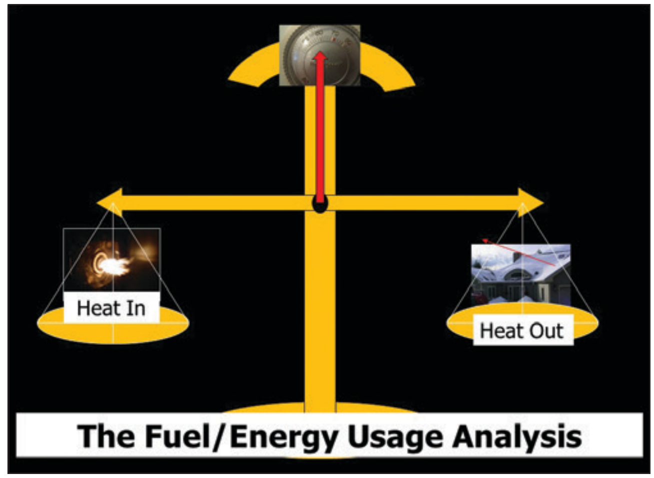


Figure 3
The balance of heat gain and heat loss to maintain temperature.

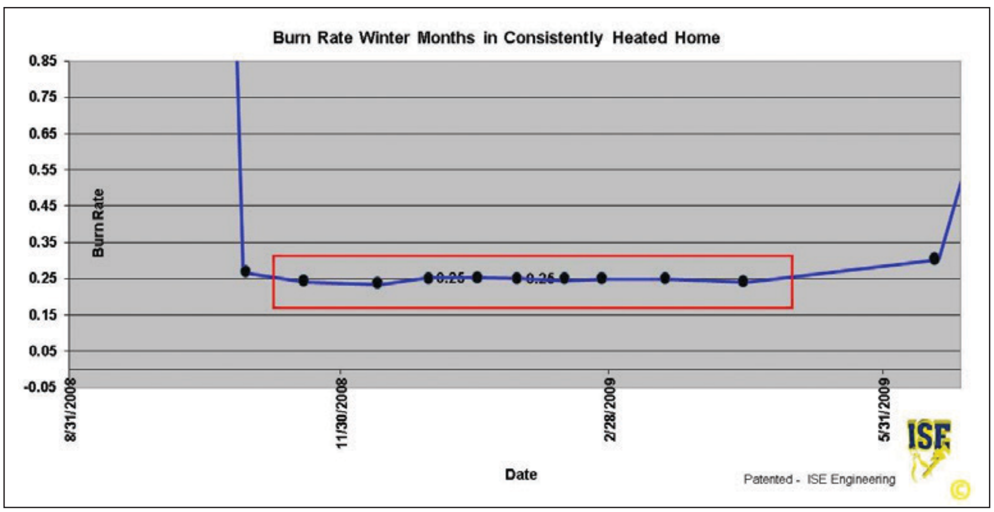


Figure 4
Author's patented fuel usage analysis method showing conditions of consistently heated home.

Using the K Factor or Burn Rate as an Investigative Tool

By examining historical consumption rates during times of known building occupancy and comparing these rates to those leading to a frozen pipe loss, insight as to the time (and potentially the cause) of the heating system inconsistency (compared to times of known operation) can be identified, such as:

- Excessive thermostat reduction
- Mechanical breakdown and utility failure
- Fuel tank runout

The use of the HDD methodology as an investigative tool relies on evaluating the building's actual performance only against itself, comparing the previous winter season's fuel consumption readings (when occupancy and temperature conditions are known) against the time when these conditions are uncertain. This procedure does not rely upon the calculation of the building's "theoretical" overall coefficient of heat transfer, nor does it apply ASHRAE or similar design calculations. The analysis measures the house's actual thermal resistance performance and not its design performance. Since unknown defects in workmanship or material performance may exist, theoretical heating system design calculations (as to how the building's heating system should perform) may not reconcile with actual "as-built" performance results.

Addressing the possibility of a *Daubert* challenge when the HDD methodology is used for analysis of fuel delivery purposes, it should be recognized that this is the standard practice of trade in the fuel delivery industry. Basing the analysis on a common methodology disputes claims of the HDD analysis basis being a rare and untested procedure. As such, it is less subject to disqualification.

Tank-Based System Delivery Practices and Calculation Adjustments

Actual amounts of fuel consumed by a structure's heating and combustion equipment are evident in natural gas or other "gas meter" measured fuel supply systems. Likewise, tank-based systems (such as propane and No. 2 fuel oil tanks), as shown in **Figure 5,** may be on an HDD delivery method where the tank is filled between deliveries; this makes fuel consumption — and hence the K factor or burn rate — self-evident. Care must be taken, however, with tank-based systems that are not on an automatic "fill-to-capacity" HDD delivery practice when calculating the building's consumption rate during winter months.

Figure 5
Typical home heating oil tank.

For various reasons, many building owners do not allow the fuel provider to use the HDD delivery method to schedule tank fillings and choose to have fuel deliveries for tank-based systems by other means. For example, some homeowners prefer fuel delivered based upon a "will call" tank gauge observation that is initiated when the tank gauge reading indicates it is near empty (**Figure 6**).

Figure 6
Heating tank gauge reading empty.

Likewise, a calendar-based schedule may be in effect that results in fuel being delivered after some number of days have passed, omitting the consideration of the degree of "coldness" in weather conditions.

Complicating this situation is the possibility that tanks may be supplied with fuel by filling them to capacity, by delivering a requested volume of fuel or by having fuel delivered based upon a final cost to the building owner.

Care must be used (when observing the amounts of fuel delivered) to make sure a list of fuel delivery dates and amounts are not confused as being HDD-based "automatic" or "fill-to-capacity" amounts when making fuel calculations. This can usually be resolved by asking the building owner or fuel provider what specific delivery method was in effect at the property.

Observing a Fair Burn Rate for "Will Call" Delivery Calculations

When a "will call" delivery practice is in effect, a schedule of fuel delivery amounts may be presented for evaluation similar to this example.

Date	Amount
November 11, 2014	100 gallons
November 21, 2014	150 gallons
December 3, 2014	100 gallons
December 16, 2014	125 gallons
December 23, 2014	125 gallons

The identification of a burn rate from a "will call" requested delivery schedule is potentially hampered by the starting point of the calculation because it may be unknown how much fuel was in the tank after the first delivery of the period being evaluated. That being said, the longer the period of multiple will call deliveries being evaluated, the less the final cumulative burn rate will vary, since a longer period is being evaluated as well as cumulative fuel consumption amounts. The question is where to start?

As shown in **Figure 7**, considering the outcome of the extreme limits of each scenario, the starting point that embraces the *known* amount of fuel delivered to the tank (at the beginning of the cycle) provides the most reasonable and accurate net outcome burn rate for the entire period.

The extreme limits of the tank being empty or full result in conditions that show either the homeowner was out of fuel or the consumption rate was excessive, providing a calculation point that will not represent actual burn rates within the home. Considering these possible burn rate scenarios, a check of tank size capabilities and identified burn rates can be performed and evaluated against subsequent fuel deliveries to determine if adequate space is present in the tank to receive newly delivered fuel amounts. For example, in the event that a low burn rate is "assumed," resulting in there being 150 gallons in a 250-capacity oil tank, then the accuracy of the lower burn rate would be disputed if a 150-gallon delivery (exceeding the tank capacity) was made.

Figure 7
"Will call" starting point.

Change in the K Factor or Burn Rate

Some insurance carriers now mandate that heat be maintained at a specific "lowest" temperature during winter months. This has been identified as being a minimum temperature of 55°F.

The importance of knowing what temperatures are being maintained applies to both the interests of a property owner as well as a contractor (who may be held liable for improper piping installation). Plumbers or insulation contractors may be blamed for a burst pipe in a susceptible framing cavity or space. It is possible, however, that the temperature maintained in the building was the major contributing factor to this event and not the manner in which the pipe was installed. Likewise, opinions regarding defects in installation can be supported if a fuel usage analysis quantifies proper heat levels being maintained. The correlation of a heating system "failure" to the date of a utility outage or other such event is dependent on knowing the actual fuel consumption rates prior to the loss. As such, verification as to what burn rate was in effect is necessary for this analysis.

The Dangers of Excessive Thermostat Setback

Public service notifications encouraging energy conservation through thermostat setback began with the oil embargos of the early 1970s and continue to this day. As a result, thermostat setback may seem like a simple and safe means for energy cost savings to the public.

An unheated water pipe installed in an exterior wall or in a ceiling abutting an attic (or other unheated building cavity) is reliant upon the heat level maintained and the insulation between it and cold unheated air. Likewise, a wrap-insulated hot water or hydronic heating water pipe that passes through an unheated space relies on frequent cycles of flowing water to prevent the water from freezing.

What's the problem with modern insulation techniques? Pipes installed in unheated building cavities share the same cavity space as the insulation filling this cavity, thereby altering the intended consistency of this same insulation within the cavity (**Figure 8**). Additionally, current use of fiberglass batting or loose fill insulation is prone to separation causing gaps, compression, and settling — all of which reduce their intended performance.

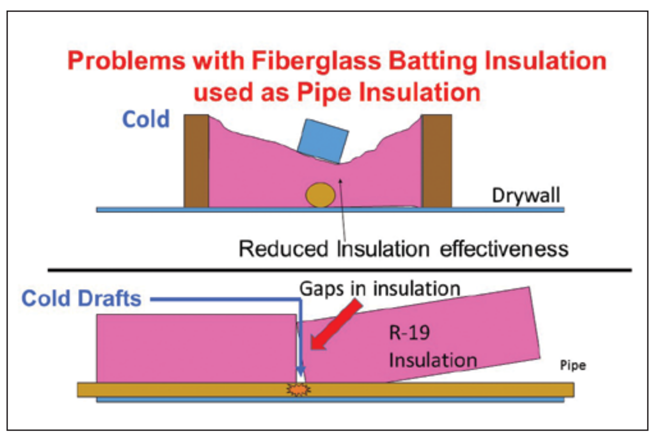


Figure 8
Typical problems with batting-type insulation.

The fastening point of the pipe is also usually on the wooden framing members within the wall cavity. This locates the pipe in the coldest portion of the wall cavity, securing it to the fastening point with the least thermal protection and in an area where the consistency of the insulation is likely at its lowest (**Figure 9**).

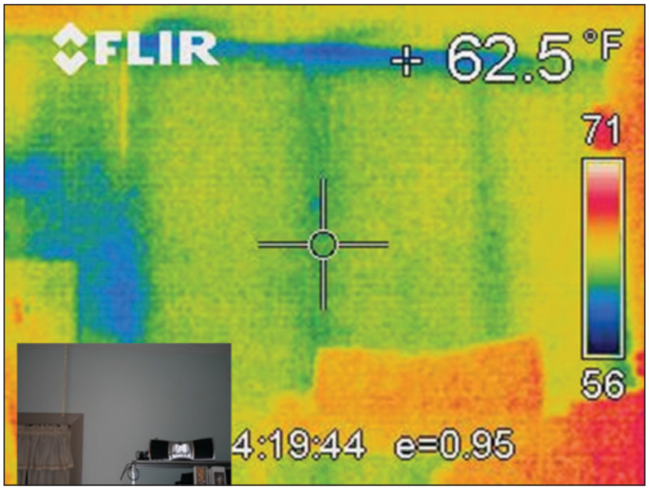


Figure 9
Thermal image of exterior wall shows poor insulation conditions at wooden frame areas. This is known as "thermal bridging."

The poor insulation qualities of the wooden framing — as well as the tendency for air gaps to be present where the insulation meets the framing — all act together to undermine the thermal integrity of the wall system and increase the chances of freezing (**Figure 10**).

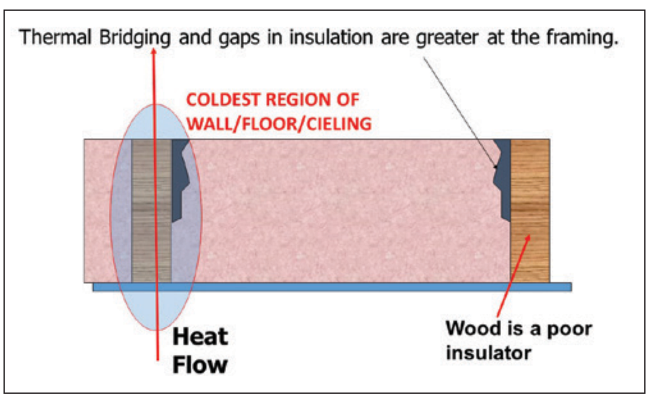


Figure 10
Thermal bridging is a combination of the poor insulating capability of wood and typical gaps where the insulation and framing meet.

All building piping configurations are different. Some may have piping located in chase ways positioned within the interior of the building, while others may have the piping installed in exterior walls or ceilings abutting unheated spaces. This results in vast discrepancies in freeze protection performance during winter months.

Complicating matters are variations in choices as to where the pipe is placed within the framing cavity, fastening methods, as well as insulation placement and thickness. Pipes placed adjacent to exterior wall sheathing are going to be less resistant to cold outdoor temperatures than pipes adjacent to interior sheathing with more insulation between the pipe and the exterior cold.

Additionally, poor details are provided in the installation guidance within the current codes. Statements like "pipes shall not be installed in any location prone to freezing unless they are protected with heat, insulation, or both", without detailing how this is done (in the various piping-insulation configurations encountered), adds to continued problems. There is also no provision for freeze protection of hydronic heating system pipes in the governing mechanical codes other than for energy conservation reasons. Finally, the lack of coordination and the "that's not MY job!" finger pointing mentality between the installing pipefitter and the insulation contractor ensures a never-ending supply of civil cases for the legal system.

