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Forensic Engineering Analysis of a Fatal Trailer Wheel-Separation Failure

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Abstract

A forensic analysis of a fatal trailer wheel-separation failure is presented in this paper. An older three-axle trailer carrying snowmobiles was being driven at highway speed during winter time in Michigan. The left front wheel detached due to the catastrophic failure of all six lug studs. The wheel traveled into the on-coming traffic lane and struck the roof of a sedan driven by a local student. The driver of this vehicle was killed instantly due to passenger compartment intrusion. One possibility was that the lug nuts were improperly tightened during a recently performed service — and that this looseness diminished clamping forces and led to cantilever bending of the studs and fatigue fracture. An analysis of the defendant's narrative and of the failure were performed.

Keywords

Trailer, torque, lug nut, wheel detachment, clamp force, fatigue, corrosion, forensic engineering

Accident Overview

According to the state crash report, "Vehicle one was traveling N/B when the front driver's side tire came off of the trailer, crossed the median barrier, and struck vehicle two going S/B. Ultimately, the driver in vehicle two was killed as a result of this accident." The conditions were cloudy, daylight, and cold, with a dry roadway and no snow. The towing vehicle was a Ford Expedition with three occupants. They were traveling out of state for a snowmobile trip. The accident trailer with the failed wheel had three axles with a Gross Vehicle Weight Rating (GVWR) of 15,600 pounds. The southbound driver of the oncoming sedan was killed instantly as the wheel and tire struck the windshield header (the roof header buckled, and struck the driver in the head). The police diagram illustrating the accident is shown in **Figure 1**. The trailer is shown directly after the accident in **Figure 2**.

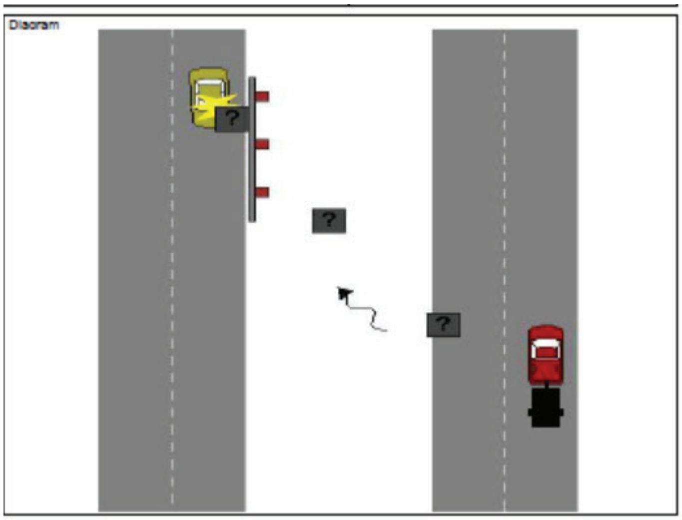

Figure 1
Accident diagram from police report.

Figure 2
Accident trailer at a gasoline station; the left front wheel is missing.

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When interviewed, the Expedition driver indicated to the police that he exited the highway and stopped at a gas station when he realized something might be wrong with the trailer. He determined that he had lost a wheel, and remembered witnessing ambulances going southbound. He called 911 in the event that the ambulances had anything to do with the wheel detachment. He was called back by state police who told him that the wheel had killed the oncoming driver — and to stay put until they could investigate. The Expedition driver was interviewed along with the other two vehicle occupants. There was no suspicion of alcohol usage, and no citations were issued.

The driver of the Expedition did not own the trailer, which was used for interstate commerce. It was owned by his employer. The trailer was built in 2000, making it 13 years old at the time of the wheel detachment. There were no written maintenance records for the trailer. Within a month prior to the incident, the trailer had been serviced and repaired. The mechanic of the company that owned the trailer did the work. After elevating the trailer, each wheel was removed, and the bearings were greased. Three tires were replaced, including the left front along with its wheel. The brakes were checked for proper function. The mechanic testified that standard practice was to put the wheel/tire combination on, put on the lug nuts, and snug them up to lightly seated, using a quarter-inch, battery-operated drive electric wrench. Then he lowered the trailer to the ground and used a torque wrench to seat them, with a specification of 100 foot-pounds for half-inch studs, which he derived from an information sheet from a tire retailer. He testified that he torqued all the trailer's lug nuts using a torque wrench that had been recently calibrated.

On the night of the accident, the trailer mechanic was informed of what happened. He drove 150 miles to the gas station, bringing his torque wrench and checking all remaining nuts. He testified that they were not loose and had been properly torqued. The trailer was driven back without unloading the contents. Although only two wheels remained on the left side, there were no further incidents.

Forensic Analysis

An obvious candidate cause of the detachment was loose lug nuts — that is, after the left front new wheel and tire were mounted, the lug nuts were snugged into position but not properly torqued. The evidence was compared to this hypothesis and others. Not all evidence could be analyzed, as the stud ends and lug nuts were lost. However, neither of these losses consequentially diminished the confidence of the analysis. The six lug studs were not newly installed, and they had not failed previously under similar use — which represents a field test of their performance. The remnants of the studs were carefully examined using a variety of sophisticated techniques. Lastly, the six lug nuts that were not recovered had not been replaced just prior to the failure, and had not failed in previous service, which represented another field performance test.

The wheel, tire, hub, and stud remnants were examined, according to a mutually agreed-to joint protocol at a regional metallurgical lab. Both plaintiff and defense experts were present at the time of the inspection. The materials present for the examination included:

1. Detached damaged wheel.
2. Tire (still mounted to the wheel).
3. Hub (containing six lug stud remnants).
4. Subject torque wrench and calibration certificate.

The damage to the stamped steel wheel (**Figure 3**), shows that there had been significant undesirable rotational interaction between the wheel and the studs prior to stud failure. The observed damage to the stud holes must have occurred during the trip. It is not credible that anyone would mount a wheel that showed damage of the sort evident on the wheel. The elongation of the mounting holes showed violent and sustained back-and-forth relative motion of the wheel relative to the hub. Marking on the wheel indicated that it had a 2,600-pound capacity, which indicated that the six-wheel trailer could hold a nominal 15,600 pounds on the wheels plus some additional load through the tongue and trailer hitch. Since the trailer's GVWR was 15,600 pounds (as listed on the data plate), the detached wheel was of the appropriate weight capacity. Loading was also not an issue for the tire, nor the contents, as the driver of the Expedition estimated that the total trailer load was only 6,500 pounds. Furthermore, there was no problem encountered when the trailer was driven back with the same load on only five wheels.

The wheel was in new condition when mounted prior to the subject trip. As shown in **Figure 3**, the detached wheel showed no rust whatsoever, while the other wheels on the trailer exhibited light to moderate rust.

