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Forensic Investigations of Low-Clamp-Force Type Wheel Separations

By Mark Bailey, PE, DFE (NAFE 1222S) and Dwayne Toscano, PEng

Abstract

Wheel separations are a common non-operator cause of damage and injury in road transport systems. Forensic investigators are often engaged to determine why a wheel separated from a moving vehicle. In 100 investigations, the authors observed wheel separations due to axle, bearing, or fastener system failures. Fastener system failures dominate, and the authors show that low fastener clamp force is their necessary and sufficient condition. Examples of physical evidence of low fastener clamp force commonly found in forensic investigations are presented. The reasons for low fastener clamp force are explored using known wheel installation-to-separation times and distances, torque audits, and interface corrosion. From these, it is often possible to form a sound explanation for a low-clamp-force type wheel separation. Finally, wheel nut re-torquing is identified as a probable effective measure in preventing low-clamp-force type wheel separations.

Keywords

Wheel separation, fastener, studs, clamp force, torque, fatigue, deduction, induction, forensic engineering

Introduction

Investigators use the term “wheel separation” to describe an event where one (or sometimes two) wheels detach from a moving passenger vehicle or heavy truck. In the authors’ experience, the event often becomes the proximate cause of an incident. Three types of incidents occur: the affected vehicle experiences a sudden undesirable change in velocity vector (usually from understeer or braking enfeeblement), leading to a single vehicle accident; the separated wheel continues at its pre-separation pace, becoming a heavy fast-moving projectile that collides with a vehicle or pedestrian target; or the separation-affected wheel and vehicle both come to rest with some minor cosmetic damage.

The authors investigated 81 of the first two types, and five of the third near-miss sort (wheel separations reported in the literature and considered in the paper bring the total to 100). One could speculate that these investigation counts underrepresent near-miss incidents, since near-misses warrant no forensic investigation. This could lead to the conclusion that overall wheel separation counts are some factor *n* of the first two types (i.e., for each serious accident, there are *n* near misses). The authors’ belief that *n* is more than zero is justified by their experience, but there appear to be no reliable data to quantify *n* or the frequency of wheel separations generally.

One heavy truck industry commentator quoted a fleet representative in a 2020 podcast episode titled “Industry’s Darkest Secret”[1]: “Hey, we kept it under a hundred wheel-offs this year. It was a pretty good year.” Wheel separations in the vicinity of 100 per year from just one fleet in 2020 make the NTSB’s[2] 1992 nationwide estimate of 750 to 1,050 per year seem too low, which that study’s authors concede. Monster[3] reports there were a total of 745 commercial vehicle wheel separations from 1997 to 2003 in Ontario, which had only about 4% of the population of the United States during that period, implying about 300% more separations than the NTSB estimated. Turner et al[4] report that the Ontario Provincial Police logged 327 left side and 57 right side wheel separations from non-commercial vehicles from 2013 to 2016 in a geographic area of Ontario where the population was approximately seven million, according to census data. The National Highway Traffic Safety Administration (NHTSA) reports three wheel separation incidents in its Large Truck Crash Causation Study (2001 to 2003) and National Motor Vehicle Crash Causation Study (2005 to 2007)[5]. The studies’ data are from selected police crash reports, so they do not represent the overall number of wheel separations in the time periods considered.

Three commonly observed types of wheel separations are reviewed in this paper; however, the focus is wheel separations from fastener failures. In the next sections,

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two distinct fastener failure mechanisms, which relate to low clamp force (LCF), show how LCF can be deduced from available evidence. Inductive approaches to finding probable causes of LCF are also discussed.

Wheel Separation Investigation Observations

The authors compiled data from 100 wheel separation investigations involving passenger cars, light trucks, sport utility vehicles, travel trailers (collectively referred to as "Group I") and heavy trucks (referred to as "Group II"). Of these 100 investigations, 84 came from internal investigations, seven were found in the literature[2,6,7,8,9,10], two were from coroner's investigations[11], and seven were from published Reasons for Judgement in Canadian civil courts[12,13,14,15,16,17,18]. In the court and coroner investigations, only facts that were not in dispute are used. The data are summarized in **Figure 1**.

From these investigations, the number of ways wheels most commonly separate comes down to bearing failure, axle failure, or fastener failure. **Figure 2** shows examples of bearing and axle failures. For fastener failures, the authors observed two types: missing-nut and stud breakage. Examples of missing-nut failures are shown in **Figure 3**, and examples of stud breakage failures are shown in **Figure 4**.

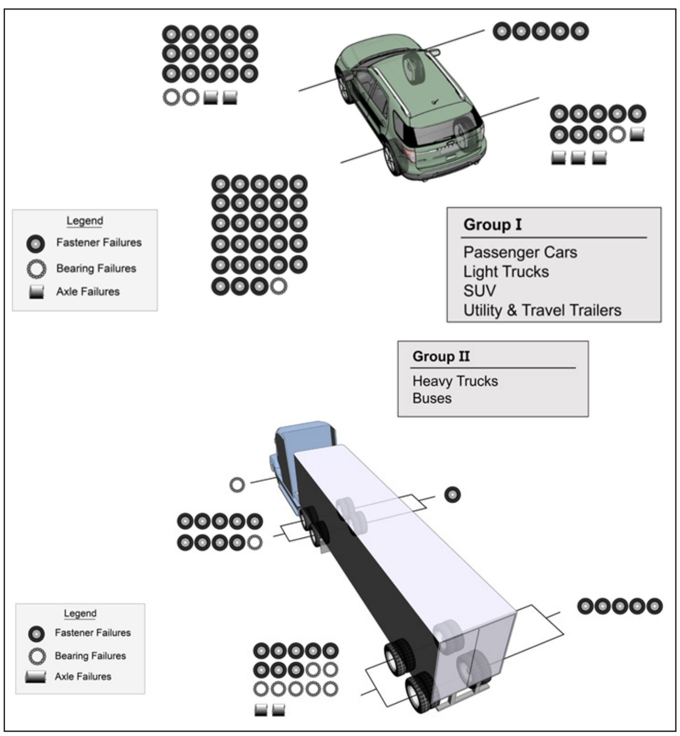

Figure 1
Summary of 100 wheel separation investigations. Group II includes tractor trailer combinations and single heavy trucks.