When is Thermostat Setback Too Much?

Although encouraged by energy conservation efforts, excessive thermostat setback (especially in extremely cold weather) can have grave consequences.

When temperature settings are reduced, the rate of heat loss through the building wall system is also reduced. If piping is installed in these cavities, there is a corresponding reduction of heat flow and thermal inertia, diminishing the flow of heat through the wall system and reducing the ability of the pipe to overcome any pipe insulation inconsistencies.

Conductive Heat Transfer through Sandwiched Plane

Figure 11 is a theoretical wall system and analysis of conductive heat flow through a sandwiched plane. This model demonstrates a pipe's thermal conditions within an R 13 theoretical wall cavity. The term R value is a reference to the thermal resistance of insulation materials. In this example, the outdoor design temperature is 0°F, and the pipe is positioned approximately one-fourth of the way from the interior sheathing in a 2x4 typical wall construction frame that has a width of 3.5 inches. As seen in **Figure 11** as well as the corresponding table, calculations show the pipe will experience progressively colder temperatures along a linear slope due to thermostat reduction.

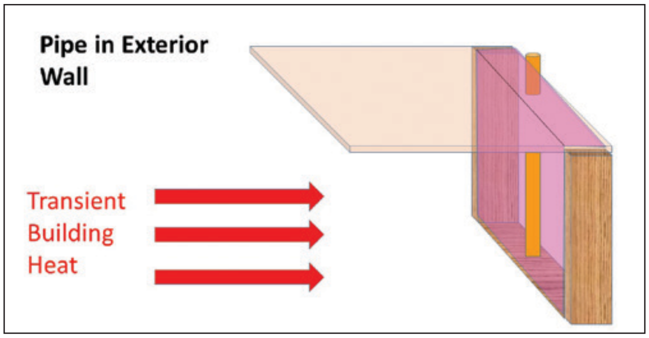


Figure 11
Pipe within theoretical exterior wall.

Inside Temperature Ti	Pipe Temperature Tp
70 degrees	54.32 degrees
65 degrees	49.28 degrees
60 degrees	44.33 degrees
55 degrees	39.32 degrees
50 degrees	34.34 degrees
45 degrees	29.33 degrees

This model also assumes uniform insulation consistencies without any defects caused by insulation compression, settling, or obstructions within the cavity. In reality, most wall systems would fall short of these calculated results, and each building has its own thermal abilities in regard to freeze protection of pipes.

Quantifying Changes in Fuel Consumption in Relation to Thermostat Changes

Various sources claim different correlations between degree of thermostat setback and fuel savings. These range from between 3 to 15 percent savings per °F of thermostat reduction.

According to *Winter Energy Savings from Lower Thermostat Settings* from the U.S. Energy Information Administration (EIA), with every degree of thermostat setback, a certain percentage of fuel savings results[3]:

Natural gas 5%
Fuel oil 4%
Kerosene 5%
Propane 5%
Electricity 6%

Since the loss of heat from an insulated structure follows a linear relationship of the **Q=UAΔT** equation (where heat flow **Q** is a factor of the overall coefficient of heat transfer **U**, the heat transfer area **A** and the difference in temperature between the high and low temperatures of the system **ΔT**), the net fuel consumption output follows a linear relationship when plotted in response to thermostat setback.

Vacant Home Study

In the late fall/early winter of 2015, the reported fuel consumption percentage relationship from the U.S. Energy Information Administration was tested in an unoccupied residential structure.

The home was a 1,750-square-foot structure built in 2001 and was supplied with natural gas. The home was heated by two identical 80,000 BTU/hour gas-fired forced hot air furnaces that did not have a standing pilot flame but rather used a hot surface igniter with intermittent ignition. Domestic hot water was supplied by a 40-gallon water heater that utilized intermittent ignition through a spark ignition system.

Gas meter readings were taken in weekly intervals where the thermostats were set at identical temperatures during periods of wintertime weather conditions. Temperature measurement periods were at thermostat settings ranging from 46°F to 65°F. For each of these weekly intervals, the amount of fuel consumed was recorded and integrated with cumulative HDDs for the interval between readings.

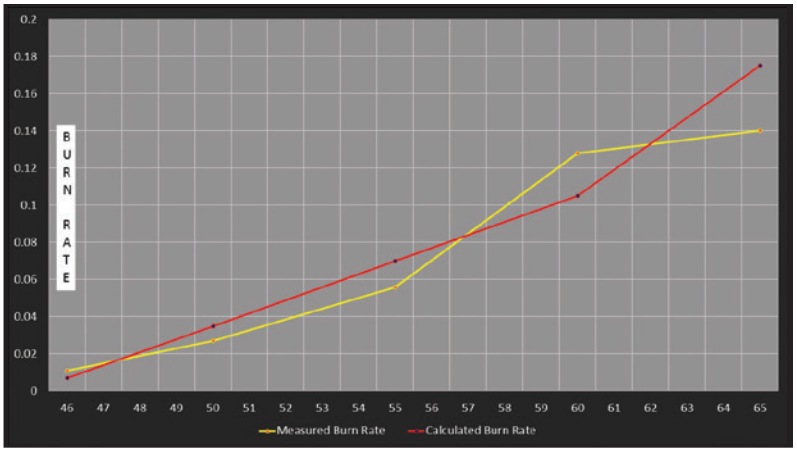
From a known burn rate (utilizing the U.S. Energy Information Administration's savings rate for natural gas of 5% per °F of thermostat setback)[3], for each of the measured gas consumption interval burn rates, the gas consumption burn rates were calculated and compared to measured rates, as shown in **Figure 12.**

Although differences of 0.004 to 0.035 resulted, these small amounts are likely attributed to the test procedure followed. This is suspected because the testing began with lower temperature settings and then moved on to higher settings, causing increased fuel to be consumed in the heating of building components – not maintaining the thermal load in an already-established thermal system.

Situation Recognition

Thermostat Setback Quantification

As seen in **Figure 13**, during a previous winter when the property was known to be occupied and no report of frozen pipes occurred, the consumption rate was 0.18 units of fuel per HDD, for a 5.5 K factor



Thermostat Settings	Measured Burn Rate	Calculated Burn Rate
46	0.011	0.007
50	0.027	0.035
55	0.056	0.07
60	0.128	0.105
65	0.14	0.175

Figure 12
Measured burn rate comparison to Department of Energy standards.

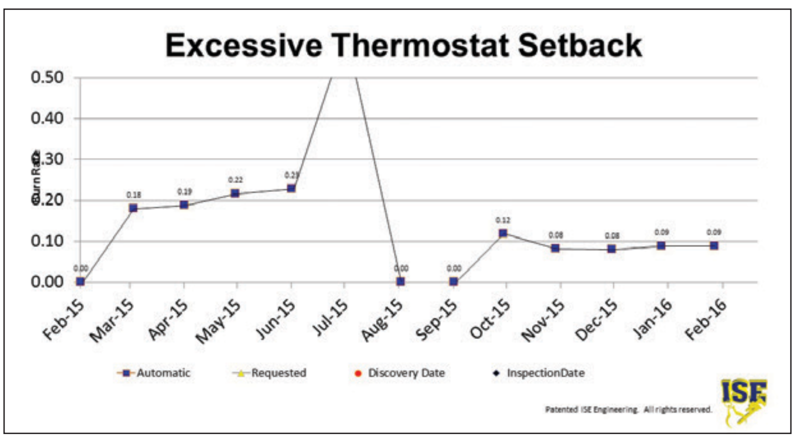


Figure 13
Fuel usage burn rates (Y-axis) showing thermostat setback.

value. Contrary to this, the following winter that burn rate fell to about 0.08 units of fuel per HDD, a difference of 44% or a 56% savings.

At the EIA thermostat setback rate for natural gas of 5% per °F of setback, this equates to a thermostat setback amount (from the previous winter's demonstrated burn rate) of 11.2°F. This is an indication that the thermostats (on average, if there were multiple thermostats) were likely set in the 58°F to 59°F range, which disputes any claim of occupancy – a common requirement for insurance coverage. Later statements from owners of the property confirmed these settings.

Example:
Natural gas DOE value for usage/degree of thermostat setback: 5%

Previous winter's occupied burn rate (thermostats @ ~70°F): 0.18 units/HDD

Current winter's burn rate: 0.08 units/HDD

0.08/0.18 = 0.44 or 44% used in comparison to last winter.

Savings of fuel = 100-44% = 56%

56%/5% = 11.2°F Thermostat Reduction

70°F – 11.2°F = 58.8°F

The same graph may also be indicative of a heating zone in a multi-zoned heating system being inoperable, which would be supported by field observations. It should also be noted that to someone only relying on quantities of fuel usage without consideration of weather conditions may not realize that this property was likely not occupied.

Meter Read Date	Therms Consumed	Calculated Burn Rate
February 9, 2015	223	Start of Calculation
March 11, 2015	230	.18
April 9, 2015	151	.19
May 8, 2015	71	.22
June 9, 2015	28	.23
July 9, 2015	9	Summer Off Scale
August 10, 2015	7	.00
September 9, 2015	6	.00
October 7, 2015	11	.12
November 6, 2015	26	.08
December 8, 2015	51	.08
January 5, 2016	54	.09
February 4, 2016	81	.09

Heat On, Hot Water Pipe Burst in Unheated Building Cavity

This example shows a situation where the fuel tank was found to be empty, and the fuel provider was targeted as being negligent. By merely looking at delivery amounts and not analyzing this data against weather conditions, it was not realized by insurance company representatives that heat in the building was not being maintained. This led to a pipe burst and the perception of there being a negligent act on the part of the fuel provider.

In **Figures 14** and **15**, both the fuel usage analysis graph and the system diagram show the effects of a hydronic heating system pipe break. The loss of heated water while being resupplied with cold make-up water causes accelerated fuel consumption.

Idle Boiler or Furnace

Patterns in the trends of fuel consumption over time may also identify conditions indicative of inoperable equipment.

Water-bearing appliances that maintain a minimum temperature, such as a water heater or boiler, will consume fuel while idle. These appliances are not intended to be shut down entirely since condensation and contraction extremes may damage them. The number of standing pilot gas-fired appliances a home has, as well as the adjustment of the pilot flame, determines how much gas a home may consume for pilot flame usage. Measurements have been made where a 1,000 BTU quantity of natural gas is consumed in a single appliance in between 45 and 90 minutes. At approximately 540 hours per month, this equates to about 540,000 BTU per month or 5.4 Therms per month.

As seen in **Figure 16**, the fuel usage burn rates show the heating system capable of operating; however, the usage rates do not show that heat is being supplied to the building. This type of failure is indicative of the thermostats being turned off or some interruption of boiler hydronic water or furnace heated air flow.

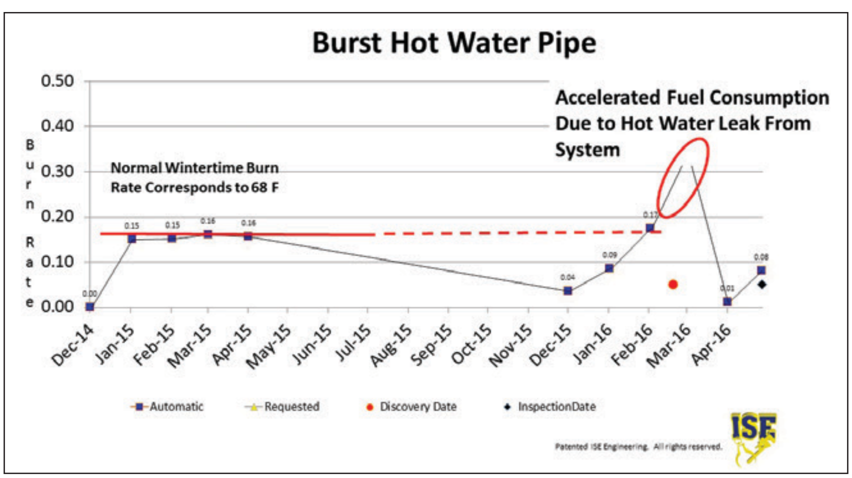


Figure 14
Fuel usage burn rates showing hot water pipe burst.

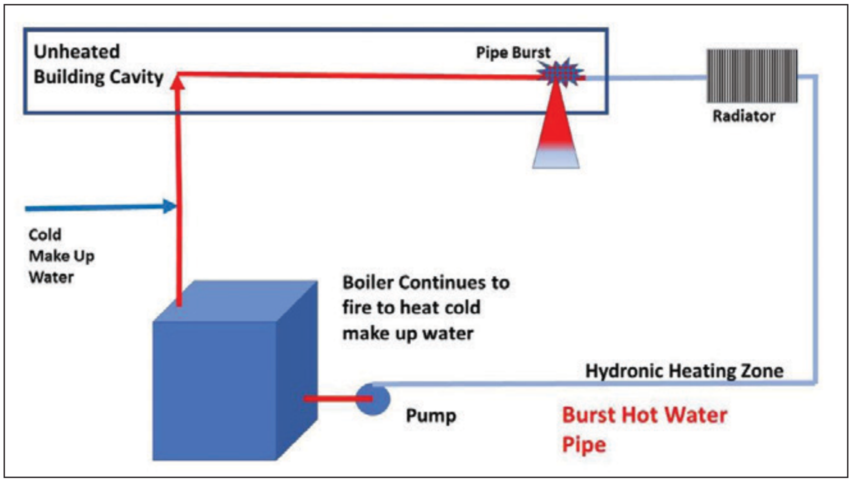


Figure 15
Hydronic heating system pipe break results in accelerated fuel consumption.