Figure 4 demonstrates both sides of the trailer in storage. These photos were taken after the trailer had been

Figure 3
Wheel at point of rest at the accident scene. Note rust-free exterior.

repaired, as six wheels (not five) were present. In addition, the wheels do not correspond one-to-one to scene photographs. They are in varying states of corrosion, and the wheel cutouts do not match, indicating that the wheels are not identical in model. This shows that various wheels had likely been replaced over time on this trailer.

Figure 5 shows the trailer's left side front hub at the scene. Flaking rust plausibly diminishes the ability of the studs to provide the clamping force that fixes the wheel to the hub. This friction is necessary to prevent the wheel from slipping and rotating relative to the hub and damaging the lug studs. There are several high points that wore through the flaking rust near the periphery of each mounting interface. Three of these are called out with red arrows. This photo also documents that the grease cap was dislodged during the wheel loss. Five of the six fractured studs are visible in this photograph. Each shows a silver-colored fresh fracture surface. The two studs at 12 o'clock and 2 o'clock are broken below flush. The fracture surfaces of these two studs are in the vicinity of the stud splines. This indicates that the mounting studs were subject to damaging cantilever bending moments, and their mounting holes through the hub were distorted. Note: In this picture, the 6 o'clock stud is not visible, and the 8 o'clock stud has

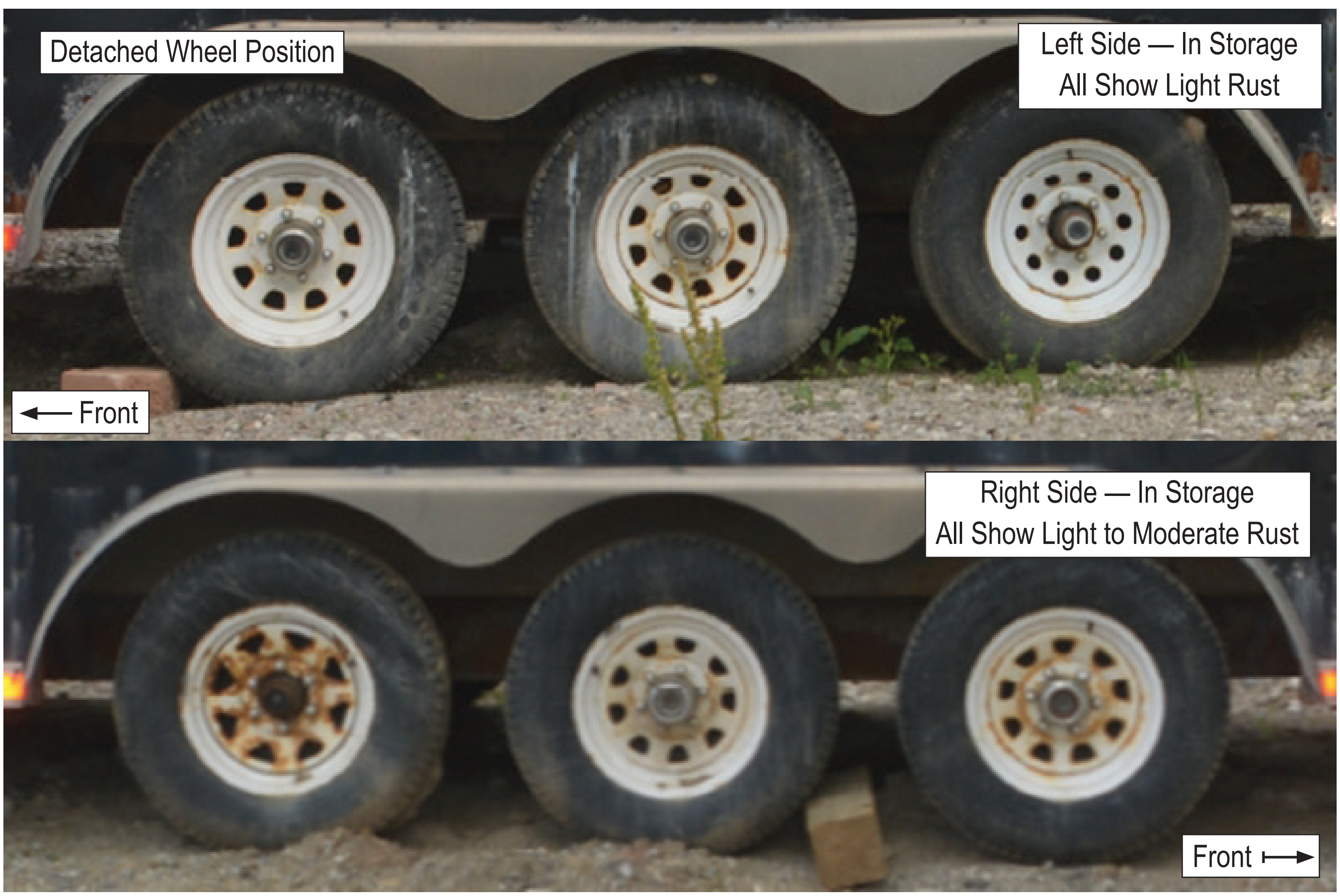

Figure 4
Accident trailer at a gasoline station; the left front wheel is missing.

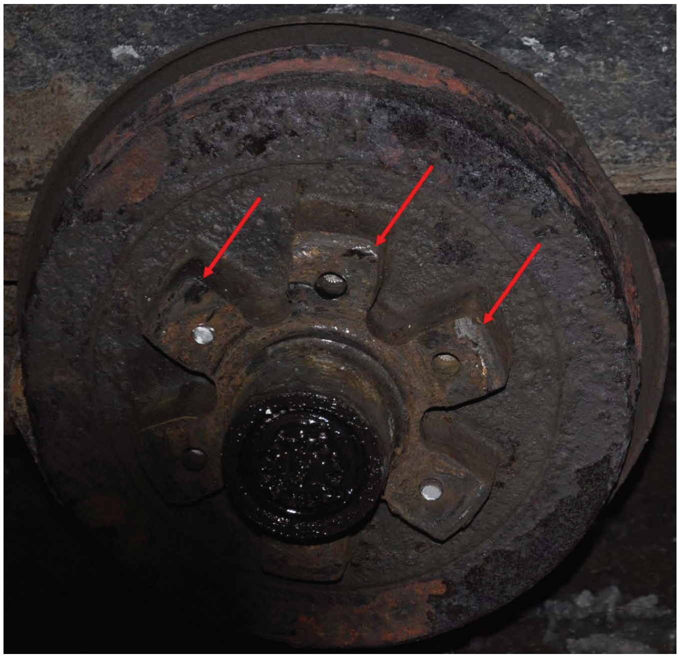

Figure 5
Accident trailer left front hub at time of accident.

fractured below flush and is only barely visible. While this hub is rusty, it is not any rustier than the five other hubs, which did not fail. Therefore, the rust is not a reasonable explanation to the loss of clamping force and failure.