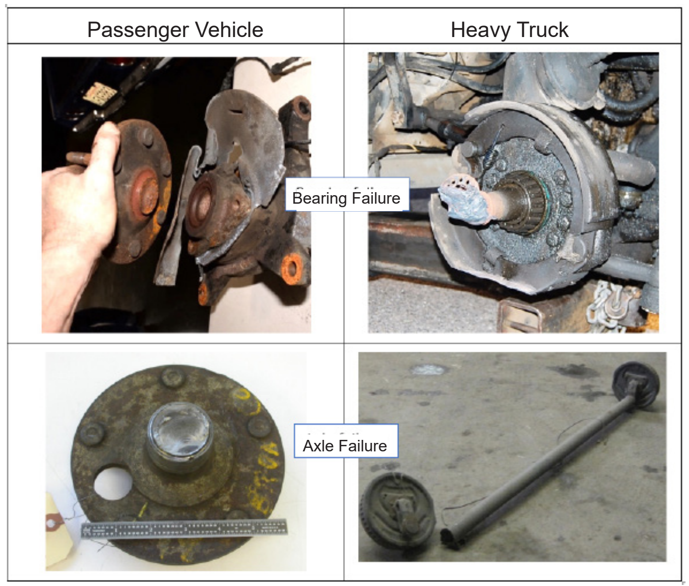

Figure 2
Examples of bearing and axle failures on passenger vehicles and heavy trucks.

Figure 3
Examples of nut spin-off fastener failures. Top row: A left rear heavy truck axle end with missing dual wheels and brake drum. The threads of all 10 stud shanks were worn down like the one shown. Second row: wheel stud hole thread imprints from bearing on a stud and wheel stud hole elongation. Third and fourth rows: wheel metal embedment in stud threads on two left side wheel separations.

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Many left side wheel separations present like the example in the upper left of **Figure 3** (wheel and all nuts missing — and all studs straight and unbroken). In addition to missing nuts, close inspection often reveals stud thread wear, wheel metal embedded in stud threads, stud thread imprinting in stud holes, and stud hole elongation. The nuts are most often not recovered.

Most right side and some left side wheel separations feature transverse stud fatigue fractures. The nuts and distal stud remnants are most often not recovered. In **Figure 4**, the five studs on the passenger vehicle and 10 studs on the heavy truck all broke transversely from fatigue.

Of the 100 investigations that were compiled, it was observed that 79 wheel separations were due to fastener failures. In **Figure 1**, Group I wheel fastener systems were like the system shown in **Figure 5(a)**. The fastener systems shown in **Figure 5(b)** are representative of Group II.

Figure 4
Examples of stud breakage fastener failures. Top row: a heavy truck hub with 10 broken studs — all with fatigue fractures like the one shown. Middle and bottom rows: an SUV right rear wheel separation. Bottom row shows a right rear wheel stud before and after cleaning. The stud fatigue fracture is readily apparent after cleaning.

For left side wheel separations, there were no broken studs in about half the cases and fewer than 40% broken studs in most cases — and the dominant fastener failure was missing nuts. In about 15% of left side wheel separations, all the studs had fatigue fractures. In these cases, it was observed that the nuts were impeded from spinning off the studs by a hub cap or dirty threads.

For right side wheel separations, all the studs were broken in most cases. The broken studs typically displayed evidence of fatigue like the studs shown in **Figure 4**. Sometimes, the stud fractures were fresh enough to readily observe fatigue features, sometimes, the fracture had to be cleaned to observe fatigue features, and other times, the fracture surfaces had deteriorated so only transverse fractures were observed. No evidence of nut spin-off was observed in any of the right side fastener failure cases.

Fastener Failure Mechanisms

The authors observed that most wheel separations are missing nuts for left side separations and stud fatigue fractures for right side separations. Both types of fastener failures have been shown to occur coincident with low