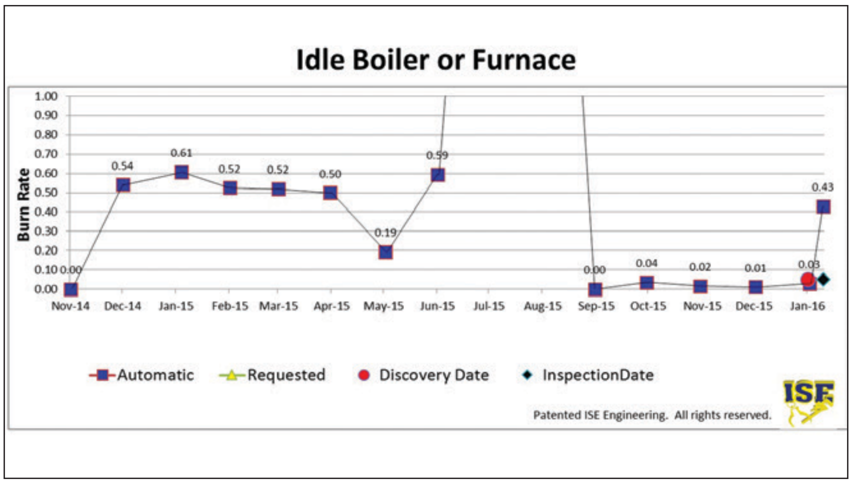


Figure 16
Fuel usage burn rates showing idle boiler or furnace prior to failure.

Meter Read Date	Therms Consumed	Burn Rate Calculated
February 10, 2015	600	.52
March 10, 2015	614	.52
April 9, 2015	420	.50
May 11, 2015	69	.19
June 10, 2015	88	.59
July 10, 2015	79	Summer Off Scale
August 11, 2015	4	Summer Off Scale
September 9, 2015	4	.00
October 9, 2015	4	.04
November 9, 2015	5	.02
December 11, 2015	7	.01
January 11, 2016	21	.03
January 19, 2016	123	.43

Domestic Hot Water Consumption Adjustment to Fuel Usage

Identification of domestic hot water needs and the associated impact on fuel consumption can be identified through the fuel usage analysis specifically for a home by using the summer gas meter readings or "end of heating season" for tank-based delivery amounts. With tank-based systems such as LP gas or heating oil, if these tanks are supplied on a delivery basis that fills the tank to its maximum capacity, the "end of summer" tank volume delivered helps to provide this value.

By identifying the amount of fuel used between the end of the previous heating season and the beginning of the following heating season — and then factoring this against the identified wintertime burn rate — the amount of fuel used for the last remnants of the previous winter (when heat was needed) can be identified. If this number is subtracted from the total fuel consumed during this period, this identifies the amount of fuel used for domestic hot water usage.

Using this volume of fuel, the total number of days between the end of heating season and the delivery of fuel prior to the start of the next heating season identifies the gallons of fuel per day per household. Dividing this value by the number of people in the home then identifies the gallons of fuel used per person per day for domestic hot water usage. This methodology can be hampered for fuel-consuming "luxury" appliances such as spas or swimming pool heaters unless consistency in their use is assumed.

Does Domestic Hot Water Usage Affect the Building's Burn Rate?

If the building's burn rate between deliveries is known and the building is assumed to be unoccupied, the effect of domestic water usage on the burn rate can be calculated by adding that period's fuel consumption amount to the amount of fuel that would have been used based upon that building's occupancy and the number of days in question. Typically, single occupancy home domestic fuel usage does not alter the burn rate past the thousands of a decimal point whereas a four-person-occupied structure may change it three one hundredths (0.03) of the burn rate.

Example:

Buildings winter time burn rate: 0.25 gallons/HDD

11 May 2016 – 7 October 2016 = 149 calendar days: 170 HDDs

Fuel used between 11 May 2016 – 7 October 2016: 124 gallons

Home housed 4 occupants

170 HDD @ 0.25 gallons/HDD = 42.5 gallons used for heat

124 – 42.5 = 81.5 gallons of fuel used for domestic hot water

81.5 gallons fuel / 149 days = 0.54 gallons per day per household

0.54 gallons/day/household (4 persons) / 4 persons = 0.136 gallons fuel/day/person for domestic hot water usage

The Effect on Burn Rate

For the period in question (March 7-31, 2016) 24 days, 108.75 gallons delivered, 435 HDD, burn rate 0.25 gallons/HDD (Occupied)

Full Household (4 People)

24 days x 0.54 gallons (4 people) = 12.96 gallons

108.75 gallons – 12.96 gallons = 95.79 gallons of fuel used for heat

95.79 gallons/435 HDD = 0.22 gallons/HDD burn rate drop for 4 person household due to non-occupancy

A change of 0.03 gallons/HDD from identified normal occupied homes burn rate

Only one Occupant in Same House

24 x 0.136 = 3.26 gallons

108.75 – 3.26 = 105.49 gallons of fuel used for heat

105.49 gallons/435 HDD = 0.243 gallons/HDD: little perceptible change

Different reports of occupancy numbers and dates can be used to apply this correction factor on a case-by-case basis.

Conclusion

Typically, from past investigations, most homes and buildings that experience frozen pipe damage are vacant or not visited on a frequent basis. This makes eyewitness, first-hand observations of daily transitions into a frozen pipe event rare.

Forensic engineers have the ability to identify occupancy and heating system time events and conditions independent of what they are told by various parties involved in the loss. Fuel usage analysis data can also support or dispute conclusions resulting from only an examination of the mechanical component evidence. The investigator must realize that what he or she may be told by a property owner, fuel delivery company, or heating system repair technician may all be potentially self-serving and not be true.

The identification of reasonable fuel consumption rates in relation to building performance, as well as the ability to quantify deviations from known baseline rates, is a vital tool to the forensic engineer in evaluating these types of losses. The ability to identify conditions such as fuel tank runout, system breakdown, excessive thermostat setback, and utility failure all require that a representative consumption rate of fuel for the building (leading to the loss date) be identified. Deviations from known consumption rates must also be recognized as to their meaning and quantified to identify their implication of changes in temperatures or the time period in which the heating system is in operation.

Since frozen pipes are a leading cause of building damage in the United States, a focused investigation procedure for these types of losses is vital as well as the ability to derive useful information from property fuel and energy usage. The reconciliation of an energy analysis with field statements and findings can be a reliable methodology in which confidence in an investigation outcome can be achieved; therefore, the ability to correlate fuel usage to identifiable, real-world implications is vital for the forensic engineer.

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Forensic Engineering Analyses of a Home Fire

By R. Vasu Vasudevan, PE (NAFE 619F) and Jeremy Britton, PE (NAFE 943M)

Abstract

A fire had occurred in a single-family home where a family of four was living. The family was asleep when the daughter woke up, saw smoke in her bedroom, and screamed. The daughter and father exited by breaking through a bedroom window, but the other two family members were overcome by the fire before exiting (and were later found deceased by the fire department). None of the witnesses heard a smoke detector (activation), and brief searches by investigators did not find any evidence of either the detector bracket or other remains. Forensic engineering analyses of the preserved evidence were performed, and Fire Dynamics Simulator (FDS) software was used to analyze multiple fire origins, predicted smoke-detector activation, and egress times. Fire growth, thermally induced electrical failure (THIEF), glass breakage, smoke-detector activation, barrier failure, and tenability (CO, temperature and visibility) were calculated. The FDS analyses were performed using a combination of factual information, timelines, fuels derived from the Fire Burning Item Database (FireBID), analyses of photographs, and witness depositions, and were verified and validated. The analyses/methodologies were explained to the trier of the facts (jury), and the results were presented; namely, the most probable origin and cause (ignition) of the fire, smoke-detector-activation times, and egress times for the residents.

Keywords

Fire cause, fire origin, first fuel, ignition, Fire Dynamics Simulator (FDS), fires by electrical failures, smoke-detector activation, egress times, forensic engineering

Introduction

In the early morning hours of August 21, 2011, a disastrous fire occurred in a tenant-occupied detached single family home. The family was asleep when the daughter woke up, saw smoke in her bedroom (bedroom 3), and screamed. The father, mother, and son were sleeping in the master bedroom (bedroom 1), were awakened by the scream, and met the daughter in the hallway (**Figure 1**). Led by the father, they slowly moved to exit through the front entry door. When the family reached the end of the hallway, the fire and smoke intensity was too severe to exit through the front or kitchen. So they retracted to the daughter's bedroom and attempted to exit through the window. The window proved too difficult to open; therefore, they moved to the bedroom (bedroom 2) across the hallway. The father broke the window glass, slid out, and fell outside. He recovered in a few seconds, helped the daughter to get out, and carried her away from the burning house to the driveway. He returned to the window to rescue

Figure 1
Family movement.

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the mother and son. The mother went to get the son and disappeared. Responding to a call by a neighbor, sheriff's officers arrived on the scene, found the father at the front door attempting to get in, and moved him away from the building for safety. One of the officers attempted to enter, but having determined that it was impossible to enter through the front door, he went to explore other possibilities. In the meantime, the fire department arrived and started extinguishing and rescue operations. The fire department found the bodies of the mother and son on the floor of bedroom 2.

Prior to the fire, the family had returned home around 9 p.m., stayed in the living room until approximately 10 p.m., and then retired to their bedrooms. The 911 call was made by the neighbor who heard screaming at 10:53:38 p.m.

Fire Scene Investigations

Sheriff and fire department investigators performed the origin and cause (O&C) investigation after the fire was controlled and suppressed. They observed the remains of a candle (**Figure 2** and **3**) in the northeast corner of the living room and then talked to the father in the hospital. When the father was asked whether candles were used the previous night, his answer was yes. Based on the fire department report, the origin of the fire was located in the northeast corner of the living room on the lower shelf of a metal & glass end table, and the candle(s) was listed as the cause of ignition.

A private fire O&C investigator, retained and shared by the gas utility and the landlord's insurance companies, performed an investigation the next morning (8/22/2011). The O&C investigator talked to sheriff's department investigators and learned about the candle. He opined that the origin was approximately half of the area comprising the east side of the living room (**Figure 4**). The electrical circuitry/wires and systems of the building were eliminated with the exception of the electrical/electronic components (namely, the remains of TV and stereo equipment) belonging to the tenant, which were found along the east wall of the living room. Though these components were within his origin area, the unattended candle was, in his opinion, the cause (ignition source) for the fire.

This private O&C investigator had collected several items as evidence (**Figure 5** and **Figure 6**). The alleged unattended candle was not saved/preserved by any of the scene investigators.

Figure 2
Origin area of FD.

Figure 3
Unattended candle remains within FD origin.

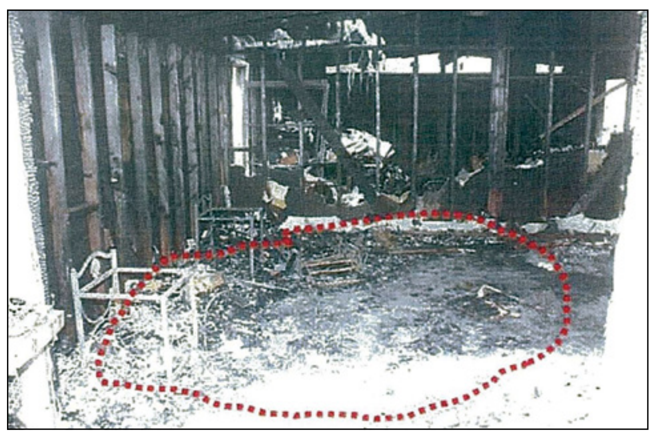


Figure 4
Origin area of private O&C.

Forensic Engineering Analyses

The attorneys representing the tenants (family) provided a brief background to the authors, including reports and photos by the sheriff's department, information collected from the various agencies, and the private O&C report. Later, numerous documents were supplied, including drawings of the home (**Figure 7**), applicable codes from the city/county/state, an invoice

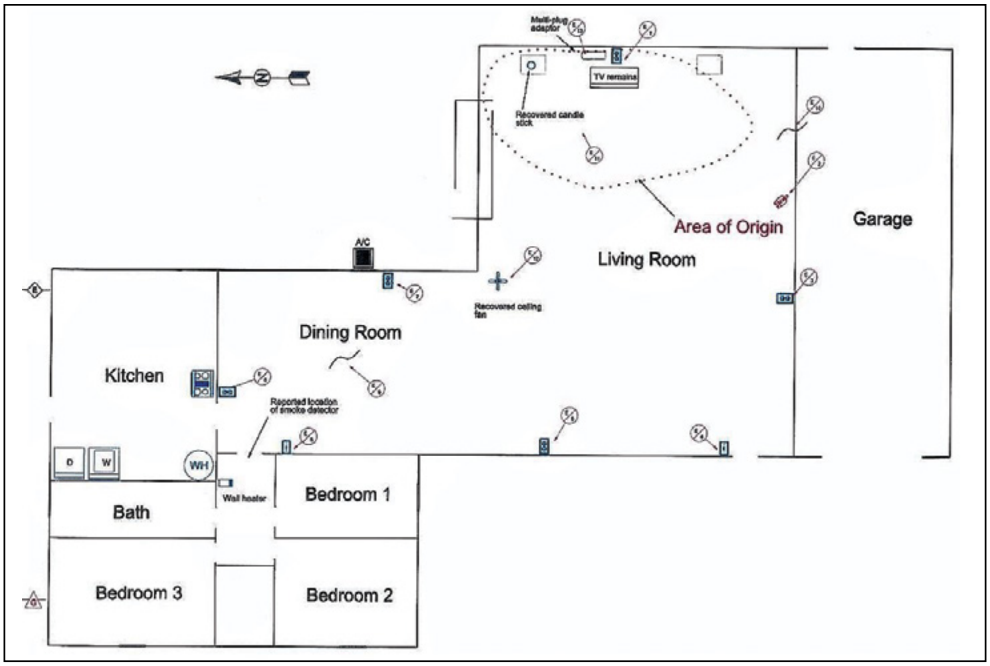


Figure 5
Evidence locations.