Examination of the hub, studs, and wheel from scene photographs showed consistent evidence of fatigue failure mechanism of the studs. In this mode, the six studs were damaged simultaneously, but they failed sequentially. **Figure 6** shows a close-up photograph of the failed wheel (at left) and the hub (at right). The least-damaged mounting hole was labeled 1. The remaining holes were labeled 2 through 6 clockwise. Shown to the right of the wheel photograph is a close-up photograph of the hub, in what is believed to be the same orientation as it was during the incident to match the wheel (hub stud position A was assembled to wheel hole 1). Note that during the forensic investigation, the studs were not labeled as they are for this paper, as the comparison and analysis had not been made. That is, the original choice of which stud was "A" was made at random, and the stud originally labeled "A" did not line up with wheel hole position 1.

The basis for the postulated match-up of wheel to hub was comparison of maximum damage at each position. Therefore, it is reasonable to assert that the maximum wheel damage, as evidenced by the most elongation of the stud mounting holes, matches the maximum hub damage, as shown by below-flush fracture of the studs. The three most damaged holes are B, C, and F. These correlate to the same positions on the aligned hub photo 2, 3, and 6. Note that the wheel in **Figure 6** is shown from the outboard side, so the hole to stud positions match; they are not mirror images, which they would be if the mounting face of the wheel were shown.

During the initial wheel wobble (due to loose lug nuts), each stud was identically loaded, more or less, by

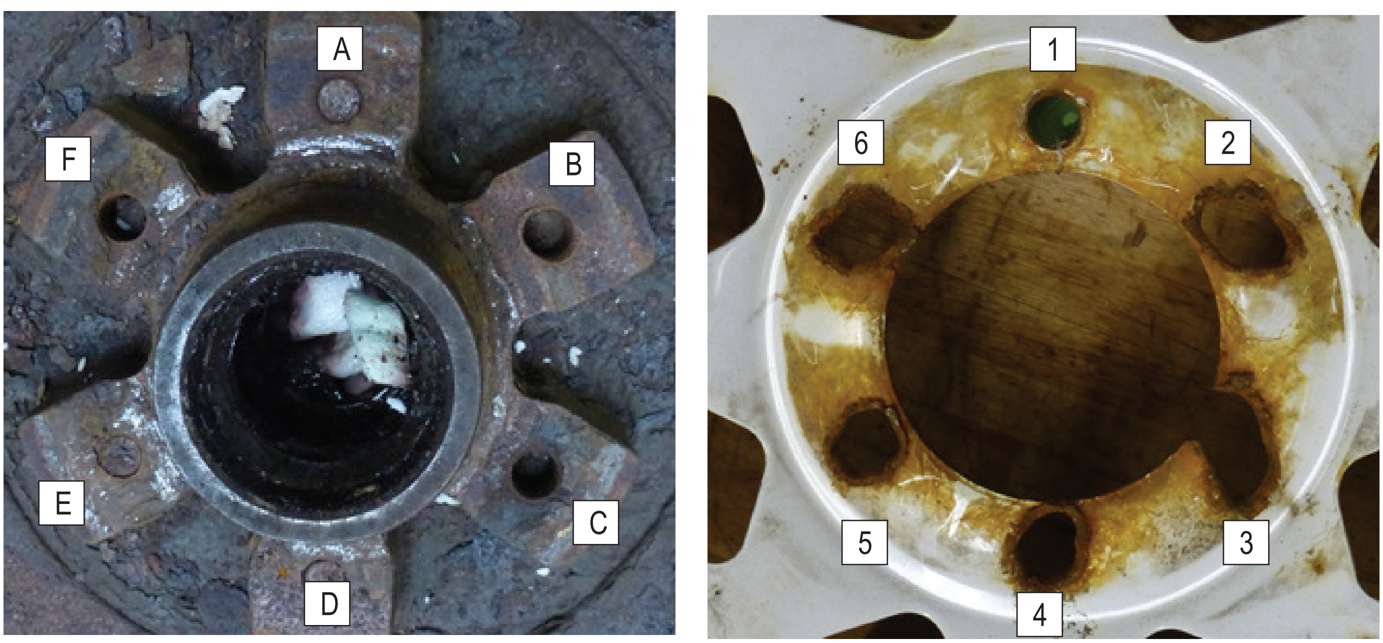

Figure 6
Accident trailer wheel and hub oriented to most likely mounting alignment.

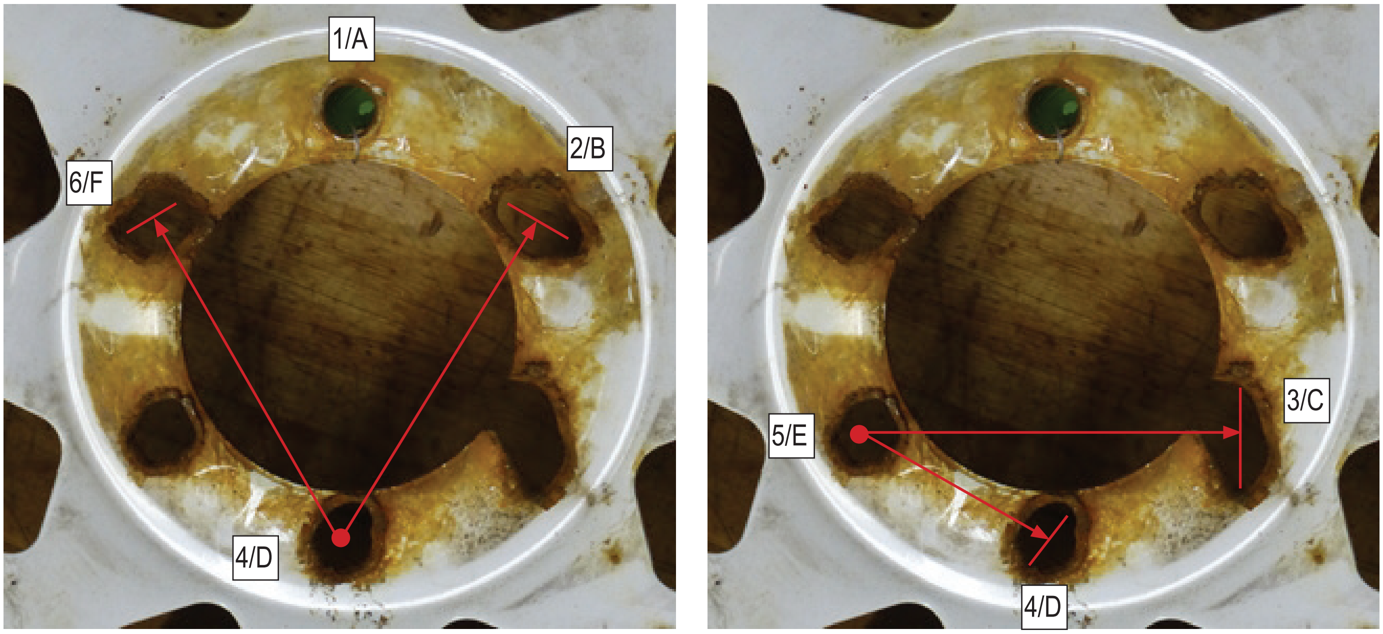

Figure 7
Graphic analysis of stud fracture sequence caused by changing fixation forces.