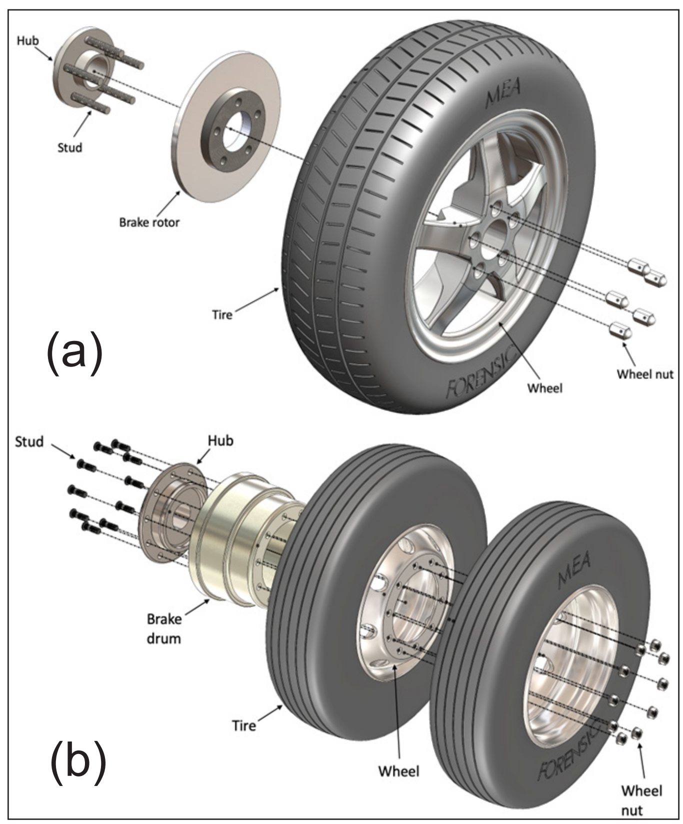

Figure 5
Axle end terminology for (a) Group I (passenger cars, light trucks, SUVs and utility and travel trailers) and (b) Group II (heavy trucks and buses).

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clamp force[19]. Clamp force refers to the job of the stud and nut to squeeze a wheel and brake rotor or drum to the axle hub. The concept is well understood in mechanical engineering and is discussed by Parisen[20] and Josephs[21].

Consider the wheel arrangement shown in **Figure 6** for a Group I wheel. Each of five studs goes through the hub, brake rotor, and wheel. The stud shanks pass through the stud holes in the wheel without ever touching the stud holes (the same is true for heavy trucks and buses). A nut goes on the end of each stud and is tightened to manufacturer specification, typically 65 to 120 foot-pounds for Group I and 400 to 500 foot-pounds for Group II vehicles. As a nut is tightened, it spirals closer to the opposite end of the stud, squeezing the material in between while stretching the stud elastically.

For 12mm studs typical of Group I, the clamp force at 80 foot-pounds torque is approximately 10,000 pounds. If there are five similarly torqued nuts, then the clamp force holding the wheels on is approximately 50,000 pounds. For 22mm studs in Group II, the clamp force at 500 foot-pounds torque is approximately 35,000 pounds. If the other nine nuts are torqued similarly, then the clamp force holding the wheels on is approximately 350,000 pounds. The large axial clamp force combined with friction between the mating parts prevents relative movement between the wheel, brake rotor or drum, and hub.

The two fastener failure mechanisms (missing nuts and stud breakage) operate when the clamp force is low enough to permit relative movement. The mechanism for the left side wheel nuts missing is that they spin off as the vehicle travels, which can be understood from the geometry of the wheel and studs when the clamp force is low enough to permit relative movement. As shown in **Figure 7**, since the stud holes are larger than the studs, the wheel can move so that it is not perfectly concentric with the axle. When the road pushes up on the tire, the wheel tends to be pushed up relative to the axle. This displaces the wheel centerline slightly above the axle centerline. The centerline offset gives rise to a relative velocity vector between each wheel nut and the part of the wheel the nuts touch. This gives rise to a circumferential relative motion in the loosening direction on the left side when the vehicle is driving forward and is able to spin wheel nuts off of left side wheel studs.

The right side nuts have that same relative velocity vector as shown in **Figure 7**, but in the opposite (i.e., tightening) direction. The vector is not strong enough to make a loose nut tight again, so, on the right side, a loose nut tends to stay loose rather than spin off. On the right side, vertical loads on the wheels that would ordinarily be reacted by the friction force transverse to the clamp force are borne by the wheel studs instead, leading to cyclic reversed bending of the studs (one cycle per wheel revolution) that leads to stud breakage by fatigue. On the left side, the same fatigue mechanism exists, but, in the author's experience, the nut spin-off mechanism is often quicker, which may explain the greater number of left side compared to right side wheel separations shown in **Figure 1**. The mechanism of both failure modes (nut spin-off and stud breakage) is low clamp force or LCF.

Deducing Low Clamp Force

In the authors' experience, investigating the cause of a wheel separation most often reduces to investigating the cause of LCF. Before pursuing investigation, however, the investigator will want to be informed as to whether the wheel separation was (or was not) an LCF type. Evidence

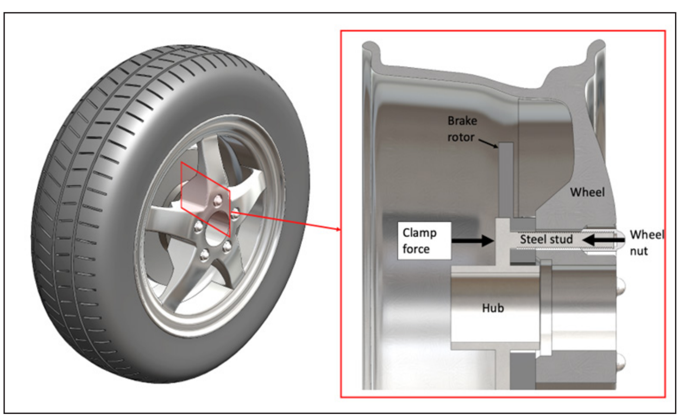

Figure 6
The wheels and brake drum are clamped to the hub between five studs and nuts.