1	Outlet	Living Room-East Wall
2	Male Plug	Living Room floor-South Wall
3	Outlet	Living Room-South Wall
4	Switch	Living Room-West Wall
5	Outlet	Living Room-West Wall
6	Switch	Dining Room-West Wall
7	Outlet	Dining Room-East Wall
8	Outlet	Dining Room-North Wall
9	Wiring	Dining Room-Ceiling
10	Unknown Wiring	South Living Room Wall
11	Motor	Living Room Floor
12	Ceiling Fan	Floor of LR/Dining Room
13	Power Cords & Debris	LR Floor-East Wall

Figure 6
Evidence list.

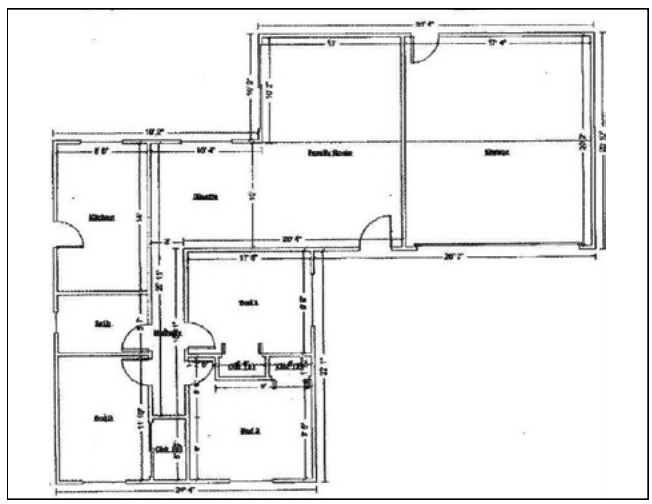


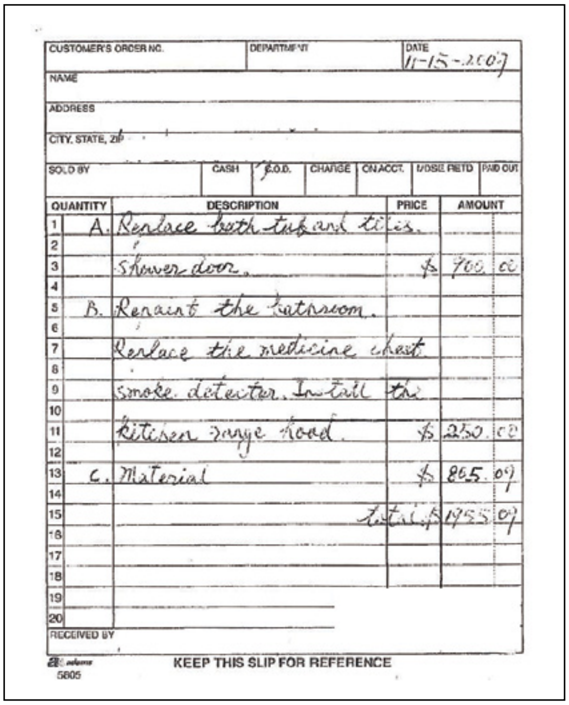
Figure 7
Home floor plan.

from a handyman (**Figure 8**), contents layout (**Figure 9**), pre-fire family photos, pre-fire water flood/loss data, depositions, and files of witnesses, investigators, and experts. Documents and information related to various topics, including physical and combustion properties of materials[1,2,3], flashover[2,4], electrical fires[5,6,7], fuel/material models[8,9], fire dynamics simulation[10,11,12,13], as well as structural elements, were reviewed.

Based upon the review of the information/documents, evidence examinations, and Fire Dynamics Simulator (FDS) modeling, a forensic engineering analysis was performed. The tasks, key observations, findings, and how this knowledge was used in performing the forensic engineering analysis are described in the subsequent sections of this paper.

Disputed Origins and Causes

Four O&C investigations were performed, and the investigators had different opinions (**Figure 10**). The fire department investigator (#1) opined that the origin was in the northeast corner of the living room, and the unattended candle was the cause (ignition source). As mentioned, the first O&C investigator of the landlord


CUSTOMER'S ORDER NO. | DEPARTMENT | DATE 11-15-2007
NAME
ADDRESS
CITY, STATE, ZIP
SOLD BY | CASH | C.O.D. | CHARGE | ON ACCT. | MDSE. RETD. | PAID OUT

QUANTITY	DESCRIPTION	PRICE	AMOUNT
1	A. Replace both tub and tiles,		
2			
3	shower door.	$ 700.00	
4			
5	B. Repaint the bathroom.		
6			
7	Replace the medicine chest		
8			
9	smoke detector. Install the		
10			
11	kitchen range hood.	$ 250.00	
12			
13	C. Material	$ 865.09	
14			
15	total $	1955.09	
16			
17			
18			
19			
20			

RECEIVED BY
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KEEP THIS SLIP FOR REFERENCE

Figure 8
Handyman invoice showing smoke detector purchase.

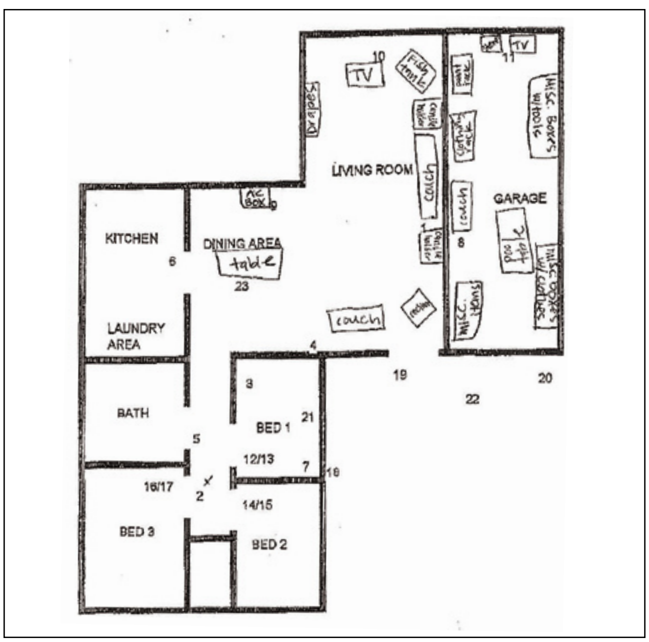


Figure 9
Pre-fire contents in home.

(#2) opined that the area of origin was approximately the east half of the living room, the building electrical system was eliminated, the tenant's electrical and electronic equipment could not be eliminated, and the unattended candle was the cause.

The O&C expert (#3) of the tenant (plaintiff) opined that the origin was in the south wall close to the east

Figure 10
Disputed origins within living room.

end of the couch. He further concluded that electrical failure/heating at the male-female plugs of the extension cords was the cause. The defendant (landlord) retained a second O&C expert (#4), who opined a flashover had occurred in the living room, the origin could not be determined, and the candle on the north wall of the living room above the couch was the cause. His origin was different than scene investigators (#1 and #2), and he stated that his opinions were based upon the review of the family photos and depositions (fire department, plaintiff experts, and family). He did not perform scene investigations nor examine the preserved evidence.

Forensic Engineering Analysis of the Evidence

Thirteen electrical items from the subject home were examined (**Figure 5** and **Figure 6**). For each item, the failure/damage hypothesis was synthesized, and postulates were generated/tested to determine whether an item had an internal failure and produced (or was capable of producing) heat for the ignition of the coterminous fuel.

Each item was photographed and documented, and in some cases macro and microscopic photography was performed. The fire scene photographs were reviewed to assess the fuels, condition, state, and severity of the fire in the locations. Key observations and findings are summarized in **Figure 11**.

Analyses of the microscopic photos of evidence item #10 (**Figure 12** and **13**) and X-rays of evidence item #13 (**Figure 14**), combined with observed failure modes of these items, supported the hypothesis that there were no internal electrical failures within the items (causative of ignition) but that these items were damaged by external exposure to fire. Evidence item

Evidence	Description	Evidence Location	Observation/Findings
1	Remains of a Wall Outlet	LR-East Wall	Plastic box, No ground screw, Old Romex 2-cond/12AWG. All Slots - Open. "Eagle" imprinted on Ground yoke
2	Remains of Male Plug	LR floor-South Wall	Remains of male prong and female slots, evidence of localized damage and fused prong within slot. Conduductor connected to prongs were ~16AWG
3	Remains of Wall Outlet	LR-South Wall	Outlet box was damaged and broken one ground yoke, male prong and a 2-conductor Romex remained ~12AWG
4	Remains of Wall Switch	LR-West Wall	Switch box. Plastic box with metal bracket 4-4AWG, 3 crimped connections pigtails. No parts of a switch
5	Remains of Wall Outlet	LR-West Wall	Plastic box with metal bracket. Two Romexes, 14AWG both
6	Remains of Wall Switch	Dining Room-West Wall	Stranded wires inside box poss dimmer. Resolidified metal. Two sets of conductors all 14AWG
7	Remains of Wall Outlet	Dining Room-East Wall	Remains of wall receptacle two sets of conductors both 12 AWG
8	Remains of Wall Outlet	Dining Room-North Wall	Remains of wall receptacle two sets of conductors both 12 AWG, ground yoke marked "LEVITON"
9	Remains of Electrical Wiring	Dining Room-Ceiling	Remains of wiring in ceiling all 14AWG
10	Remains of building Wiring	South Living Room Wall	Building wiring 14AWG ~2' in length with metal beads on conductors.
11	Remains of Electric Motor	LR Floor	Remains of electric motor with 6 conductors connected to motor
12	Remains of Ceiling Fan	Floor of LR/Dining Room	Remains of ceiling fan motor. No hotspot
13	Remains of Power Cords & Debris	LR Floor-East Wall	Remains of a power tap, metal body and 10 outlets-X-ray no localized damaged.

Figure 11
Summary of evidence examinations.

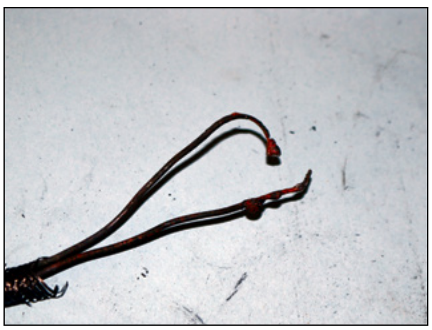


Figure 12
Evidence item #10 melted conductors.

Figure 13
Microscopic view of evidence #10.

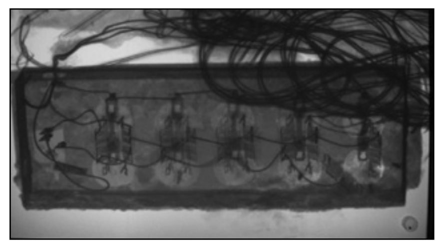


Figure 14
X-Ray evidence item #13 Power-Tap.

Figure 15
Evidence #2 male-female plug remains in the living room.

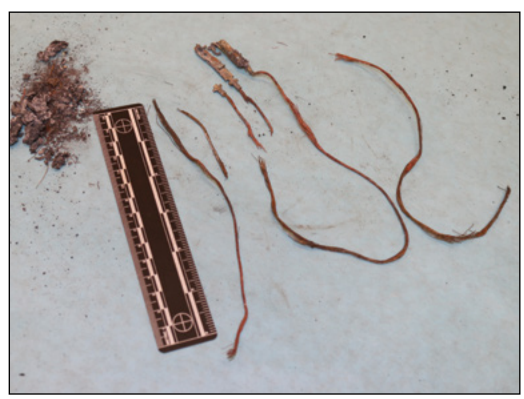


Figure 16
View of male-female plug remains collected.

#2, identified as a male plug from the south wall of the living room (**Figure 15** to **16**), had evidence of localized re-solidified and fused/bonded metal. The examinations determined that these were parts of male and female plugs of extension cords.

The two extension cords were daisy-chained, the failure-mode was localized, and internal melting of the prongs/blades was consistent with electrical resistance heating and faults/arcs (**Figure 17** and **18**). Evidence item #3 shows the remains of the outlet behind the couch in the south wall of the living room (**Figure 19**).

Figure 17
Closer view of male-female prongs.

Figure 18
Microscopic views of male-female prongs.

Figure 19
Evidence #3 outlet from the south wall of living room.

Closer examinations found the witness mark of an arc within the line-side slot of the receptacle (**Figure 20**). This suggested that there was a plug in that receptacle, and a parting arc had occurred when the energized blade was pulled/separated from the receptacle during the fire spread.

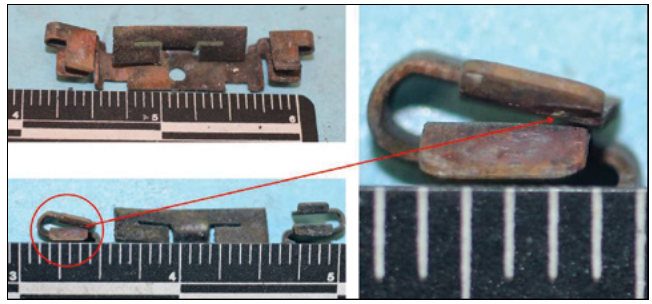


Figure 20
Witness mark of parting arc within evidence #3.