the impacting steel wheel, and the studs impacted the holes in an orbital motion, causing circumferential damage. At some point, a single stud fractured during this most minimal early stage of damage. This was hub stud A and wheel hole 1, as shown in **Figure 6**. After stud A at wheel hole position 1 fractured, each wheel hole was more or less round due to previous uniform circumferential impacts by the studs. With only five studs remaining, the wheel was less rotationally constrained, and the holes/studs adjacent to hole 1 (that is, hole 2 / stud B and hole 6 / stud F) were disproportionately and incrementally damaged as the wheel rotated approximately about stud D, which is opposite fractured stud A. This caused studs B and F to fracture in close succession, although which of the two studs fractured first is not clear. After studs A, B, and F fractured, the holes at those positions (1, 2, and 6) were no longer damaged. With three remaining studs (C, D, and E), the wheel was even less constrained, and damage occurred to these remaining three studs at an accelerated rate. The damage at wheel hole 3 shows that the wheel rotated about stud E. Both wheel holes 3 and 4 show this damage of rotation about hole 5 / stud E, and studs C and D failed in quick succession. Wheel hole position 4 shows less damage than does wheel hole position 3. Thus, stud D likely fractured before stud C. Stud E failed last, freeing the wheel and tire, which departed and struck the oncoming vehicle. Thus, the progression (as based upon the damage analysis) was likely stud A, next studs B and F, then stud D and C, and finally stud E. This analysis is shown graphically in **Figure 7**.

Tire Analysis

Examination of the accident tire shows that it was in new condition at the time of mounting, just prior to the wheel detachment (**Figure 8**). The measured tire tread depth measured minimum 9/32 inches while new tread depth is 10/32 inches. This is a radial tubeless tire, size ST225/75R15, labeled "FOR TRAILER SERVICE." Maximum load is 2,830 pounds, Load Range E, 80 psi maximum. The overall diameter is 28.5 inches. As the photo documents, the mold sprues were still present.

Stud Metallurgical Analysis

To determine if the studs incorporated a material defect, they needed to be removed from the hub and destructively tested. Prior to destructively cutting into the hub to remove each stud, outside fracture and inside head surfaces were examined using an optical microscope. Each stud was an SAE (Society of Automotive Engineers) ½-20 Grade 8 fastener (**Figure 9**). This means the thread body is nominally ½ inch in diameter with 20 threads per inch. Grade 8 fasteners are medium-carbon alloy steel that has been heat treated. This means that they have been heated above their austenitization temperature and then quenched/tempered. These studs were pressed into an interference fit within the hub using splines. The mating hole had been counter-bored to accept the head. The heads are round without wrench flats. The SAE grade marking is evidenced by six radial marks, shown at the lower left photo. The manufacturer's mark W appeared at the periphery of each head, as shown at lower right. By

Figure 8
Accident trailer tire showing manufacturing sprues and deep tread.

referencing the Fastener Quality Act registry[1], it was determined that these studs were manufactured by Westland Steel Products, Winnipeg, Canada.

Since this trailer was used in the Midwest, it was operated in the presence of road salt and moisture, which acted as corroding agents. Each stud fracture surface segment was given a stabilized hydrochloric acid cleaning

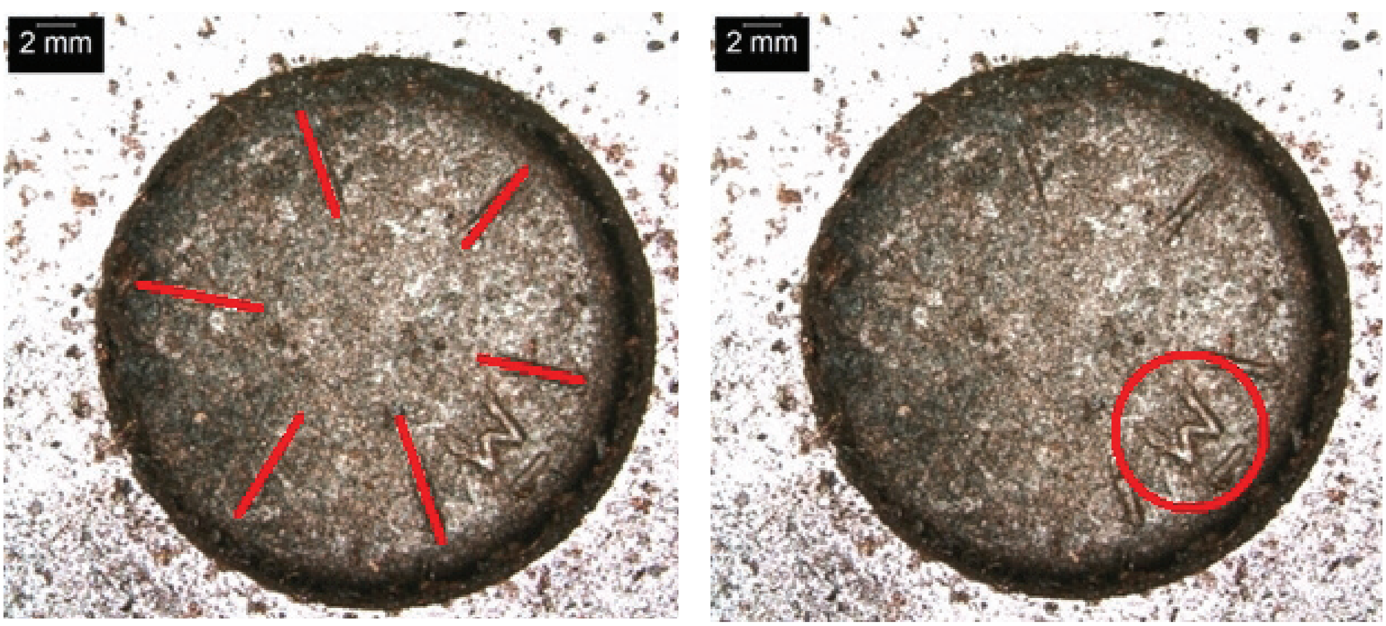

Figure 9
Stud marking indicating SAE grade (left, highlighted in red) and manufacturer (head stamp encircled in red highlight).