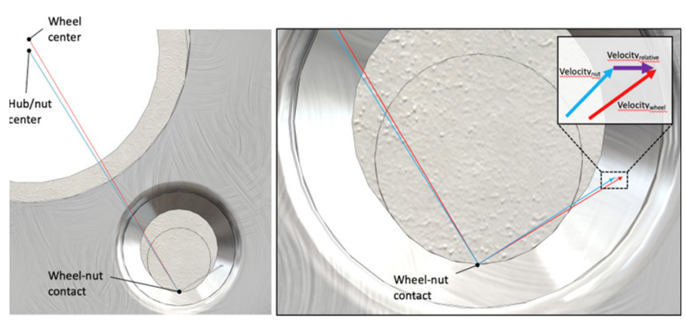

Figure 7
A left side wheel. Wheel turns counterclockwise in this view. Left: Axle weight causes axle to move down relative to wheel when relative motion between wheel and hub are permitted. Right: When wheel and axle are not concentric, there is a small relative velocity vector between the wheel and nut where the two make contact. The small relative velocity vector provides clockwise traction to spin the nut off.

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of missing-nut and stud breakage offers a reliable way for the investigator to deduce an LCF type wheel separation. The evidence consists of stud thread wear, wheel metal embedded in stud threads, stud hole thread imprinting and elongation, and transverse stud fatigue fractures (**Figures 3** and **4**). The evidence relates the missing-nut and stud fatigue mechanisms to LCF. The relation is purely deductive, and it is perspicuous to develop the formal symbolic logic relating the physical evidence to LCF.

In symbolic logic, deductive arguments are constructed of premises and conclusions. When an argument is valid (when there is no possibility that its premises are all true and its conclusion false), then it is the case that if the premises of the argument are true, then its conclusion must be true. There is not *probably* or *likely* — only of true or false. Deductive arguments are reason-conclusion connections — not cause-effect connections. In particular, conditionals (i.e., if A then B) are atemporal. So "if A then B" is taken to mean that "if A exists, then so does B" rather than in the sense that A followed B in time. The concepts of necessary and sufficient are used to model cause and effect[22,23,24]. By definition:

> Condition A is said to be *necessary* for condition B if the non-existence of A guarantees the non-existence of B,
>
> and
>
> Condition A is said to be *sufficient* for condition B if the existence of A guarantees the existence of B.

LCF and fatigue. The preceding section on fastener failure mechanisms discussed how wheel-hub relative motion leads to cyclic reversed stud bending of wheel studs that leads to their fatigue. To say that bending causes fatigue is also to say that bending had to exist for fatigue to exist — or, equivalently, if bending did not exist, then fatigue would not exist. Thus, bending is a necessary condition for fatigue. Symbolically, with obvious abbreviations:

$(\sim B \supset \sim F)$

which reads "if not bending then not fatigue." It is also the case that bending is sufficient for fatigue, since it is known from metallurgy that all that is needed for a stud to break is cyclic reversed bending, so:

$(B \supset F)$

which reads "if bending then fatigue." Overall, bending is necessary and sufficient for fatigue. By the same reasoning, the same relation exists between LCF and bending — that is, LCF was necessary and sufficient for bending. This introduces the first deductive argument:

$(B \supset F)\ \&\ (\sim B \supset \sim F)$

$(L \supset B)\ \&\ (\sim L \supset \sim B)$

$F\ /\therefore\ L$

By equivalence and contraposition rules of symbolic logic, it can be shown that the argument simplifies to:

$F \equiv B$

$B \equiv L$

$F\ /\therefore\ L$

Where ≡ is the biconditional *iff* (if and only if). The form of the argument is valid (called a "biconditional hypothetical syllogism"), and the first two premises are true by the fatigue mechanism ($F \equiv B$ and $B \equiv L$). So, if the third premise is true (that there was a stud fatigue fracture), then LCF is implied. In practice, the fatigue fractures on the studs like those shown in **Figure 4** only need to be observed to deduce an LCF type wheel separation occurred.

LCF and nut spin-off. The previous section on fastener failure mechanisms discussed how wheel-hub relative motion leads to nut spin-off on left side wheels with right hand stud threads. To say that relative motion causes spin-off is to say that relative motion had to exist for spin-off to exist — or, equivalently, if relative motion did not exist, then nut spin-off would not exist. Thus, relative motion is a necessary condition for spin-off. By the same reasoning, the same relation between LCF and relative motion exists, that is, LCF was necessary for relative motion. Finally, the authors note that relative motion is also sufficient for spin-off, and LCF is also sufficient for relative motion. The argument, which closely resembles the fatigue argument, is:

$S \equiv C$

$C \equiv L$

$S\ /\therefore\ L$

Again, the argument is valid, and so a nut spin-off

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implies LCF. In practice, the evidence of nut spin-off like those shown in **Figure 3** only needs to be observed to deduce an LCF type wheel separation occurred.

Other evidence. In some of the investigations, a vehicle or wheel were unavailable for examination, a separated wheel was never found, or available photographs did not show the wheels and fasteners in enough detail to determine the truth or falsity of the third premise of both the preceding deductive arguments. It is sometimes possible to determine if a wheel separation was the LCF type from other evidence, such as corkscrew marks inside a separated wheel[25] or brake rotor flat spots that occur after wheel separation when a brake rotor contacts the roadway. Corkscrew marks and rotor flat spots may be present after fastener failures, but are not present after bearing or axle failures — since, in those latter failures, the wheel, brake rotor, and hub remain bolted together. Therefore, they cannot interfere with each other.

The Cause of Low Clamp Force

Once a wheel separation is determined to be an LCF type, then LCF is recognized as the effect of a cause. In the authors' experience, deducing the cause is seldom possible; therefore, one must induce a probable cause by inference to best explanation. The best explanation for an LCF type wheel separation has often been a recent installation, based on a close proximity of separation to installation and the absence of design or manufacturing defects.

