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ʊ Paper presented at the NAFE seminar held in July 2023 in Kansas City.
‡ Paper presented at the NAFE seminar held virtually in January 2021.

Subjects' Ability to Characterize g's in Relation to Activities of Daily Living

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

Abstract

The amount of force associated with a specific activity or event often utilizes g's (g-force) and the unit of force. In litigation, biomechanics forensic experts provide general causation analysis of injury events, referencing the g's of the event and often the g's associated with Activities of Daily Living (ADLs). It is assumed that jurors will understand and correctly interpret any presented g values. This research explored the validity of this assumption. A survey instrument was employed that included 610 subjects to probe an individual's understanding of what g's are and their beliefs of the associated magnitude of ADL g's. The results indicated that most adults have a limited understanding of g's, often holding incorrect beliefs. For example, many believe they do not experience 2 or 3 g's during daily activities. Therefore, it is useful for the engineering expert to frame g-based analysis with references to ADLs, providing individuals (and jurors) with a proper framework to understand the analysis results. Without such reference points, jurors may misunderstand — and attorneys can misrepresent — the meaning of any g's associated with the specific case analysis.

Keywords

Activities of Daily Living, ADLs, biomechanics, g's, forensic engineering

Introduction and Background

In the analysis of injury-related events, such as vehicular collisions, falls, blunt trauma, etc., the unit of force often adopted is "g's" (or g-force). In the case of a vehicular collision, the reported g's may refer to the vehicular collision force experienced by any occupants within the vehicle. Regarding blunt trauma on the body due to an object, it would reflect the force of impact on the body due to the delivery of force by the object. Such a convention normalizes force references in that only the acceleration term from the equation F = ma is considered.

For reference, 1 g is the force of gravity. Therefore, an object's weight on the surface of this planet would be mass of the object X 1 g (using appropriate values and units). With the gravity = 1 g reference, 2 g's could be interpreted as twice the force of gravity, and so on. In addition, in the field of biomechanics, it may be difficult to determine what the "m" is. For example, in cervical injuries (where the head acceleration may be estimated in g's), it is challenging to determine if the mass is the head only, the head-neck, etc. In shoulder biomechanics, it is unclear what the mass of the "shoulder" should be in an F = ma type calculation. Thus, using g's is a common protocol in biomechanics.

People have some awareness of g's as a unit of force. For example, roller coaster rides are often reported in terms of g's (current roller coasters now approach 6 g's)[1], with higher values indicating more of a "thrilling" ride for roller coaster aficionados. The force experienced by jet pilots may be reported in terms of g's — with values sometimes approaching 9 to 10 g's. Also, many know the "zero gravity" type environment that individuals in outer space experience. There appears to be no published research on an individual's awareness of 1 g, 2 g's, 3 g's, etc. regarding day-to-day activities or any other references — whether from a psychology or a scientific literacy viewpoint. For most, g-force familiarity is attributable to the "pop culture" examples such as those cited above.

In analyzing a specific injury event, a forensic engineering expert may report that the injury event of interest resulted in 2- to 3-g force exposure (the range indicating any uncertainties that may be present). This is very common in the vehicular accident reconstruction — where the reconstructionist may report the delta-V (change in velocity) in velocity units and the associated vehicle acceleration in g's.

In the injury biomechanical analysis of the same

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event, the occupant's force exposure is often reported in g's — sometimes applying different g values to different body regions. For example, the head acceleration may be reported as 5 g's, the lumbar region as 3 g's, etc. The reported values may reflect "average acceleration" (average g's) or "peak acceleration" (peak g's) — testifying experts may not always make this distinction clear. As part of the analysis, the biomechanics expert may cite literature that investigates injury-causing events (sometimes involving human subjects) or other force applications resulting in a specific injury where the reported force values are often in g's. For example, in human head injury tolerance analysis, the injury thresholds are often presented as a combination of head acceleration in g's and exposure time[2].

In the utilization of g's as the unit of force, there may be an assumption on the part of the reader (or juror) that the individual actually has accurate knowledge of how to interpret g's. As noted above, there is no actual research on the validity of this assumption in terms of the general population and subsets of the general population (demographics such as education level, age, etc.). This manuscript reports a human subject study where this question was posed. More specifically, this investigation probed if individuals had any understanding of g's in general as well as in terms of what an average human actually experiences in their daily lives. The results of such a study could provide insights into the possible utilization of references of g values associated with so-called ADLs and how such references could assist in ensuring that individuals had some reference points to properly understand and interpret g values.