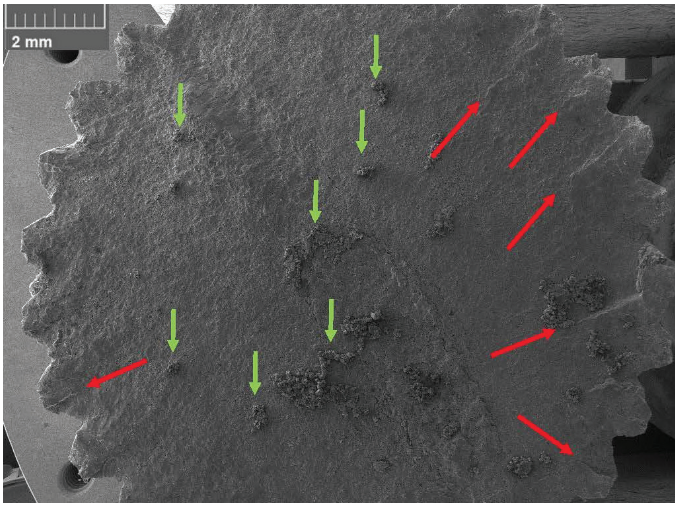

Figure 10
SEM photograph of stud fracture surface.

bath to remove superficial corrosion. Each stud was removed from the bath before the corrosion transformation was complete to prevent collateral damage. The remaining corrosion is clearly depicted by the SEM (scanning electron microscope) photograph set forth in **Figure 10**. Various untransformed surface corrosion areas on the fracture surface of stud A are called out with short downward-facing green arrows.

Element	Wt %	Method	Comment
Fe	Matrix	ISO1	Base metal
Mn	0.79	ISO1	Alloying element
C	0.39	L	Strengthening element
Si	0.21	ISO1	Alloying element
Mo	0.21	ISO1	Alloying element
Cu	0.07	ISO1	Recycling impurity
Cr	0.03	ISO1	Recycling impurity
Ni	0.03	ISO1	Recycling impurity
S	0.016	L	Ore impurity
P	0.007	ISO1	Ore impurity
Co	0.006	ISO1	Recycling impurity
W	<0.01	ISO1	Below Detection Limit
V	<0.005	ISO1	Below Detection Limit
Al	<0.005	ISO1	Below Detection Limit
Ti	<0.005	ISO1	Below Detection Limit
Zr	<0.005	ISO1	Below Detection Limit
Nb	<0.005	ISO1	Below Detection Limit
Ta	<0.005	ISO1	Below Detection Limit
B	<0.0005	ISO1	Below Detection Limit

Figure 11
EDS analysis of representative stud.

A macro-indication of fatigue is contained in the SEM photograph. These ratchet marks are called out by red arrows pointing to the periphery, which, in this case, are the splines. SEM photographs of studs A, B, C, E, and F exhibited peripheral ratchet marks, a common feature of fatigue initiation. The uncleaned fracture surface of stud F was subjected to an EDS (energy dispersive spectroscopy) analysis. The principal elements recorded included Fe, O, C, Ca, Cl, Si, and Mn, as documented in **Figure 11**. Trace aluminum was also present. The explanation of each element is straightforward. Iron (Fe) and manganese (Mn) are components of the steel. Oxygen is ubiquitously present and a component of the corrosion product. Carbon may come from oil or biological contamination. Calcium (Ca) and chlorine (Cl) are present in road salt, and are contained in the corrosion products. The aluminum likely came from bearing grease or dirt. A portion of stud F was then destructively tested to provide bulk composition analysis to determine conformance with grade 8 fastener composition. The results of this further analysis are recorded in tabular form in **Figure 11**.

The EDS analysis is consistent with 4037 steel, which is an appropriate alloy for heat treated Grade 8 threaded fasteners. Metallography was conducted on a longitudinal segment of a representative stud (**Figure 12**). This sampling technique was appropriate as the raw material used to manufacture these studs is drawn wire, which produces linear inclusions. No objectionable impurities or pores were detected.

The stud sample was then given a nital (nitric acid 2% in alcohol) etch. This revealed the microstructure as shown in **Figure 13**. This photograph shows martensite,

Figure 12
Metallographic sample of representative stud to examine inclusions.

Figure 13
Metallographic sample of representative stud to examine grain structure.

indicative of an austenitized, quenched and tempered heat treatment to provide strength and toughness. No objectionable grain structure or alloy segregation was detected.

It was agreed by the experts to do no tensile tests unless something "unexpected" occurred during analysis. In a practical sense, that agreement between the experts meant that no tensile tests would be conducted if no outlier hardness test results were produced. Core hardness tests were taken. The results are tabulated in **Figure 14**.

The minimum measured average hardness was 34.4 HRC, and the maximum average hardness was 35.5 HRC, a difference of 1.1 points. The hardness testing measurement of a sample is used to accurately estimate the tensile strength. The approximate tensile strength of a sample with a uniform HRC 34 hardness is approximately 155,000 pounds per square inch (psi)[2]. For 35 HRC, the approximate tensile strength is 160,000 psi. For a uniform hardness of 36 HRC, the tensile strength is approximately 165,000 psi. For the minimum measured fastener with a hardness of 34 HRC, the tensile strength (by interpolation) should be 157,000 psi. Studs with a ½-20 thread have a stress area of 0.1599 square inches (in^2). This gives a calculated minimum tensile strength of 25,104 pounds. These studs have a tensile strength minimum requirement of 24,000 pounds, and thus the hardness measurements

Stud	Measured Average Hardness (HRC)	Stud	Measured Average Hardness (HRC)
A	34.9	D	35.5
B	35.5	E	34.6
C	34.4	F	35.0

Figure 14
Hardness test of each recovered stud remnant.

evidence that the tensile strength of each stud was within the SAE specification. Note that fatigue resistance is well correlated with hardness. When used in a properly designed wheel fastening system, these studs should be "fatigue proof" for this application in the absence of severe corrosion, usage, or mounting error.