The recent installation/explanation is strengthened by data from the fastener failure investigations represented in **Figure 1**. Including all of Group I (passenger cars, light trucks, SUVs, utility and travel trailers) and all of Group II (heavy trucks and buses), there were 79 wheel separation attributed to fastener failures, all of which were determined to be LCF type. For the total of 79 LCF type wheel separations, the time or distance from installation to separation was known in 55 of them. The time-to-separation was known in 44 cases, distance-to-separation in 41 cases, and both time and distance to separation in 30 cases. The separated wheel location and average time and distance from wheel installation to separation are summarized in **Figure 8**.

Including all of Group I and Group II, the overall average distance from wheel installation to separation was 3,172 km, and the overall average time from installation to wheel separation was 59 days. The overall median distance from wheel installation to separation was 2,324 km, and the overall median time from installation to wheel separation was 38 days.

Group	Wheel Location	Installation to Separation	
I (Passenger Cars, Light Trucks, SUVs, Utility and Travel Trailers)	Left front	66 days	1,559 km
	Left rear	41 days	2,887 km
	Right front	120 days	3,116 km
	Right rear	98 days	3,423 km
II (Heavy Trucks, Buses)	All	29 days	6,533 km

Figure 8
Average times and distances from wheel installation to wheel separation from 79 LCF type wheel separation investigations.

The distributions shown in **Figure 9** (*time* in the top chart and *distance* in the lower chart) show that 50% of all wheel separations occurred less than 40 days and less than 2,400 km after the wheel was installed. The LCF separations have two different mechanisms (as discussed previously), but the time and distance to separation was short for both mechanisms.

Statistical hypotheses. There are more than 50 data points showing time or distance from installation to LCF type wheel separation. However, the data are not helpful for testing statistical hypotheses about wheel retention. As discussed previously, the rate of wheel separations appears to be extremely low. Therefore, any two-wheel separation populations are likely to have the same near-zero failure rate. So the influence of some distinct parameter between any two populations is likely to have no statistical significance. It is not the size of the data set — but the extremely low failure rate — that makes statistical analysis of failures in wheel retention populations impractical.

A probable necessary condition for LCF. Investigators of unique or infrequent failures do find causes of failures — just not from any statistical correlation type of analysis; nor are their findings substantially deductive. Instead, failure analysts frequently practice induction — specifically *abduction*, or *inference to best explanation*, which entails evidence and information gathering and the scientific method. An investigator gathers information and evidence, creates hypotheses to explain the observations, and then tests the hypotheses. If no hypotheses emerge with sufficient explanatory power, the cause is undetermined. If some emerge, then the best one may constitute a

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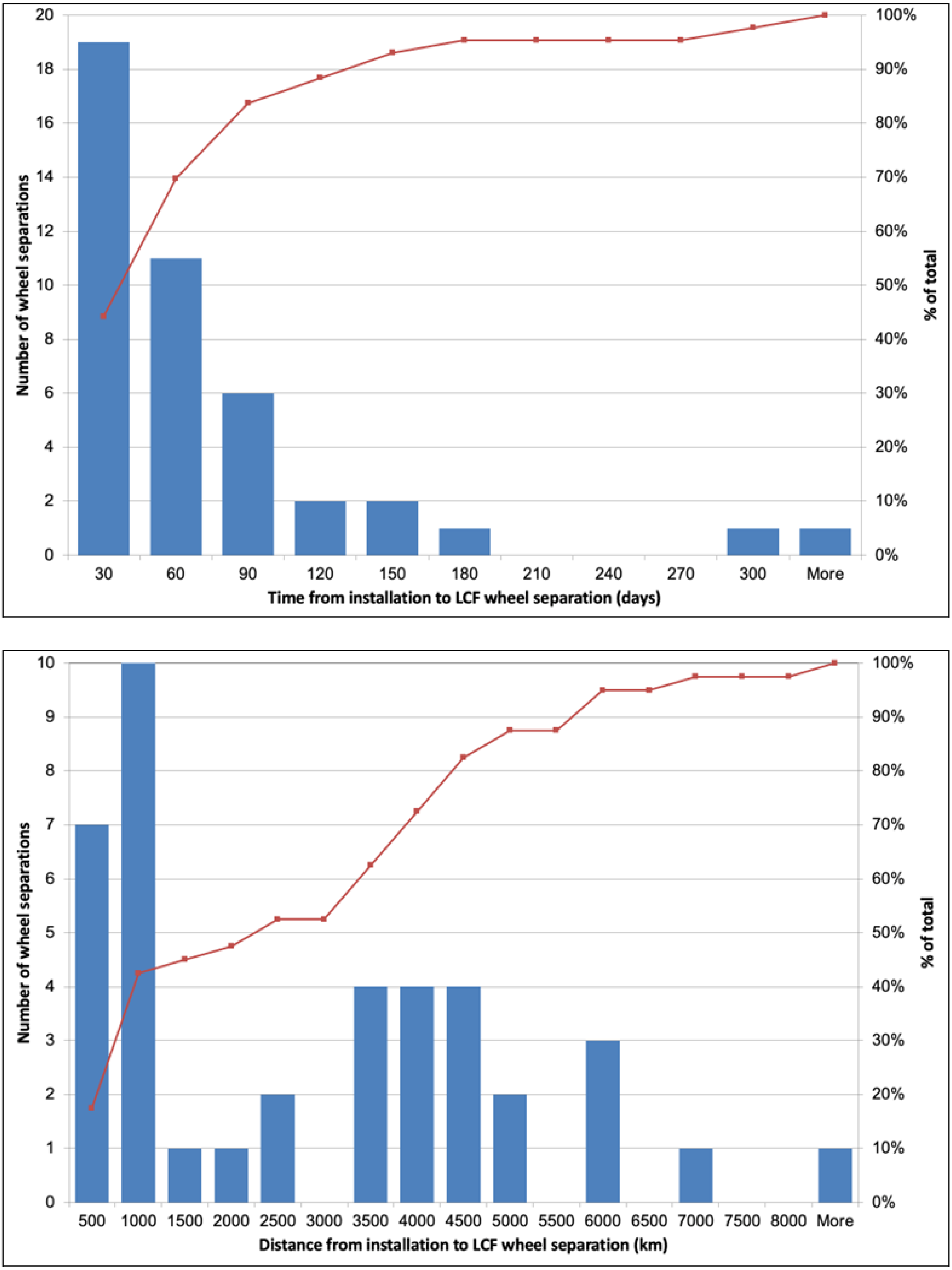