The scene photographs of evidence items #2 and #3 indicated that the male-female plugs were located on the left (east) side of the couch. The wires of the male plug went through the wall toward the garage (**Figure 15**). The wires of the female plug came into the living room and were severed approximately 6 inches from the female blade/slots. The severed wires of the cord went along the floor toward the wall outlet (closest) that was behind the couch. The residents (father and daughter) indicated that there was an extension cord plugged into the outlet that ran on the floor along the wall. The extension cord disappeared into a hole in the wall located next to the satellite TV cable box.

The scene photos of the south wall of the living room and the corresponding areas of the garage were reviewed. The review found a fire damaged orange-colored extension cord in the garage. The cord ran from the garage side of the male-female plugs up to the bottom cord of the main roof beam (north to south; **Figure 21**). The cord wires continued to a damaged junction box that was located approximately in the middle of the roof beam near the garage door opener (GDO). Fire damaged and hanging wires were found downstream of the junction box of the receptacle ("receptacle box") and the remains of the GDO, as shown in **Figure 21** (viewer in living room looking toward garage; north to south) and **Figure 22** (view from front to rear of garage; west to east). The father stated that, on occasion, he had used a stick to push a fallen down extension cord onto nails in the beam. Two nails were found in the main beam in the supplied scene photos.

Engineering analyses determined that the male plug of the short extension cord (A) was plugged into the receptacle (Evidence item #3) behind the couch. The male plug of another extension cord (B) was plugged into the female plug of extension cord (A). The daisy-chained cords went through the wall into the garage, up to the bottom of the roof beam, and ran (north to south)

Figure 21
Trace of extension cords from living room to garage.

Figure 22
View of the trace of cords in garage.

along the side of the beam (supported by nails) and into the receptacle box, where the power cord of the GDO was plugged (**Figure 22**).

The GDO and the daisy chained extension cords were installed around the year 2000 by a person retained by the landlord. The garage was used for storage by the tenants. Various items, such as a pool table, stereo, an old TV, and other items were stored in the garage. There was no pedestrian door between the house and the garage, and the GDO was used for access.

The electrical wires within the wall cavity (upstream of item #3, exposed after the fire origination) and the other collected evidence had no traces of electrical fault(s). The TV and stereo equipment (upstream of item #3 and the same circuit) did not contain any evidence of an internal electrical failure. The evidence of electrical fault/arc was found only at items #3 and #2 (furthest downstream site of arcing).

Information learned from the family indicated there were materials present or stored along the south wall between the couch and the east wall, including an aquarium tank and stand, electrical wires, cables (including the TV/satellite dish cables), plastic junction box of the TV cables, and other items. Analyses of the wall studs by the O&C investigator (#3) determined that there was a "V" pattern (**Figure 21**) on the wall studs, and the apex of the V was at the location where the male-female plugs (evidence item #2) of the extension cords (A to B daisy chain) were found. These and other observations indicated electrical resistance heating had occurred and served as a source of ignition heat for the fire.

Tracing the remains of the electrical circuit wires of the building in the wall cavity found that the circuit originated in the breaker panel of the building and ran along the west wall — and then continued to the outlet on the south wall (last on the circuit). There was also a branch in the south wall upstream of the receptacle that went up approximately 7 feet above the floor and ran to a junction box within the garage. Based upon the review of the photos and the information learned from the tenant, it was concluded that there was a circuit wire for the pull chain-operated light fixture in the garage.

Analyses of the photos of the meter and the breaker panel found that there was no main breaker for the electrical system (**Figure 23**). Furthermore, it was noted that most of the breakers were of the "pushmatic" type, implying that they were 1960s vintage electrical breakers with associated installation. The trace indicated a ganged-pair of circuit breakers were utilized

Figure 23
Meter and circuit-breaker panel for the home.

for the window AC (air conditioning) unit that was located in the dining room area. Scene examinations found that the electrical system of the home was not grounded. The receptacles were of the 3-prong type (ground), but there was no ground conductor wired to the receptacles.

Based upon the examination of the evidence and review of the scene photos, it was determined that the GDO did not have a dedicated circuit — and that it was plugged into the duplex receptacle via two daisy-chained extension cords, which passed through a hole in the south wall of the living room. Further, the specifications of the garage door opener were compared to the measured gauge size of the conductors of the extension cord, and the extension cord conductors were under sized. These and other observations indicated that the garage door opener installation did not meet the National Electrical Code and the International Fire Prevention Code (which prohibit the use of extension-cords as permanent wiring), and the electrical system was inherently unsafe.

Based upon these observations and analysis, it was concluded that electrical resistance heating occurred in the male-female plugs (A-B) of the extension cords, which, over time, progressively damaged the plastic material of the plugs and caused electrical faulting/arcing. This electrical resistance heating and subsequent electrical faulting/arcing was the cause of ignition of the adjacent fuel-material (plastic box, wires, cables, table, wood) which, in turn, spread to the combustible materials in the room as well as into the wall space. This was the most probable ignition and fire origination scenario consistent with the evidence (fire scene and collected evidence items).

The supplied invoice from a handyman (**Figure 8**) listed "smoke detector" as a part for the work, but the handyman couldn't provide any information/details in his deposition. The witnesses stated that there was no annunciation/sound from the smoke detectors. The search by the fire department and the private O&C investigators did not find any remains nor marks (bracket) of the smoke detector. The code requires a smoke detector in all sleeping quarters, hallways, and high-point(s) of the living space. As a part of the forensic engineering analysis of the fire, analyses were performed to determine the egress times for the residents with and without smoke detectors using the Fire Dynamics Simulator.

Fire Dynamics Simulation

Based upon the supplied and reviewed information, a 3D model of the subject single-family home was developed. The building geometry and layout were derived from the supplied drawings and photographs. After the 3D model was developed in the Fire Dynamics Simulator (FDS) program[10,13], it was verified to match the subject building. The combustible materials (fuels), such as the sofas, mattresses, dining table, TV, wood ceiling beams, drywall, and other items, were approximated and placed within the building. The positions of the items and type of items were based upon information and photographs supplied by the tenants. The combustible materials (fuels) placed within the building were mathematically represented based upon the various tests and published data. The electrical wires and the male-female plug were represented using the thermally induced electrical failure (THIEF) cable model within FDS[8].

FDS software includes the two most common residential smoke detector types: ionization and photoelectric detectors. Both smoke detector types were placed in two ceiling locations in the hallway and in each bedroom (**Figure 24**). The sliding door and window glass panes were instrumented in the model with an array of temperature and heat-flux detectors to break the glass at the appropriate conditions. The drywall was instrumented in the model to cause failure of the wall to allow the fire to spread from the living room to the garage. The carbon monoxide (CO), temperature, heat flux, and smoke levels were monitored throughout the interior of the building at various locations.

Figure 24
Hypothetical smoke detector locations.

The mathematical models/representation of the fuels in the FDS were checked, validated, and verified. As needed, fuel models were constructed/synthesized, and the published data were simulated to validate the fuel models. The simulation results were validated by information from witnesses, the timeline, O&C investigators, scene photographs, and physical evidence.

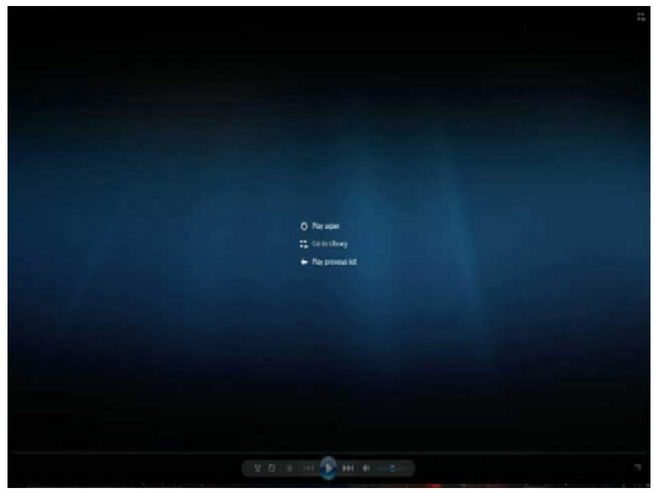
Parametric analyses of the mesh, dynamics of combustion, the door/vent status, and timeline were performed. Based upon these parametric analyses, the optimum grid size, fire dynamics and the timeline were developed.

Three potential origins were analyzed: (1) northeast corner of the living room near the sliding glass door (fire department); (2) origin on top of the sofa (defendant); and (3) origin near the floor level on the side of the couch (plaintiff). For all three analysis scenarios, slow and fast fires (T^2 heat-release rate profiles) were implemented, and the smoke detector activation times, glass breakage times, and severity of the fire (temperature, carbon-monoxide, visibility, and heat-flux levels) were monitored. Seven of the simulations are summarized in **Figure 25**.

Eight different simulations of the fires on top of the sofa (candle fire) and side of the sofa at floor level (male-female plug) with the cords are summarized in **Figure 26**.

Using photographs, fire damage patterns, timeline(s), and witness information, the simulation labeled as Q5 was the best fit and most probable simulation for the subject fire (origin at the south wall of the living room near the east edge of the sofa) per #3 plaintiff investigator. The smoke level, CO (ppm at 2-meter elevation) and temperatures for the smoke detector activation time of 45 seconds are shown in **Figures 27, 28,** and **29**, respectively. The temperature, carbon monoxide and visibility levels, smoke detector activation, and egress times are presented, and the computed values for selected times (slices/snap-shots) are illustrated in **Figures 30** to **32**.

The video of the Q5 FDS simulation for 210 seconds (actual time) is in the attached multi-media file (Q5 Real Time.avi). This video-simulation includes freeze-frame snapshots of parameters for illustration (total run time ~5 min 30 sec).



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IT CAN BE DOWNLOADED AT: HTTPS://GET.ADOBE.COM/FLASHPLAYER/

The model for the Q5 simulation (most probable) was modified and updated to determine whether the subject house fire produced fire, flux, and temperatures sufficient to melt the copper conductors of evidence items #2 and #10 and spread/propagate to the garage through the common wall. The modifications included the use of verified THIEF models of cables/wires[8]. FDS

	Wire 1	Wire 2	Wire 3	Wire 4	Wire 5	Wire 6	Wire 7	Wire 8
Model-size	Full	small	small	small	small	small	small	small
Upper wall material	wood	wood	wood	gypsum	gypsum	gypsum	gypsum	gypsum
Fire location	side of couch	on couch	on couch	on couch	on couch	on couch	on couch	on couch-hot surface only
Screen	no	yes	yes	yes	yes	yes	no-replaced w/ wall	yes
screen free area	n/a	0.4	0.1	0.2	0.05	0.2	0.2	0.15
Wire location	S-E corner	L-side of couch	L-side of couch	L-side of couch	L-side of couch	L-side of couch	L-side of couch	L-side of couch
Wire temp (*C)	1040	953	53.6	668	75	756	802	767 at 357sec
Hole in wall at wire	no	no	yes	yes	yes	yes	yes	yes
Vent in upper wall	no	no	yes-wood	yes-gypsum	yes-gypsum	yes-gypsum	yes-gypsum	yes-gypsum
Vent opening time	n/a	n/a	178	364	not open yet	181	282	330
Vent criteria	n/a	n/a	900*C & 60kW/m^2	1100*C & 130kW/m^2	1100*C & 130kW/m^3	00*C & 130kW/m^	100*C & 130kW/m^	1100*C & 130kW/m^4
Slider opening time	163	66	85.8	86.4	not open yet	86.8	85.2	200
Slider criteria	4-dvcs	4-dvcs	4-dvcs	4-dvcs	6-dvcs	4-dvcs	4-dvcs	6-dvcs
ire Size - HRR (MW	30+	14.5	5.9	14.3	4.3	14.1	16.5	15
Total Time - sec	250	322	184	378	210	400	400	
				crashed	crashed-O2 Constrained			

Figure 25
Summary of wire model features and results.

	Time (s)						
	Q1	*Q2*	*Q3*	*Q4*	*Q5*	*Q6*	*Q7*
Smoke Detector (East end of Hallway)	N/A	N/A	N/A	33.9	34	79.2	42.4
Smoke Detector Heskestad Ionization (West end of Hallway	42.0	42.0	36.6	41.7	41.5	86.4	45.6
Smoke Detector Cleary Ionization I1 (West end of Hallway)	42.6	42.6	37.8	41.7	41.8	87.6	46.4
Smoke Detector Cleary Ionization I2 (West end of Hallway)	43.2	43.2	37.8	42.6	42.5	87.6	46.4
moke Detector Cleary Photoelectric P1 (West end of Hallwa	43.8	43.8	38.4	42.6	42.5	88.2	47.2
moke Detector Cleary Photoelectric P2 (West end of Hallwa	45	45.0	40.2	44.1	44.3	88.8	48.8
Smoke Detector (Bed 2)	N/A	N/A	N/A	56.4	56.3	113.4	57.6
Smoke Detector (Bed 3)	N/A	N/A	N/A	57	56.8	112.2	56.8
Smoke Detector (Bed 1)	N/A	N/A	N/A	200.7	156.3	216	
Slider Breaks	162	162.6	112.8	162.9	163.3	293.4	
Dining Room Window Breaks	186	181.8	256.2	184.5			
CO in Entry Reaches 5000+ ppm	148	150.0	268.2	145	147.8		
Temperature in Entry Reaches 200+ F	100	100.0	85.2	105	105.3		
CO in Kitchen Reaches 5000+ ppm	N/A	158.0	159	155.1	156.3		
Temperature in Kitchen Reaches 200+ F	145	128.0	95.4	125.7	124.8		
CO in Hallway Reaches 5000+ ppm	200	222.0	279.6	177.3			
Temperature in Hallway Reaches 200+ F	145.8	145.8	285	160.8	151		
CO in Bed 1 Reaches 5000+ ppm	188.4	192.0	274.2	213.3			
Temperature in Bed 1 Reaches 200+ F	190.2	195.0	281.4	212.1			
CO in Bed 2 Reaches 5000+ ppm	188.4	190.2	330.6	182.1			
Temperature in Bed 2 Reaches 200+ F	175	156.0	324	162	164		
CO in Bed 3 Reaches 5000+ ppm	193	180.6	N/A	182.1			
Temperature in Bed 3 Reaches 200+ F	223	154.2	324	159.3	162		

Q1 - preliminary FDS model with origin near couch long runtime
Q2 - preliminary FDS model with origin near couch and more output files
Q3 - FDS model with origin near drapes of sliding glass window
Q4 - FDS model with origin near couch with more devices and updated timeline
Q5 - FDS model with origin near couch with updated timeline after depo review
Q6 - Same model as Q5 but changed to slow growth T-squared fire
Q7 - Same as Q3 but changed to slow growth T-squared fire and updated timeline

Figure 26
Summary of results of simulations.

analyses showed that simulation temperatures at item #2 were significantly below the melting temperature of copper, the temperatures at item #10 exceeded this threshold (**Figure 33**), and the fire would burn through the drywall into the garage. These were consistent with the evidence and damage.