Activities of Daily Living (ADLs)

ADLs refer to activities that most people might perform during a typical day, such as sneezing, coughing, vehicular braking, walking on a level surface at various speeds, sitting down/standing up, stepping off a curb or a stair, etc. While others have investigated various exercise, occupational, and sports activities (e.g., jumping jacks, box lifting, soccer heading, etc.), these are not ADLs for most individuals (although such references may be helpful in situations where the individual actually performed such activities). There have been several peer-reviewed publications that report the forces associated with ADLs[4-7], often based on experimental protocols where human subjects were fitted with accelerometers to measure the associated forces while the activity of interest was performed. It should be noted that most accelerometers employed in such studies measure the forces in units of g's. The reported ADL values are usually in the range of just over 1 g to 6 to 8 g's.

Experimental Design

A survey instrument was developed to probe individuals' understanding of g-values. Many questions employed a five-point Likert scale to respond to a specific question. Likert scales are employed to measure beliefs, opinions, attitudes, etc. of human subjects. The methodology typically consists of a statement followed by several possible responses (usually five) where the subject selects the response that is (in his/her judgement) most correct. The possible responses should be balanced in terms of equal numbers of positive and negative statements and one neutral statement. Here is an example:

I believe that I do not experience a force of 2 g's or higher in my normal daily activities.

__ Strongly disagree
__ Disagree
__ Neither agree nor disagree
__ Agree
__ Strongly agree

Several questions used an open response to the stated question. Here is an example: Please estimate how many g's would be associated with normal walking on a flat surface.

In general, survey questions probed the following:

- What force do we experience for various given activities such as walking?
- One's belief that forces of 2 g's or higher are not experienced by individuals in their daily normal activities.
- Self-evaluation of one's understanding of g's.
- Perception of other individuals' understanding of g's.
- Estimated g's to cause bodily injury.

In addition, demographic questions were included that sought to classify respondents according to:

- Age
- Gender
- Highest level of education
- If a college degree was completed, what was the major?
- Have you completed at least one year of college physics?
- Do you regularly read scientific magazines and/or watch scientific-based educational programs or documentaries?

The survey was administered using Qualtrics, a popular platform employed by researchers to develop, run, and analyze online surveys. Participants were provided the link and otherwise completed the survey anonymously. Participants were recruited from a university (students) and regional church, civic, and professional groups. A total of 610 persons participated. Basic demographic information is summarized in **Figure 1**. The male and female percentages were 44.4% and 55.6%, respectively.

In terms of those who completed a college degree (n = 279 — where n indicates the number of relevant responses), 8.2% earned an engineering degree; 14.3% a science degree; 28% a liberal arts degree; and 24% a business degree — with the remainder earning an arts, health sciences, social sciences, or other degree. For participants who completed some college or completed college (n = 511), 21.9 % completed at least one year of college physics and 78.1% did not. Just over 18% of all participants (n = 112 respondents) agreed/strongly agreed that they regularly read scientific magazines or journals and/or viewed scientific programming.