Figure 9
Time from installation to separation in LCF type wheel separations.

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probable explanation for the cause of failure.

The inference to best explanation is stronger the more similar failures there are. In the authors' experience, patterns emerge when there are multiples of the same failure. In induction, the utility of emergent patterns is called "Mill's Method of Agreement"[26]. According to Mill:

If two or more instances of a phenomena under investigation have only one circumstance in common, the circumstance in which alone all the instances agree is the cause (or effect) of the phenomenon.

The "circumstance" in the Method of Agreement is a probable necessary condition for an effect. The reasoning is that if an antecedent condition is present in all cases of an effect, then that condition is probably necessary for the effect.

The LCF wheel separation data show that the median distance and time from installation to LCF wheel separation was 2,324 km and 38 days. The distance and time are very low and very early compared to the expected service life of the installation. Other than a recent installation, the separations are diverse: the data cover a spectrum of vehicle sizes and weights, wheel types and sizes, tire sizes, number of fasteners, age of vehicles, and wheel locations on vehicles. The circumstance the LCF separations have in common is that the affected wheels were installed a short time and distance prior to separation. Therefore, the time and distance to separation data justify a claim that a recent wheel installation is a probable necessary condition for an LCF type wheel separation.

In a previous section, the authors showed how clamp force was made by tightening a nut onto a stud. The tightening is done at installation. It is beyond the scope of this paper to discuss wheel installation best practices. However, in general, a wheel installation involves cleaning the mating surfaces of wheel and hub, placing the wheel onto the hub and then tightening the nuts to a specified torque. The clamp force should be made by the end of the installation process. **Figure 10** lists some examples of how the clamp force may not be made or may be made and lost.

Clamp Force Not Made Examples	Clamp Force Lost Examples
Wrong torque applied	Embedment (localized plastic deformation between mating surfaces)
Torque wrench not used	Paint coating crushing
Torque wrench improperly calibrated	Dirt and corrosion product crushing from failure to clean mating surfaces
False torquing (e.g., incompatible threads, corroded or damaged studs or nuts)	

Figure 10
Installation factors related to LCF.

The data from wheel separation investigations showed that LCF type wheel separations frequently occur after a recent wheel installation. It is also the case that the steps in the wheel installation process offer a number of opportunities for LCF. Therefore, the claim that a recent wheel installation is a probable necessary condition for an LCF type wheel separation is justified by the available investigation data and plausibly related to the wheel installation process.

When a recent wheel installation is suspected to have led to an LCF wheel separation, the authors have found valuable evidence specific to the installation in two areas: measuring the wheel nut torque on the wheels that did not separate and closely observing the interfaces between the wheels, brake drum or rotor, and hub.

Torque audits. Obviously, determining the nut torque on a wheel that separated is not possible. However, it is possible to measure the peak breakaway nut torques on the wheels that did not separate, which the authors call a "torque audit." When possible, a torque audit can be done using a calibrated digital torque wrench, measuring the torque to just move a nut in the tightening, and then loosening, then tightening direction (or the so-called "ON-OFF-ON" technique). The nut to be measured first has it position scribed relative to the wheel. Then, the nut is turned in the tightening direction a few degrees (usually less than five), loosened counterclockwise of the scribe, and tightened back to the scribe — yielding three torque values per nut.

Torque audits can yield meaningful insight about the wheel that separated if the other wheels were also installed at the same time (e.g., for new tires or a tire rotation). Many vehicles are repairable after a wheel separation and a torque audit must be done before any other wheels are tampered with during repairs. If an LCF type wheel separation is deduced soon after an accident — from observations like those shown in **Figures 3** and **4** — then the investigator can promptly take steps to preserve the evidence for a torque audit.