When examined, the cleaned fracture surfaces of the studs showed a variety of features, including residual corrosion products, rubbing of the fracture surfaces, overload dimpling, and fatigue marks. Three different stud SEM micrographs are now shown. The most frequent observation was "no fracture data," as is shown in **Figure 15**. **Figure 16** shows a region of a stud with residual corrosion products and overload dimples. **Figure 17** shows what was found clearly in five of the six studs: fatigue crack marks. As for the sixth stud, which did not show clear

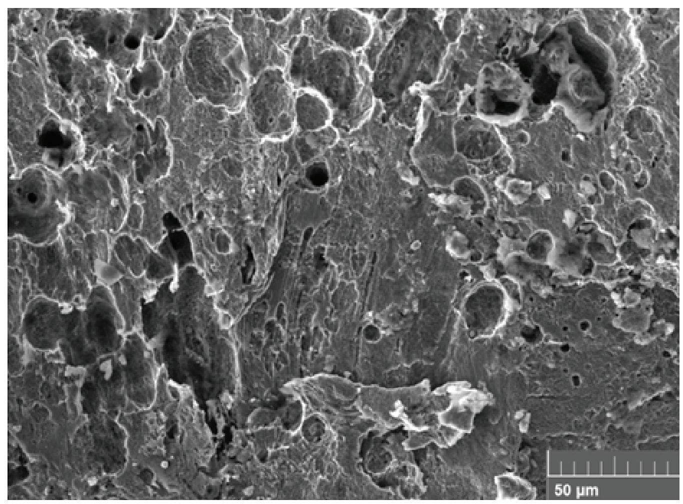

Figure 15
Corrosion pits caused by acid during cleaning.

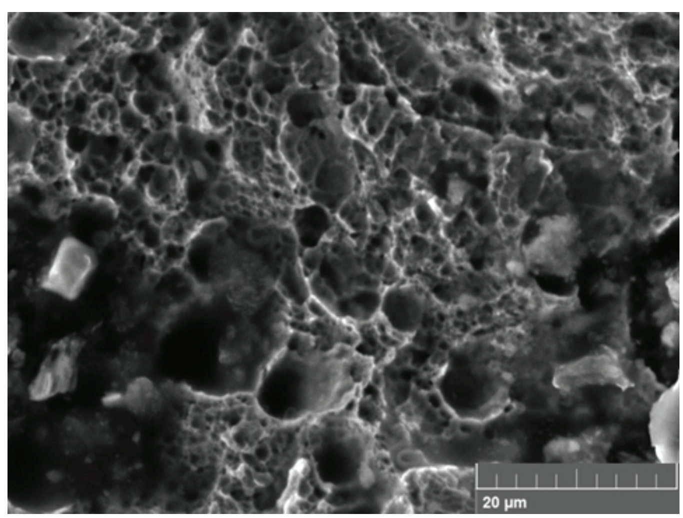

Figure 16
Overload fracture with some residual corrosion products.

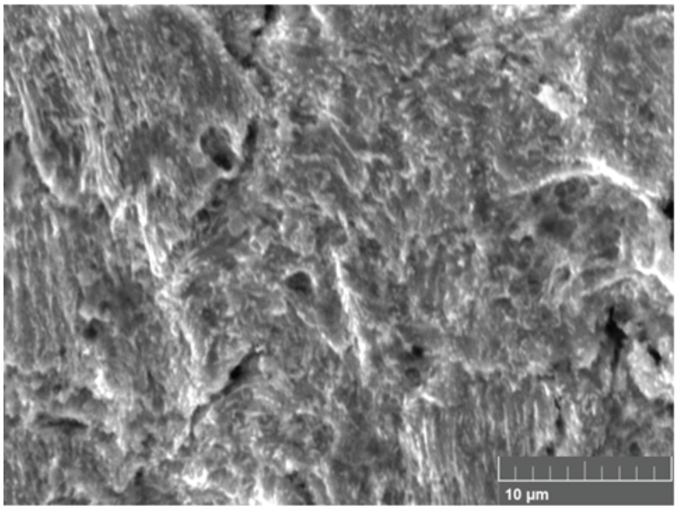

Figure 17
Fatigue striations documenting the stud failure mechanism.

residual fatigue marks, fatigue as a failure mechanism could not be eliminated.

Trailer Destructive Testing

To better understand the progression of the damage to failure, destructive testing was conducted using an exemplar trailer. A 16-foot-long unenclosed conventional ball hitch flat trailer with two axles was purchased new for the testing. This was demonstrative testing to shed light on trailer wheel detachment. It was not performed to replicate the accident. The test setup is shown in **Figure 18**.

The four white steel wheels were each mounted to six studs identical in specification to those of the subject trailer. The wheels had tires (ST225/75R15) labeled for trailer service only. The tires were inflated to their normal pressure of 65 psi cold. The wheel chosen to fail was the right side rear wheel. This choice of tested wheel position was done for safety. The right-side wheel does not face oncoming traffic, and the front wheel is somewhat closer to the center of gravity of the trailer as loaded — and should better support the loading once the tested wheel failed. The trailer load was a 1999 Ford Explorer 4-door SUV; the weight was approximately 3,700 pounds. The goal was to drive at somewhat less than highway speed on rural "farm to market" roadways until a stud failed, but before the tested wheel detached. Each lug nut was put on hand tight. Holes were cross drilled through the studs to accommodate cotter pins, which prevented complete loss of the nuts.

The trailer was run with two wheels on the right-hand side for approximately 104 miles of travel with a combination of closed track travel and travel on rural Michigan roads. Frequent stops, on the order of every five miles, were made to check on the condition of the wheel. The test was done by a driver and a passenger, whose job was to watch the wheel for out-of-plane wobble during travel using an extended side mirror. The wheel stud threads were progressively damaged, but it was not obvious that the studs would fail in a reasonable amount of time with the loading conditions chosen. Thus, the right front trailer wheel was removed to double the force against the right rear wheel and accelerate the damage to the studs. After this doubling of load, continued testing was limited to a closed asphalt track. It was noted that two lug nuts would automatically cinch up against the wheel and provide a more secure wheel against the hub — a known performance characteristic of right-handed fastener threads on right handed wheels. One of these lug nuts was removed, and the testing was continued on the track with only five lug nuts — four of which were loose and one of which was tight. The nut that was removed was marked with red ink, as was its mounting stud. After 11 miles on the asphalt closed track, a single stud had broken, and the testing was suspended.

The wheel at the time of the suspension of the testing is shown in **Figure 19**. Notice that the one hole with the removed nut is marked in red and is at the 12:00 position.

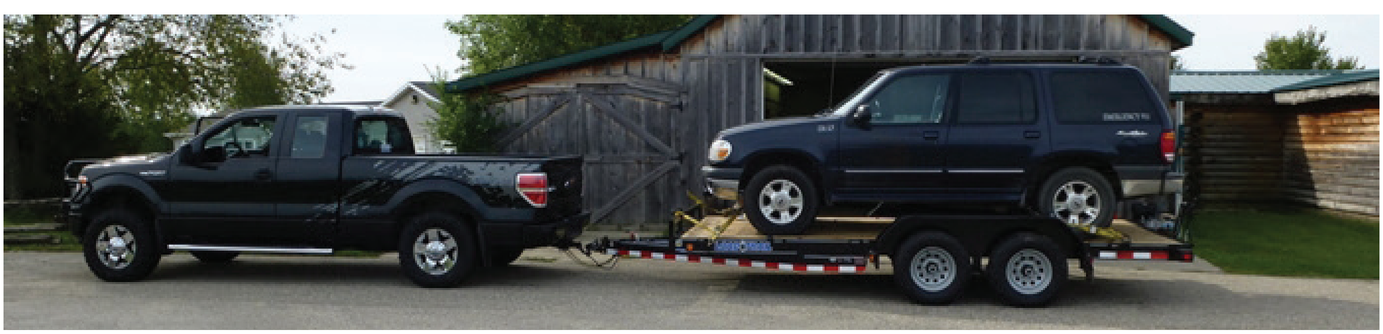

Figure 18
Setup of trailer wheel testing.