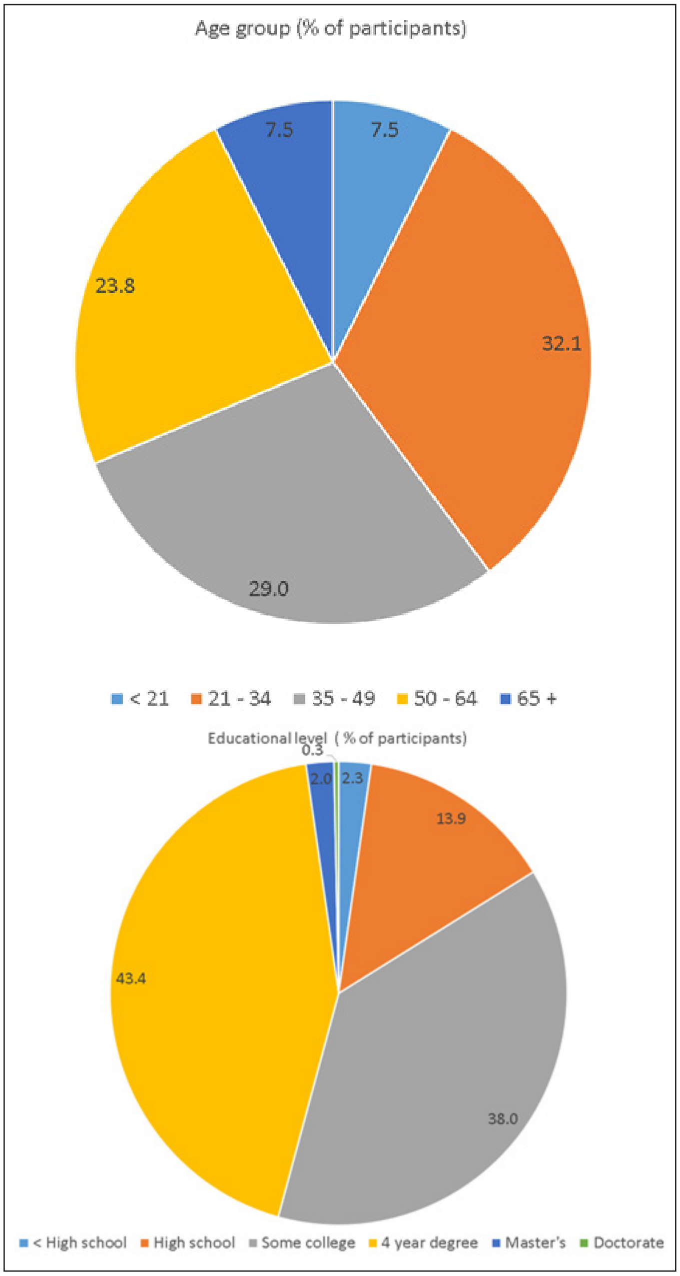

Figure 1
Age group of the study participants (top) and educational level (bottom). Total participants: 610.

Results

Participants were asked if they believed that they had never experienced 2 g's or higher in their normal daily activities. **Figure 2** presents the results for all 610 respondents (top) and a separate breakout (bottom) for those who attended some college and completed (or not) a one-year

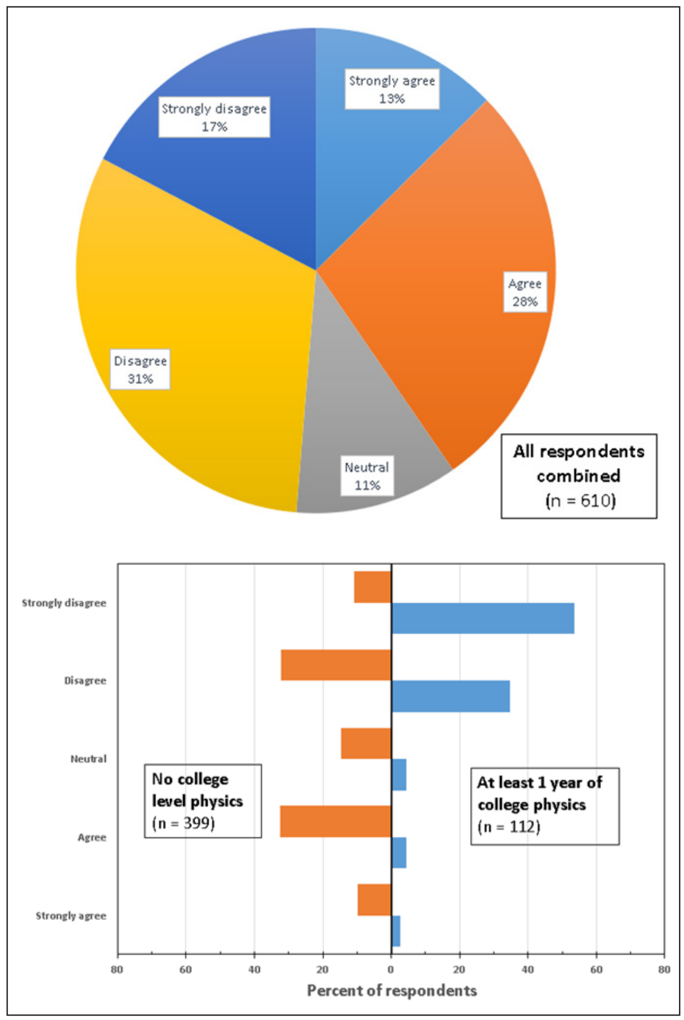

Figure 2
Participant responses to the question (top): "I believe that I do not experience 2 g's or higher in my normal daily activities." Responses for all participants and (bottom) broken out by completion of at least one year college physics class (right) or never completed a college-level physics class (left).

college physics class. A five-point Likert scale was used for these questions.