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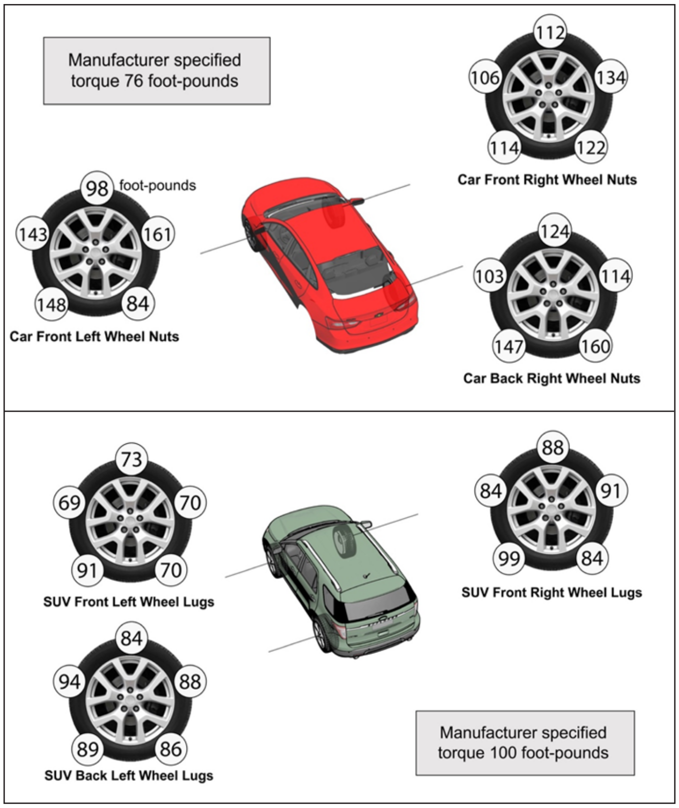

Figure 11
Top: Torque audit on a passenger car.
Bottom: Torque audit on an SUV.

Figure 11 shows the results of two torque audits. In the upper instance, the specified wheel nut torque was 76 foot-pounds, but torques on the remaining nuts were all too high — some as high as 160 foot-pounds. In the lower instance, the specified wheel nut torque was 100 foot-pounds, but the torques on the remaining nuts were all too low.

The wrong torques prompted thorough audits of the wheel installation practices in both instances, where it was found that best practices were not being followed. In both instances, the non-adherence to best practices — along with the erratic torques on the remaining wheels — became the best explanation for these LCF wheel separations.

Torque audits are insightful when nut torques are far from specified (e.g., 161 foot-pounds when it should be 76 foot-pounds). When the difference is not so large, care must be taken to infer the installation torque from the audit torque. The installation and audit torque will be the same only if the stud stretch and coefficient of friction at the nut are the same at the time of installation and audit. But the stud stretch can be different if there has been embedment, and it may be possible for the nut coefficient of friction to change over time.

Leffler[8] reported tension variation among studs in a six-stud wheel of more than 20% when wheel nuts were carefully installed to 120 foot-pounds on the same wheel, which may imply differences in coefficient of friction among different nuts installed at the same time. While these results do not lead to a conclusion that nut friction changes over time, it seems reasonable to consider that it might. If the nut friction changed over time, then the installation torque could be modeled from the audit torque, but would not be equal to the audit torque. The authors' research on torque audits is ongoing.

Interfaces. When a wheel is installed, the area of the aluminum or steel wheel surrounding the studs is clamped forcefully against the ferrous brake rotor or drum. If there are dirt or corrosion products already on the mating surfaces, then the dirt or corrosion products can be crushed and lead to loss of clamp force.

Figure 12 shows an aluminum SUV wheel that was

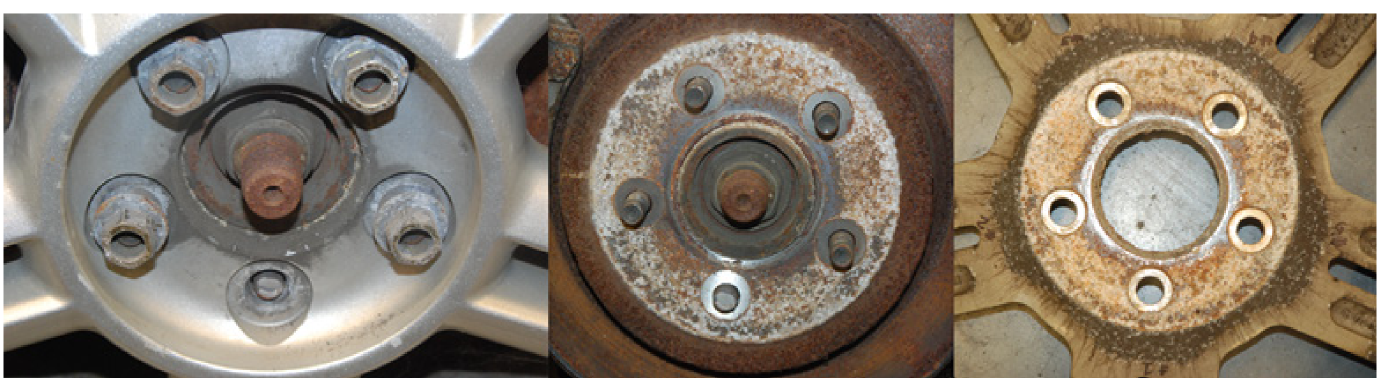

Figure 12
Left: One stud fatigue fracture on SUV right rear wheel. Middle and left: Corrosion and dirt on interfaces
(the five shiny rings around the stud holes correspond to circular recesses around the wheel stud holes).

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installed without proper cleaning of the wheel and brake rotor interfaces. Shown is the right rear wheel. The left rear wheel had already separated, leading to an accident. The depicted right rear wheel already had one broken stud from a fatigue fracture, confirming LCF on this wheel. Debris on the rotor and hub were clamped in the interface at the last wheel installation. Optical microscopic observation showed the debris was crushed and smeared, which likely thinned the material being clamped, led to LCF on this right rear wheel, and caused the LCF type separation of the left rear wheel.

Figure 13
Debris from a wheel after it was removed from an SUV with a wire brush.