Figure 19
Trailer wheel directly after first stud fracture showing the position of the fractured stud.

At the 2:00 position is the failed stud. This stud failed below the surface of the hub, as was seen in 50% of the accident trailer stud failures.

At no time during the testing did any wobble of the wheel give a tactile feedback to the driver or the passenger tasked with observing the wheel. This testing provided valuable experience regarding the progression of the failure of the studs of the accident trailer. In the both cases, as the loosely held wheel moved relative to the studs, the holes enlarged due to striking the studs in a rapid and circumferential fashion. This accounted for the enlarging of the holes seen on the incident and test wheels. It also accounted for the substantial thread damage that was seen on the test studs, but that could not be documented on the failed trailer studs — as those studs were not recovered. Wheel paint damage at the inboard side of the wheel was observed on both the failed accident trailer and the test wheel. Another detail the test confirmed was that in this sort of loading the studs fail progressively, not all at once. Another similarity of the test to the accident is that the first stud to fail left a largely circular enlarged mounting hole in the wheel.

Forensic Methodology Documentation

The forensic methodology used in this investigation is outlined in the text, "How to Organize and Run a Failure Investigation" by Dennies[3]. The task outline, as given by Dr. Dennies, is reprinted below along with tasks that were followed. The text reprinted below was included within the expert report and was provided in anticipation of a Daubert challenge. This text is modestly changed to remove the names of the involved parties.

1. Understand and negotiate the investigation goals.

The client and investigator discussed qualifications and methodology at length with the client prior to the investigation. It was noted that this was a typical assignment. Nothing was found to be particularly unusual about the circumstances of this unwanted wheel detachment.

2. Obtain a clear understanding of the failure.

All information made available was reviewed, and both visual analysis/destructive testing of the relevant artifact was conducted. The failure consisted of the unwanted fracture of the six lug studs at the left forward wheel of the towed trailer. None of the other components (tire, wheel, hub, lug nuts, or bearing) failed, though several of these components were damaged. The evidence indicates that an initial fatigue crack at each stud formed and then progressed until final separation of the outer aspect of the stud from the root. According to the classic text "Understanding How Components Fail" by Donald Wulpi, there are numerous other damage classifications for a failure besides fatigue. These modes are discussed below:

- Distortion. This was not a distortion failure, although the hub did distort during the chain of events that led to failure. The wheel was lost by fracture of the studs. The studs did not fail because they changed shape, as a wooden door can fail when it warps over time. The hub and wheel did not show distortion; they both showed damage from impact as the loose wheel repeatedly struck the studs.

- Basic Single Load Fracture. This failure mode indicates that a single event caused the failure, such as a baseball striking a window. This mode did not occur. Had there been a single overload, there would be other indicators present, such as a damaged tire or wheel rim, and other wheels on the left-hand side would have likely shown similar damage.

- Wear. The components did not wear out; they were rapidly damaged progressively throughout the trip. The wheel showed no abrasive wear. The tire was practically new, although the trip obviously caused accelerated tread wear as the tire wobbled. No significant wear — only corrosion — was observed for the hub and studs.

- Corrosion. The new tire and new wheel were uncorroded. The hub and studs both showed surface corrosion. However, the accident hub and studs were not significantly different than at the five other positions of the trailer. Thus, corrosion as a causative mechanism of stud failure and wheel detachment can be safely rejected.

- Temperature Related Failure. The conditions were neither severely hot nor cold. Had the operating temperature been objectionable, other wheel positions would have shown damage or have failed.

3. Objectively and clearly identify all possible root causes.

In this case, there has been a mechanical failure of all six lug studs through fatigue. This has been documented by visual and SEM examination of the fracture surfaces. For a comprehensive listing of possible usage-related causes of the stud failure and wheel detachment, the author referenced an instructional pamphlet from the New Zealand Transport agency[4]. The listed "Main Causes of Wheel Loss of Wheel Insecurity" included the following (text is quoted verbatim using British English). After the quoted text, the case analysis is presented in italics.

- Failure to follow manufacturer's instructions for fitting wheels, particularly applicable to after-market products such as aluminum wheels. *Not likely. The correct wheel was used.*

- Failure to tighten wheel nuts to the specified torque, in the correct sequence, or fully tightening the wheel nuts one at a time rather than in stages. *The fatigue failure in a short distance indicates that this failure mode occurred.*

- Failure to retighten wheel nuts after a short period of in-service running (between 50 to 100 kms is commonly recommended). *According to deposition testimony, a re-tightening process was not done.*

- Failure to regularly check tightness of wheel nuts. *This is not applicable as the distance to failure was too short to regularly check the wheel nut tightness.*

- Over-tightening, causing stretched/broken studs or studs to be pulled through the hub. *There is no evidence that this occurred. Since a calibrated torque wrench would reportedly have been used for final tightening, this is an unlikely mechanism.*

- Damaged threads on wheel studs and nuts resulting in insufficient clamping force. *Thread damage to the studs did occur as documented by testing, as the wheel oscillated about the normal travel axis. However, no threads remained on the six accident wheel studs. Thus, there was no evidence to confirm or exclude thread damage causing the eventual fatigue crack initiation.*

- Paint, rust/scale or dirt between contact surfaces of wheels and hubs or nuts. The mating surfaces must be kept clean (and preferably paint-free) to reduce settlement. *This hub was objectionably rusty, but no rustier than the other five hubs on the trailer that did not fail. Thus, corrosion on the hub cannot be a principal cause.*

- Severe corrosion and/or wasting of wheel studs. *The stud remnants were rusty, but no more so than the other corroded studs which did not fail.*

- Damage to the mounting surface of the wheels. *Other than the distorted stud mounting holes, the hub was still serviceable. There is no evidence that pre-existing corrosion damage to the mounting surface of the wheel caused the fatigue failure.*

- Wheel spigot fixing centre 'ground out,' i.e., enlarged. *This was a new wheel, and it does not center via the boss. This wheel centers via the studs. Thus, this mechanism is inapplicable.*