Opinions

The electrical wiring system was inherently unsafe, and the electrical circuitry of the garage door opener did not comply with the prevailing electrical and fire codes and standards. In addition, the operation of the garage door opener caused currents greater than the nominal capacity of the wires, and the cyclic electrical resistance heating at the weak link (male plug and female receptacle slot of the extension cords) led to overheating and arcing (catastrophic failure). This internal electrical resistance heating (and the subsequent arcing) was the competent and viable ignition source for the adjacent materials (plastic box, wires, cables, table, wood) and hence the cause of the fire.

FDS analysis showed that the most probable origin and the ignition source/scenario was the male-female plugs of the extension cords of the garage door opener, producing electrical resistance heating, arcing, ignition, and fire.

The results of the FDS analyses were consistent with the physical evidence, including the temperatures at item #2 and at item #10. The analyses also showed fire propagation through the common wall to the garage.

Based upon the most probable simulation, a smoke detector in the hallway would have annunciated between 34 and 45 seconds after ignition-flame/fire originated, depending upon the detector location, and provided approximately 1 minute for egress through the kitchen and front entry doors. The annunciation would have provided approximately 2 minutes for safe egress through the bedroom windows.

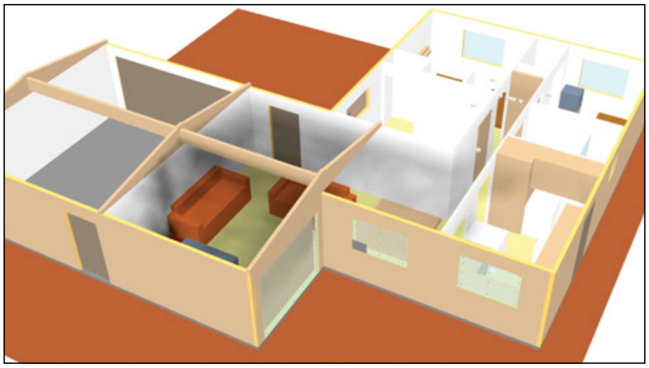

Figure 27
Smoke @ 45 sec.

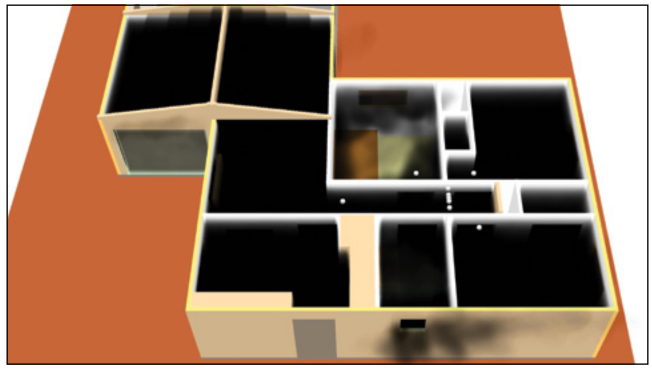

Figure 30
Smoke @ 160 sec.

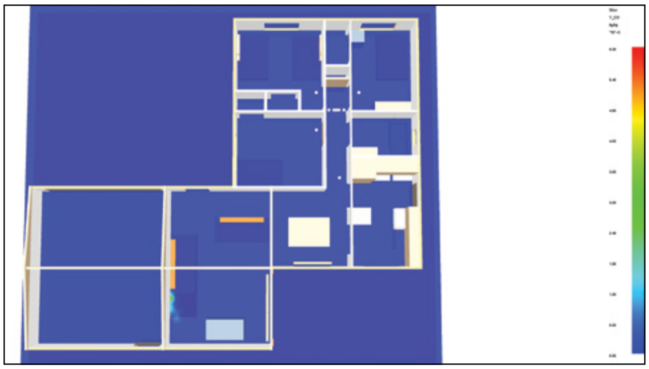

Figure 28
CO @ 45 sec.

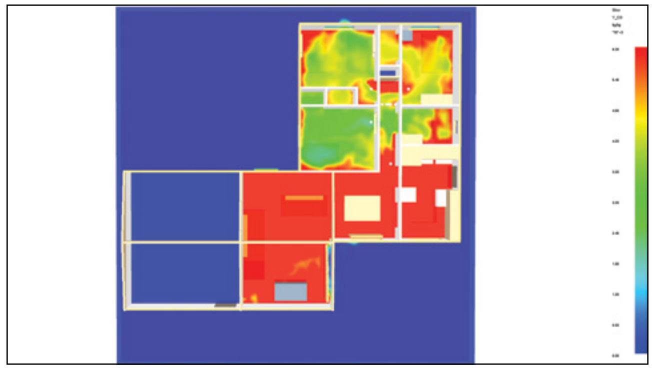

Figure 31
CO @ 182 sec.

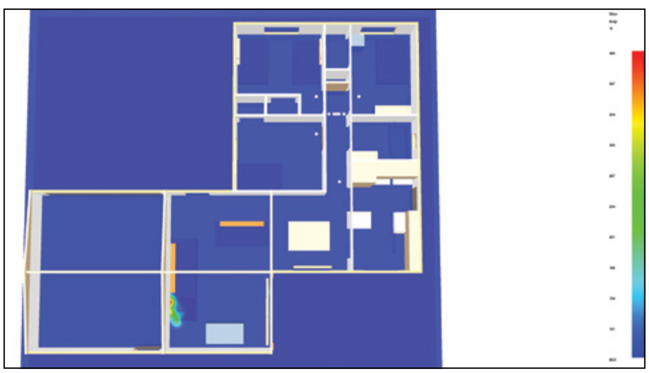

Figure 29
Temps @ 45 sec.

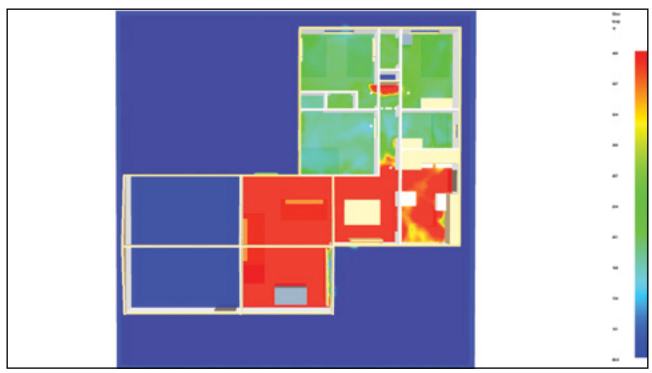

Figure 32
Temp @ 182 sec.

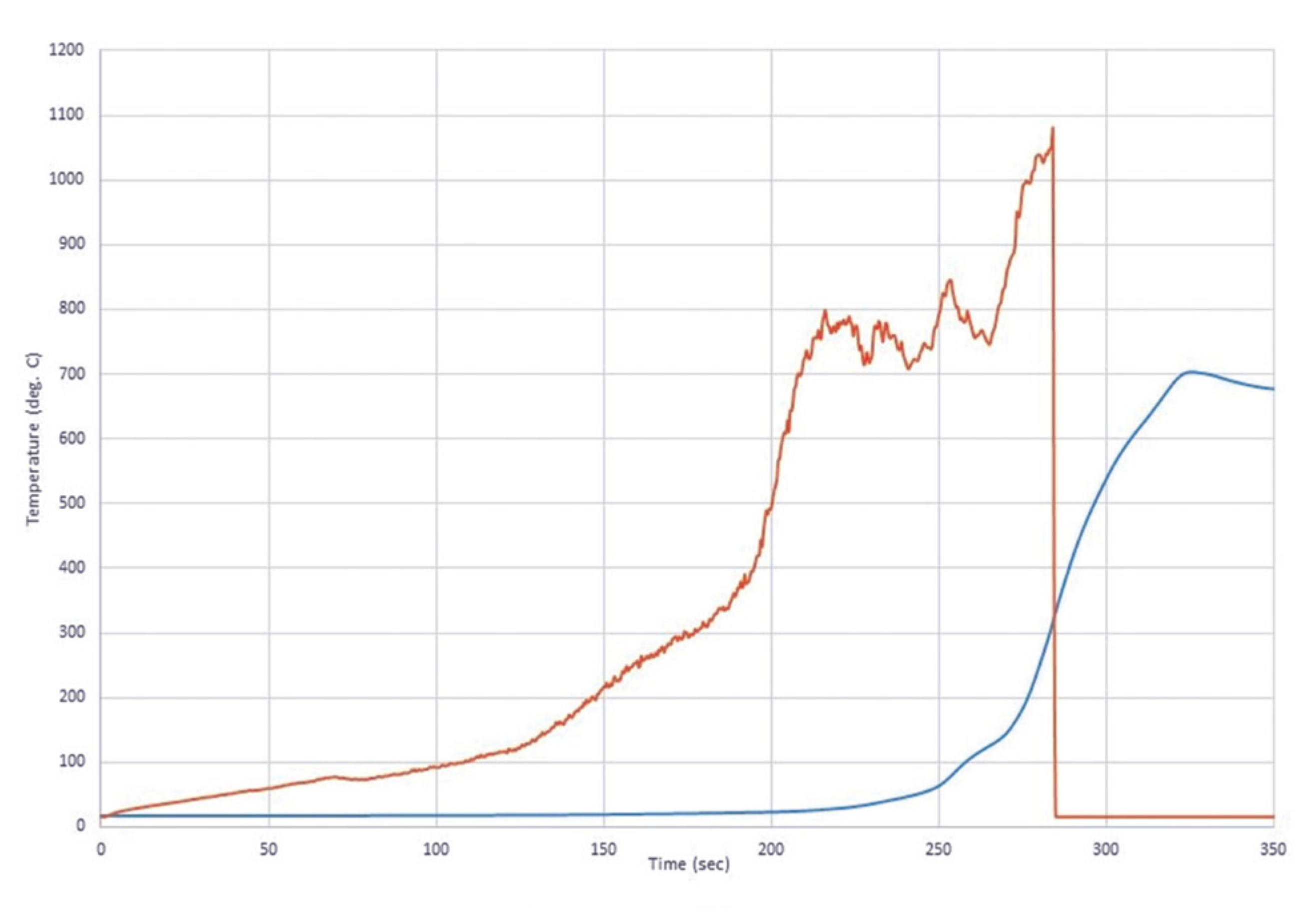

Figure 33
Q5 modified simulation temperatures @ 1-foot and 8-foot (red) elevations south wall.

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Biomedical Engineering Physical Evidence-Based Analytical Methods

By Laura L. Liptai, PhD (NAFE 339A)

Abstract

This research provides insight into the causation of injuries using peer-reviewed and generally accepted biomedical engineering methodologies. The case studies to demonstrate these methods illustrate various outcomes from the nonuse and misuse of safety equipment: seatbelts, motorcycle helmets, and bicycle helmets. Utilizing these cases, this paper will report examples of how biomedical engineering contributed to the analyses of vehicular, pedestrian versus auto, bicycle versus auto, and motorcycle impacts. Examples illustrate where the biomedical engineer is qualified to utilize his or her specialized knowledge, education, and training to: 1) offer insights on quantification of forces/accelerations on the human body; 2) interpret biological tissue physical evidence like cutaneous trauma and pattern evidence; and 3) use fracture mechanics methods to contribute to the analysis of causation and liability. Comparing information from experiments and/or biomedical analysis of the physical evidence, the biomedical engineer serves to supplement traditional accident reconstruction methods. Testing methods are also discussed to illustrate how case-specific experiments can be performed to acquire data not available by any other source.

Keywords

Biomedical engineering, biomechanics, physical evidence, trauma, seatbelt, airbag, pedestrian, motorcycle, bicycle, automobile, helmet, analytical method, testing

Introduction

The case studies for this report demonstrate various outcomes from the nonuse and misuse of safety equipment: seatbelts, motorcycle helmets, and bicycle helmets. The biomedical engineer contributes to the analysis of both causation and liability by educated observation of the physical evidence combined with knowledge of engineering/physics and injury biomechanics. The biomedical engineer does not offer an opinion on the diagnosis of injury to a particular plaintiff, since medical diagnosis, prognosis, and treatment would be outside the scope. The field of biomedical engineering is long established and a subject of engineering, not medicine. It dates back to 1968 where a biomedical engineering program grant from the National Institutes of Health was awarded to the University of Southern California. A biomedical engineer's education is uniquely inclusive of engineering and medicine to assist physical evidence evaluations and analysis of the mechanics of injuries to the human body.