Cleaning wheel and brake rotor or drum interfaces is always part of wheel installation best practice. A considerable amount of debris can be quickly removed with a wire brush as shown in **Figure 10**. If the amount of debris shown in **Figure 13** became trapped in the interface, then it could lead to LCF.

Preventing LCF Type Wheel Separations

Wheel installation best practices are beyond the scope of this paper, but many auto maintenance facilities have their own internal practices that generally entail interface cleaning, initial nut tightening to less than manufacturer-specified torque, and final tightening with a calibrated torque wrench[27]. The Technical Maintenance Council of the American Trucking Association lists best practices for heavy trucks[28]. In the authors' experience, LCF type wheel separations are often accompanied by non-adherence to installation best practices. However, whether adherence to best practices would have prevented a wheel separation has been dependent on the nature of the installation error.

Many manufacturers and installers recommend that wheel nuts be re-torqued a short time after installation. Two examples are shown in **Figure 14**.

A re-torque is done by tightening each nut on recently installed wheels to the specified torque (with the vehicle on the ground). Re-torquing is theoretically effective because it might make or restore the clamp force that was not made or was lost for reasons including, but not limited to, the reasons in **Figure 10**. It is not feasible to estimate re-torque effectiveness using statistics because, as discussed previously, the extremely high success rate of wheel fasteners would probably not change significantly (with or without re-torques), even if re-torques were highly effective. However, since recent installations are a probable necessary condition for LCF wheel separations — and the recent installations have a strong relationship between clamp force and nut torque — it is likely that re-torques represent a negation of the necessary condition.

For any given recently installed wheel, nut re-torquing may do nothing, or it may remedy a low clamp force that existed for the reasons listed in **Figure 10** or other reasons. It cannot be known why re-torquing might work for any given recently installed wheel because it is not known what (if any) condition is being remedied. But that doesn't

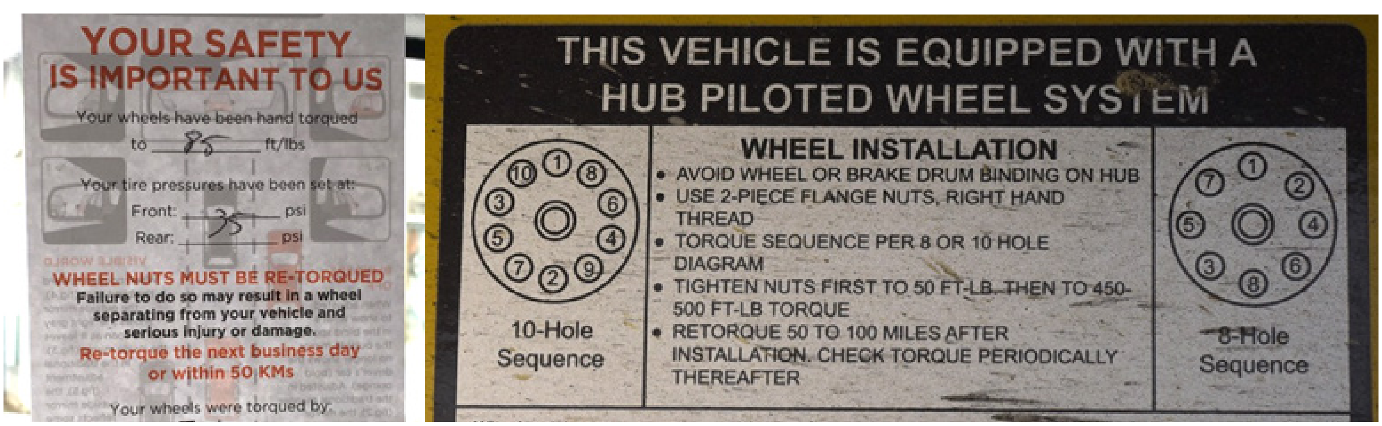

Figure 14
Left: One day, 50 km re-torque reminder for an SUV. Right: 50 to 100 mile re-torque placard on a commercial trailer.

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matter. What matters is that re-torquing likely negates a probable necessary condition for LCF, and, by doing so, is likely to prevent a wheel separation.

Summary and Conclusions

"Wheel separation" describes an event where one or sometimes two wheels detach from a moving passenger vehicle or heavy truck. Wheel separations occur at least in the thousands per year and often lead to serious accidents. The proximate cause of most wheel separations, based on the literature and 86 of the author's investigations, is nut spin-off or stud fatigue fracture. The mechanism for both fastener failure types is low clamp force, where the fastener clamp force is either not made properly when the nuts are tightened, or the clamp force is made but lost due to wheel-hub interface issues.

An LCF type wheel separation can be confirmed deductively from physical evidence. Observations of wheel metal embedded in stud threads, wheel stud hole elongation and stud thread imprinting, or wheel stud fatigue fracture all confirm LCF.

The median distance and time from installation to separation for 55 LCF wheel separations was 2,324 km and 38 days. The very low distances and times indicate that a recent wheel installation is a probable necessary condition for an LCF type wheel separation. Since a wheel nut re-torque soon after a wheel installation likely negates the probable necessary condition, it is likely that re-torques are effective at preventing LCF type wheel separations.

In the authors' investigations of LCF type wheel separations, fastener design or manufacturing defects were not observed. In cases where the authors have been able to find a probable cause of LCF, the best explanation has been related to wheel installation, such as improper torquing or improper cleaning of mating surfaces. Insights into these factors can be gained from torque audits on remaining wheels or close inspection of wheel interfaces.

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