- Incorrect matching of wheel nuts and wheels. (Two-piece flange nuts for hub-mounted wheels and single piece conical seated nuts for stud mounted wheels). *There is no evidence that the nuts at this position were any different than the nuts at any other position that did not fail.*

- Incorrect matching of wheels and wheel hubs (hub mounted and stud mounted). *The accident wheel and hub were functionally identical to those at the other positions. There was no incorrect matching.*

- Incorrect matching of wheel studs and wheel nuts when non-OEM ("aftermarket") wheels have been fitted, reducing the stud length available for correct wheel nut engagement (insufficient "stud standout"). *As the studs were identical across the trailer, and the steel wheel mounting flange / nut seat proportions would all be similar, this is not a likely mechanism.*

- Use of inappropriate (impact tools) or non-calibrated equipment when tightening wheel nuts. *The procedure was correct. That is, it is unobjectionable to use a lower power impact wrench to "snug" the lug nuts prior* *to torquing. The evidence is that this two-step process was not followed.*

4. Objectively evaluate the likelihood of each root cause.

The analysis has been provided in italics above so that each candidate mechanism does not have to be restated.

5. Converge on the most likely root cause.

The evidence indicates that the insufficient torquing of the nuts occurred in this case.

6. Objectively and clearly identify all possible corrective actions.

In the future, the wheel mounting procedure should be validated by taking the trailer for a short trip and then re-torquing each lug nut. This second action will detect lug nuts that were only snugged up, not torqued, and any that have loosened. This is the consensus "best practice" and requires no other alternatives.

7. Objectively evaluate each corrective action.

See ¶ 6.

8. Select the optimal corrective actions.

See ¶ 6.

9. Evaluate the effectiveness of the selected corrective actions.

See ¶ 6.

Summary and Conclusions

For this forensic investigation, the following professional opinions were generated and incorporated into the report given to the client.

- The oncoming driver was blameless.

Basis: He had no reason to expect a wheel and tire to come into his lane, and thus had no reason to take evasive actions. Further, the closing velocity of the tire, a relatively small object, exceeded 100 mph. This is an unexpected event that will occur to few drivers. Perception and reaction times increase when such an unexpected and unfamiliar event occurs.

- The roof strength of the decedent's vehicle was not a contributory cause of the injuries incurred.

Basis: This vehicle has a roof stronger than many of its peers at the time of manufacture. This roof is designed to deal with rollover collisions, not this type of severe, high-velocity impact loading.

- The torque wrench at issue was not a contributory cause of the stud failure and wheel detachment.

Basis: This tool was the correct type of tool; it was in good condition and properly calibrated. None of the other five wheels failed even though this torque wrench was reportedly used before and after the wheel detachment to check torque. The torque wrench could not be contributory if it was not used.

- The wheel, hub, and lug nuts were not defective. Neither those three components nor the pre-existing hub corrosion were contributory causes of the failure of the six studs and resulting wheel detachment.

Basis: The wheel was made of stamped steel, and its weight rating was appropriate to this application. The wheel was damaged in use, but it was not destroyed — that is, it only detached after the last lug stud had fractured. The hub showed no geometric or other defect; the hub deformed rather than fractured when severely loaded by the studs. Note that the corrosion on the hubs was objectionable, but no different than that of the corrosion at the other hub positions that did not fail. These hubs are cast steel and are not made of corrosion-resistant stainless steel; they are designed to still perform safely even with substantial corrosion if the proper pre-load clamping force is applied by the studs.

- The observable remains of the lug studs were non-defective; no material or manufacturing defect of the studs caused the stud failure.

Basis: The studs are appropriate to this application, and identical to the other non-failed studs. They showed no metallurgical defects in microstructure or hardness. Fasteners of this type are expected to fail under severe off-axis loading, which develops fatigue cracks.

- Weather, speed, and roadway conditions were not contributory causes of the stud failure and wheel detachment.

Basis: None of the 30 studs on the remaining five wheels fractured even though they experienced the same weather, speed, and roadway conditions, as did the wheel that failed. In fact, the two remaining wheels on the left side of the trailer endured a more severe loading than did the incident wheel. These two left-hand wheels and studs were driven both to and from the incident location, and they had 50% more loading than did the lead left trailer wheel during the outbound trip.

- The root cause of this wheel detachment was the failure of all six studs on the left front wheel hub of the trailer. This was a fatigue failure caused by insufficient clamping force, which was caused by an insufficient tightening of the lug nuts onto the lug studs.

Basis: The wheel and tire were new and recently installed. Comprehensive metallurgical testing showed no anomaly within the tested six studs. Since no other stud on the trailer failed, there must have been a mounting error. No credible alternative existed other than a lack of clamping force due to insufficiently tightened lug nuts.

- None of the lug nuts at the failed position were properly torqued.

Basis: This wheel suffered "crib death" in that it failed soon after mounting. This type of wheel configuration is highly reliable, and it has an incorporated factor of safety. There is no reason to believe that if only one or two lug nuts had been missed that this wheel position would have failed in fewer than 200 miles.

- This was a preventable failure. Had the lug nuts been re-torqued after a short post-mounting validation trip that followed the servicing of the axles, the error would have been detected and corrected.

Basis: Best practices for tightening lug nuts as well as deposition testimony.

In summary, the default hypothesis (that one of the six sets of lug nuts were untightened) was completely consistent with the evidence. It was particularly likely, given the fact that the wheel was progressively damaged and detached within 150 miles of the maintenance that had been recently performed. However, in any forensic investigation, it is necessary to soberly evaluate contrary opinions. Six candidate explanations for the failure were presented by the opposing expert defending the owner of the trailer, including:

1. The mechanic may not have tightened the left front wheel's lug nuts, and the plaintiff's expert's explanation was correct.

2. Relaxation of the left front wheel's clamp load may be due to the known problem of paint compression after proper wheel lug nut torquing.

3. Potholes and other poor roadway conditions caused wheel to hub slippage, damage, and loss of clamp load after proper wheel lug nut torquing.

4. Although properly installed, the lug nuts were loose due to "an attempted but interrupted theft of the left front tire/wheel" during a stop at a fast food restaurant during the trip.

5. A single wheel stud fractured prematurely and therefore reduced the clamp load and overloaded the other studs, leading to overall failure.

6. The wheel material was not to specification and allowed the relaxation of the clamp load at each of the wheel lug nut positions.

The defense expert pursued none of these explanations and simply presented them as possibilities that diminished the confidence that could be placed in the plaintiff's expert's analysis. He found no evidence either supporting or disconfirming any candidate explanation. Therefore, he had no reason to rule out any explanation or to say that any one of the six candidate explanations was any more likely when compared to any of the other five. His testimony was subjected to legal challenge, and his opinions were excluded as the presiding Circuit Court Judge found the opinions he expressed to be "beyond the scope of his expertise."

The underlying case settled prior to trial.

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