For illustration, a biomedical engineering analysis may reveal: 1) what factors caused the accident and injuries; and/or 2) whether or not the injury would be reduced or eliminated with the proper use and design of a safety device or safety processes (including an air bag, helmet, occupant restraint, machine guard, and/or methods to reduce repetitive stress/lifting trauma, for example). The medical training of the biomedical engineer provides insight as to the mechanics and causation of the injuries (per the medical professional's diagnosis) from the engineering perspective. In the cases presented, a specialized evaluation of physical evidence by a biomedical engineer made a significant difference in determining causation and liability.

Methodology

The forensic engineering method is generally utilized for forensic analysis in biomedical engineering in order to interpret the relationship among observations of physical phenomena, while reducing the influence of human bias and improving objectivity. Engineering forensics most commonly involves analyzing parameters, causes of incidents, and/or hypothetical prevention methods. It aims to apply known, established science (e.g., Newton's Laws) in conjunction with the knowledge, experience, and skill of the engineer to determine

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causation. The forensic engineering method differs from the scientific method in that hypothesis generation is rarely utilized, and testing may also include iterative analysis[2]. Specific procedures for the application of the forensic engineering method differ from one field of engineering to another, but the technique is a universal template that provides an analytical framework to acquire, collect, and/or integrate knowledge.

Protocol for conducting biomechanical analysis has been well established, and there are several articles that are peer reviewed and published, a few of which include: *Forensic Engineering Case Analysis in Biomedical Engineering*[3], *Forensic Engineering and the Scientific Method*[1], *Trauma Causation*[2], *Accident Reconstruction*[4] and the *Reference Manual on Scientific Evidence, 3rd Edition*[5].

A forensic engineering analysis is a multifaceted examination, combining observation with knowledge, education, experience, training, and skill. A hypothesis is rarely utilized because rarely is new science developed in the application of biomedical engineering to forensics. The process begins by defining the problem to a precedent event. Most simply, the forensic engineering problem may change as new factual data arises and as the iterative process of data collection progresses. Often, engineers with an expertise in forensics are asked to evaluate whether the incident or product failure could have occurred as described by witnesses based on the available evidence. The collection of data includes study, experimentation and observation. Records are received through discovery. After data is collected, it is iteratively analyzed with the goal to minimize bias and maximize objectivity. Some of the records reviewed would be (but are not limited to): medical records, radiological films, interrogatory and deposition documents, photos, physical evidence, and witness testimony. Conducting a peer-reviewed literature search would be another step to supplement the findings with research. Often times, evidence is available for a physical inspection. However, photos may be used when physical evidence is unavailable. In these situations, it is recommended that the forensic engineer properly widen the confidence interval of the reported findings. Also, if the subject product or vehicle isn't available, a kinematic study using a substantially similar exemplar can also be used to provide a better visual understanding of what can result from the subject incident. Finally, if necessary and economically feasible, testing may provide the missing force, acceleration or displacement data needed in the analysis. As the data collection proceeds, causal analysis is initiated in an iterative manner. The proper interpretation relies, in part, upon knowledge, experience, and training. Information gleaned from the observed evidence and data can be compared to known benchmarks, such as tolerances or standards, and can be evaluated for individual or cumulative consistency in logic. The comparisons may allow the biomedical engineer to determine if mechanical or biomechanical failure occurred. The cumulative logic and reiterative analysis utilizes the results and determines whether the weight of the supplemental data is consistent or inconsistent with existing data. The findings or conclusions should be presented with the certainty in the result; if it is not possible to quantify the certainty, then (when possible) an attempt should be made to report certainty qualitatively. If the findings are inconsistent, the engineer should equally report these results with the associated certainty or confidence interval.

Analysis/Results Include Three Examples

Case backgrounds, forensic questions, and brief results are presented; however, this is not a summary of three cases. The paper utilizes three causal analyses to illustrate the methods. Therefore, each analysis will include a brief discussion of the engineering approach, fundamental principles employed, methods, results and conclusions as illustrative tools. The clients were defense counsel in the following three cases.

Analytical Example #1: Seatbelt Analysis of a Minivan

This case presents a 68-year-old woman and her 65-year-old husband pulling out to make a left turn onto a rural two-lane highway directly into the path of a moving truck. The resulting side impact had a change in velocity (Delta V) equaling 25 mph and principal direction of force (PDOF) of negative 37 degrees (**Figure 1**). The driver sustained minor soft tissue trauma while the husband, sitting in the right front passenger seat, sustained large bilateral subdural hematomas as well as bilateral frontal lobe subarachnoid hemorrhage as detailed below.

Diagnosis from the emergency room included:

1. Multiple traumatic brain injuries.
2. Hemopneumothorax (blood in the thorax) on left with rib fractures 2 through 6.
3. Pre-accident neuropathy.

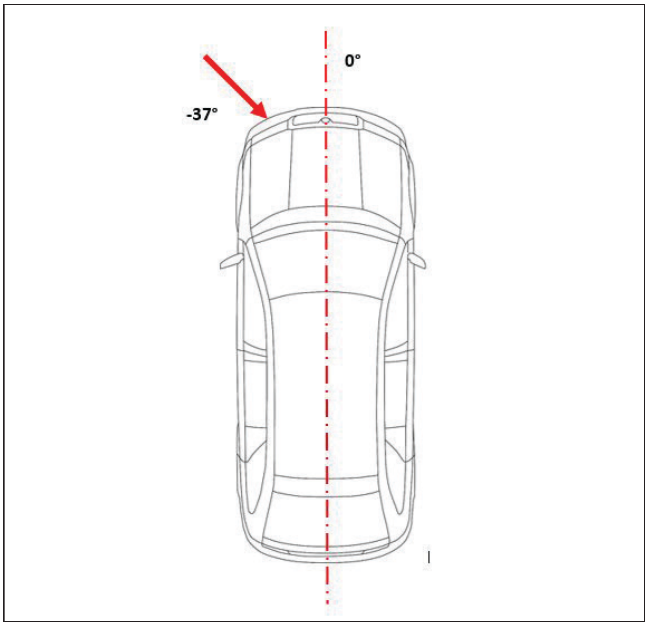

Figure 1
Diagram of principal direction of force (PDOF) of negative 37 degrees on plaintiff vehicle.

In medical terminology, the CT head diagnoses included:

1. Large bilateral subdural hematomas measuring 17 mm in thickness on the left and 8 mm on the right. There is a 3 mm midline shift to the right, uncal herniation through the foramen magnum and transtentorial herniation,
2. Bilateral frontal lobe subarachoid hemorrhage, and
3. Small focus of high density in the right thalamus, concerning for hemorrhage.

The plaintiff's wife argued that her husband was wearing a seatbelt, but nonetheless suffered a fatal injury. The defense argued the husband was not wearing a seatbelt, and he would have likely survived the accident if seatbelt restraints were utilized (**Figure 2**).

Since the vehicle was not available for inspection, photos analyzed were supplemented by the point of rest information from the first responder reports, which specifically noted the position of the passenger at point of rest (partially in the foot well). Since the body was in a crouched position at the point of rest, this raised doubt that a seatbelt was worn because his hips would have likely remained in the seat if restrained. However, his wife testified that he was belted as there was no warning chime (audible warning chime that occurs with the occupant is unrestrained). In addition, the plaintiff argued that it was minutes before the emergency medical technicians were on the scene so he could have been unbelted post incident. Contrarily, if the seatbelt (which had a pre-tensioner to remove slack from the seatbelt upon impact) had been worn — and the belt remained unlatched post impact — the passenger's buttocks would clearly be expected to be on the seat after the collision. The injuries sustained (as diagnosed by the health care providers) supplemented the data; there were multiple traumatic brain injuries and a hemopneumothorax on the left with left side rib fractures (#2-#6) that would be consistent with left-sided impact into vehicle interior structures. A thorough analysis of the evidence at the scene found a baseball hat, worn by the decedent, at the point of rest consistent with a negative 37 degree principal direction of force, since it was in a position that would have required proximal contact. Surprisingly,

Figure 2
Photo on left shows an exemplar vehicle after a frontal impact at 35 mph where there was no contact with the interior, and the photo on the right is the subject vehicle post impact. This illustrates that the use of seatbelts prevented contact of the body with interior structures in the anthropometric dummy tests.

the wiring diagram exposed that there was no warning chime for the right front occupant's restraint, and the airbag and pre-tensioner could deploy without seatbelt use. This is consistent with the driver not hearing the warning chime and the pre-tensioner deploying with an unrestrained right front occupant. **Figure 3** shows the seatbelt on the passenger side is extremely taut compared to the driver's seatbelt post impact consistent with non-use of the restraint by the passenger.

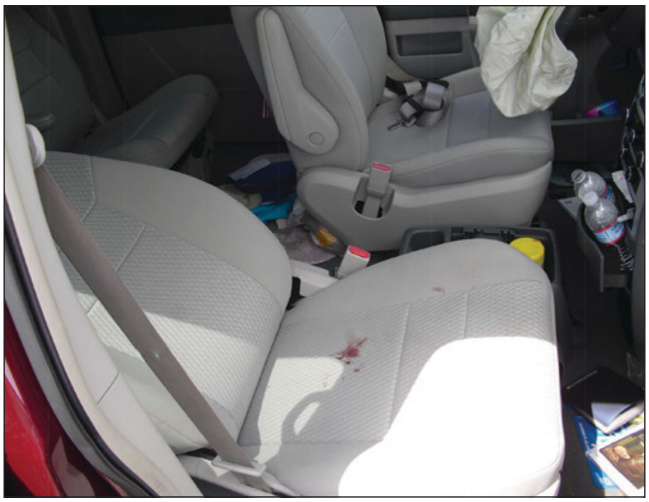

Figure 3
The photo above of the right front passenger seatbelt illustrates extremely taut webbing. Note the difference between a used (driver) and unused (right front passenger) seatbelt after the pre-tensioners fire bilaterally.

The NCAP crash test data of a substantially similar vehicle at 35 mph revealed that both the driver and passenger would sustain less than the federal motor vehicle safety standard for head injury (the Head Injury Criterion). Specifically, the Head Injury Criterion for the driver and passenger equaled 477 and 386, respectively, both of which are under the HIC tolerance of 1,000 for adults based on Federal Motor Vehicle Safety Standard 208. **Figure 4** illustrates that the subject impact was much less severe than the crash test; therefore, it is reasonable to assume that if the HIC was under tolerance in the more severe impact, HIC would likely be below tolerance in the lesser subject impact. Another key to the forensic analysis was the revelation that the multiple rib fractures were in a left lateral and linear juxtaposition (i.e., the fractures were in a line below the left arm) on the opposite side of the seatbelt. Contact points away from the airbag to cause the rib fractures would be the steering wheel (laterally) or the dash, which would be reachable by a 5 foot 8 inch, 121-pound male if no seatbelt was worn. These concepts were re-tested using a substantially similar height and weight human model in the exemplar vehicle that illustrated it was unlikely for the chest to impact the steering wheel if restraints had been in use at the principal direction of force of the incident. In conclusion, based on the information analyzed, the decedent was likely unrestrained at the time of the collision.

Analytical Example #2: Motorcycle Helmet Analysis

This case presents a 19-year-old female who was a passenger on a motorcycle. The rider was going uphill on a left-hand curve, struck a guardrail on the right (**Figure 5a**), which ejected the young woman from the back of the motorcycle. Her face was struck consistent with the facial trauma that included open fractures of the nasal complex, maxilla, frontal sinus, and mandible as well as extensive facial lacerations most prominently to the upper right lip (**Figure 6**). Prior to the forensic engineering analysis, the striking object was unknown and the narrow-most issue in the case. The

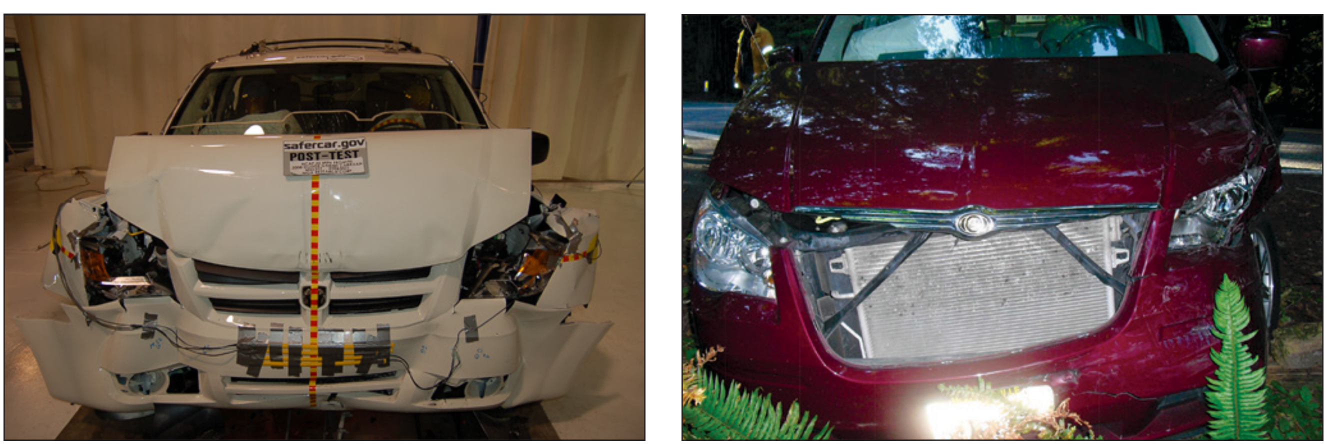

Figure 4
Frontal impact of an exemplar vehicle at 35 mph versus the less severe impact of the subject vehicle (ΔV = 25 mph according to the accident reconstructionist).

Figure 5a and Figure 5b
Incident scene with stop sign and thrie-beam barrier as well as a close-up of nails present in the stop sign post.

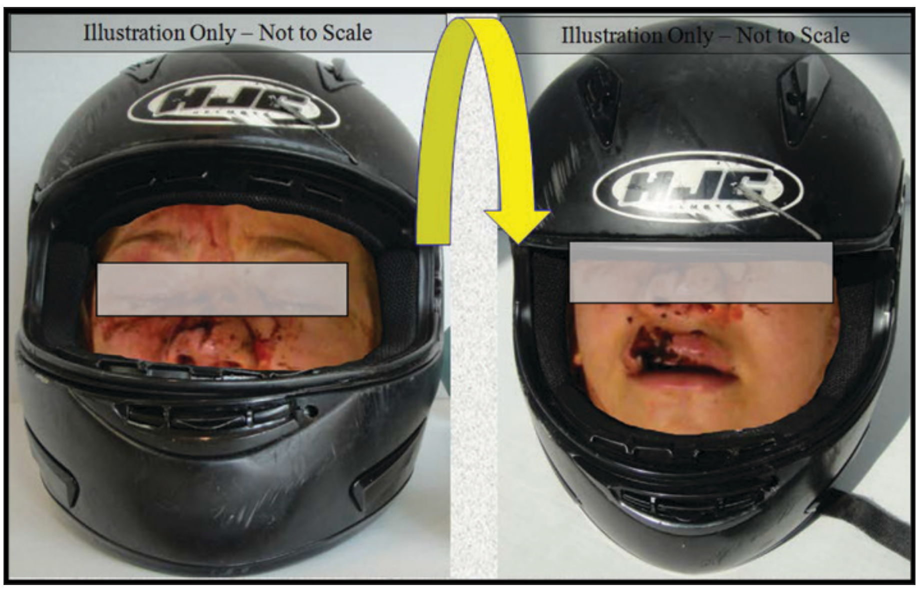

Figure 6
Loose-fitting helmet likely caused open fractures of the nasal complex, maxilla, frontal sinus and mandible as well as extensive facial lacerations most prominently to the upper right lip.

plaintiff alleged she struck one of five nails sticking out 4 inches on the stop sign post (**Figure 5b**) to cause the extensive lacerations and trauma to the face. The scope of the defense retention in this case was to determine the likely cause of the facial trauma.

Evidence included gross inspection of the scene and both gross and microscopic inspection of the helmet. Photos of the motorcycle were evaluated because the subject motorcycle was no longer available. It turned out that it was imperative that the helmet was inspected and photographed microscopically. In the helmet inspection, no evidence of forceful impact to the helmet was found internally, specifically to the expanded polystyrene (EPS), a rigid closed-cell foam comprising the interior of the helmet. Evidence found on the helmet included:

1. Blood evidence at the bottom of the helmet,
2. A flat surface scrape on the right side (parietal aspect) of the helmet,
3. Signs of blood and tissue proximal to the helmet opening, and
4. Scrapes and gouges above the face shield, including a focal gouge with a polymer curl, were found on the exterior forehead area of helmet.

There was no evidence of sign posts and/or guardrail intrusions that breached the facial perimeter of the helmet. Most of the helmet damage was localized on the right temporal/parietal area and the left mandibular area, which is consistent with impact to left chin bar and glancing shear to the right parietal/forehead. A focal gouge with curled polymer (helmet material) was found on the exterior forehead area of the helmet. A microscopic analysis found that there was blood inside this peeled and curled up area of the helmet shell, as shown in **Figure 7**. Therefore, blood was deposited on the outside of the helmet prior to contact with the straight non-yielding surface that caused the gouge. This surface was determined from the scene investigation to be consistent with a thrie-beam barrier at the side of the road.

Anatomically, the motorcycle operator noted that the plaintiff's helmet was worn large and loose, which corroborated the physical evidence. It was determined that the plaintiff's loosely worn helmet likely rotated forward to impact her face during impact and ejection from the motorcycle, resulting in blood/tissue-like

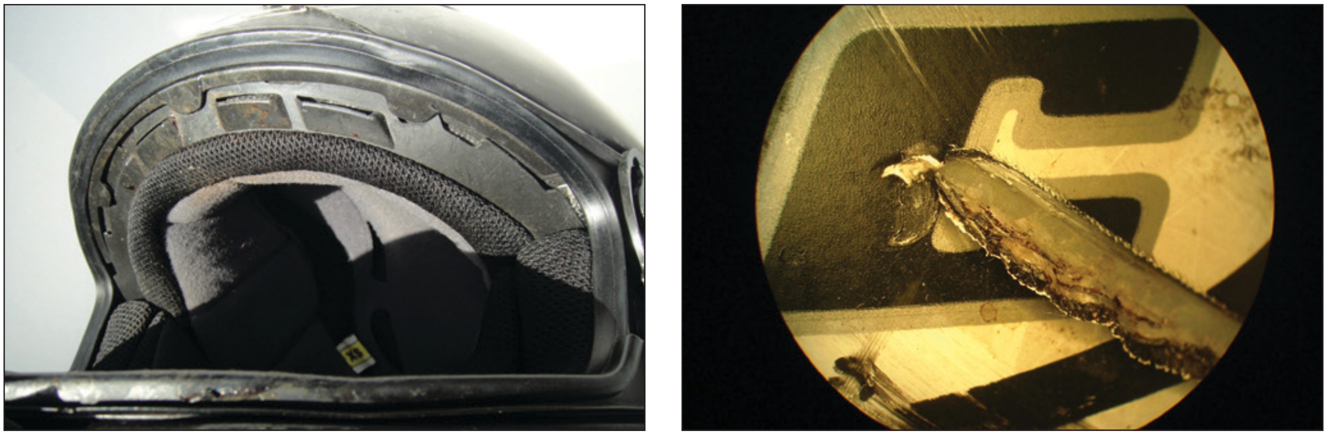

Figure 7
Blood/tissue-like evidence at the superior opening of the helmet internally (left) and in the interior of the curled polymer, resulting from the gouge externally (right).

evidence on the superior opening of the helmet as well as to its exterior (**Figure 7**). In conclusion, the physical evidence on the helmet, scene inspection, and testimony were consistent with the injuries sustained from a loose-fitting helmet. In this specific case, the careful microscopic inspection was imperative to a full interpretation of the physical evidence and proper causation determination.

Analytical Example #3: Bicycle and Vehicle Collision Analysis

Figure 8 illustrates the subject vehicle and bicycle from an un-helmeted male child bicyclist struck by a Toyota Prius in California as he crossed a freeway on-ramp. He impacted the roof of the vehicle/windshield, and then struck his head on the asphalt, suffering severe traumatic brain injury and comminuted fractures of the right orbit, complex facial fractures, and right frontal and temporal fractures involving the TMJ (temporomandibular joint). The most significant residual trauma was the diffuse brain injury rather than the right orbit or TMJ.

Figure 8
With the vehicle at point of rest at the scene, the bicycle evidence is matched up to the Prius. The un-helmeted bicyclist stated he was not riding but was a modified pedestrian at the time of impact so therefore helmet use wasn't required.

First, with regard to whether a helmet was required, the plaintiff bicyclist argued he was not astride his bicycle, but was riding it as a scooter, with his right foot on the left pedal — and because he was not "riding," he was not required legally to wear a helmet. Defense counsel argued he was riding his bicycle, and the injuries would have been prevented or mitigated if a helmet was worn. The scope of the defense retention was to determine whether or not the available evidence could determine whether plaintiff was riding his bicycle, and, if so, would the use of a helmet have mitigated the head and brain trauma.

Biomedical engineering assessments pieced together the physical evidence that supplemented the analysis of the accident reconstruction and bicycle experts. First of all, there was an absence of evidence on the front of the vehicle that would be consistent with right side bicycle contact, which would have been the exposed side of the bicycle had the plaintiff been riding it like a scooter. **Figure 9 a-b** show the dent to the down tube of the bicycle as well as the scuff mark on the right side of the bike frame adjacent to where the plaintiff's right foot would be positioned, which is consistent with plaintiff riding the bike at the time of the incident. Although it could not be definitively determined, in analysis of the totality

Figure 9a and 9b
The white scuff and indentation on the right side of the bicycle frame are consistent with color transfer from a white sole of a sneaker that was worn by the plaintiff.

of the evidence, it was likely that the plaintiff was riding his bicycle at the time of the impact.

Next experiments were performed to quantify whether or not a helmet would have limited head impact to below the federally mandated HIC15, Head Injury Criterion[6] under a tolerance value of 700 for adolescents. The experimental apparatus involved an inverted pendulum with the Hybrid III dummy head and neck attached to the end (see **Figures 10 a-b**). According to the accident reconstructionist, the impact speed of the head to the vehicle equaled 25 mph. The objective was to compare the data with helmet use — both the impact with the vehicle roof as well as the secondary impact with the asphalt where the plaintiff was located at point of rest.

Data Collection Methodology

Data collection follows federal standards, acquiring data using software at a collection frequency of 10,000 Hz utilizing a 4^{th}-order Butterworth filter with a cut off frequency of 1650 Hz, as per SAE J211. To determine and replicate impact speeds in head impact tests, an inverted pendulum impact protocol methodology was used on an exemplar vehicle. Triaxial piezoelectric ICP accelerometers were instrumented onto an anthropometric crash test dummy head and neck.

Results

Experiments revealed that a helmet drastically reduced the HIC15 value from 1130 (over tolerance) to 590 (under tolerance). To simulate the secondary impact with the asphalt, after impact with the roof/windshield, the inverted pendulum apparatus was shifted laterally to impact the ground. Note that the rotational components of acceleration that may have existed in the subject incident were not evaluated in these experiments; HIC criteria pertain to translational accelerations only. Results indicated the helmet reduced the secondary impact with the asphalt by 65%.

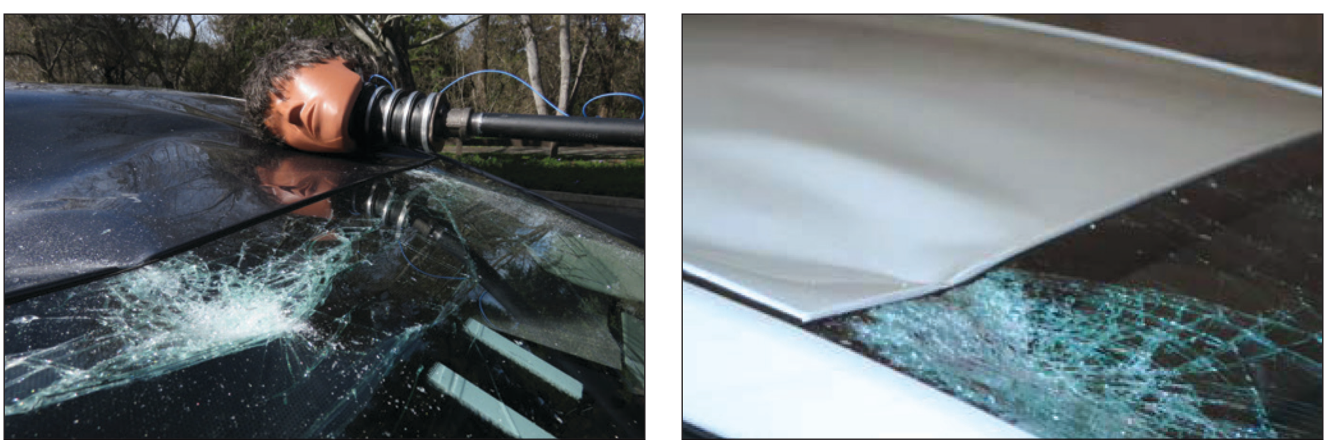

Figure 10a and 10b
Damage to the roof and windshield of the test exemplar vehicle is substantially similar to damage of the subject vehicle.

Methodologically, these experiments revealed that the HIC was below tolerance for head injury, according to FMVSS 208.

Lastly, a variety of articles were researched to determine if the results of the experiment were consistent with generally accepted research in the scientific community. Many studies simulated a head impact for bicyclists and found that more than 65% of head and brain injuries could be mitigated by wearing a helmet[8,9]. In summary, the physical evidence on the bike frame shows that the plaintiff was likely riding at the time of the impact. Consistent with these research articles, the experiment indicated that head trauma could have been substantially mitigated with helmet use. However, it should be noted that typical bicycle helmets do not cover the lower portion of the face, and, as such, they may not prevent facial trauma, depending upon the directions of force. Additionally, typical bicycle helmets may not be designed to protect against multiple significant impacts.

Conclusion

Examples were utilized to illustrate forensic biomedical engineering methods and contributions to the analysis of trauma causation to the human body. Often there is an abundance of biological physical evidence that goes underutilized or even completely unanalyzed. Biomedical engineering concepts can be applied to supplement the analysis of the accident reconstructionist by interpreting this physical evidence — whether it be mechanisms for trauma or identifying the bandwidth of possible causes. In the three cases presented, the evaluation of the physical evidence contributed significantly to understanding the causation and liability. The biomedical engineer with knowledge in general engineering and physics in addition to medical training and expertise has the qualifications to conduct such investigations, supplement analytical insights, and potentially create a meaningful difference in the forensic analysis.

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