It is interesting to note that 41% (28% + 13%) of all respondents (n = 610) agreed or strongly agreed with the statement that one doesn't experience 2 g's or more in one's daily activities. Only 17% strongly disagreed that the statement was incorrect.

When one looks at participants who completed or at least attended some college, 45% (35% + 10%) of those who had no college physics class agreed or strongly agreed with the statement while only 7% (4% + 3%) of those who had completed a college physics class agreed or strongly agreed with the statement. Approximately 89% (35% + 54%) of the "completed physics" group disagreed or strongly disagreed with the statement as opposed to 40% (30% + 10%) of the "no physics class" group.

Figure 3 present the responses to the open-ended question: "How many g's are associated with normal walking on a flat surface?" — with the results for all 610 respondents (top) and a separate break-out (bottom) for those who attended some college and completed (or not) a one-year college physics class.

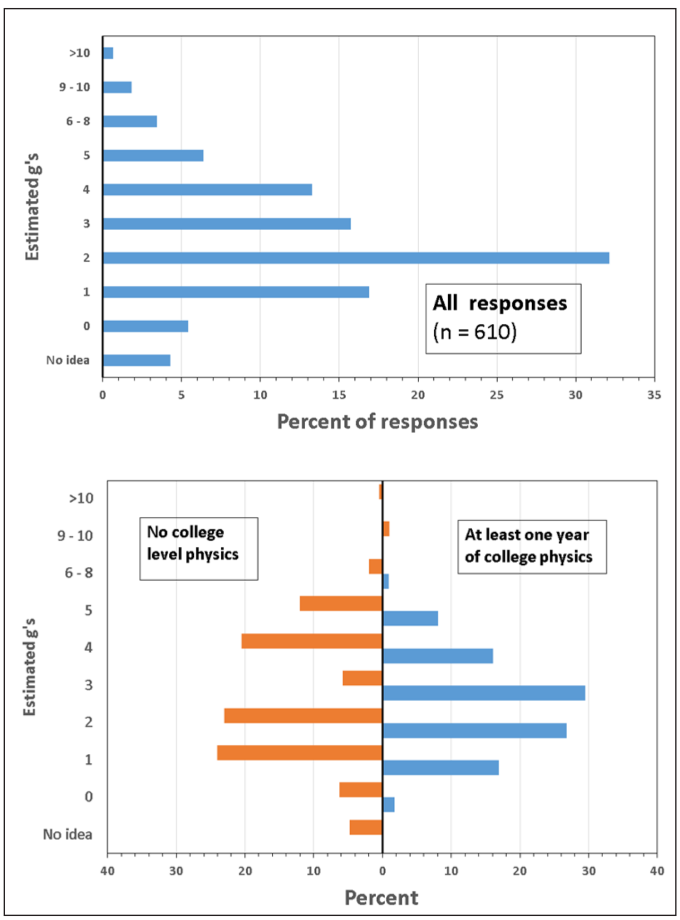

Figure 3
Responses to the question: "How many g's are associated with normal walking on a flat surface?" Responses for all participants combined (top) and broken out by completion of a one-year college physics class (bottom right) or at no college-level physics (bottom left).

Interestingly, for all responses combined, approximately 4% had no idea, and 5% thought the value for normal walking was 0 g's. For all responses, almost 17% estimated 1 g, and 32% estimated 2 g's. Furthermore, 11 respondents provided estimates of 9 to 10 g's, and four thought it was > 10 g's. When examined in terms of those who had completed a college physics class (or not), none of the "completed physics" respondents "had no idea," and just under 2% estimated 0 g's; for the "no physics class," 19 respondents "had no idea," and 25 respondents thought the value was 0 g's. Also, only one of the "completed physics" respondents thought the g's were 6 to 8 or higher whereas 14 of the "no physics class" respondents provided estimates of 6 to 8 g's or greater. For reference, the value for normal walking on a flat surface was measured for human subjects to be 1.45 to 2.07 g's in the lumbosacral region[7].

Figure 4 presents respondent estimates of how many g's it takes to cause a bodily injury.

For all 610 responses, a total of 32 participants (just over 5%) "had no idea" (only three of these were "completed physics" respondents). Fortunately, no one responded that 0 g's was a good estimate, indicating that all respondents felt that at least some force was required to cause a bodily injury. To cause a bodily injury, 14 respondents felt only 2 g's was required, 27 estimated 3 g's, 30

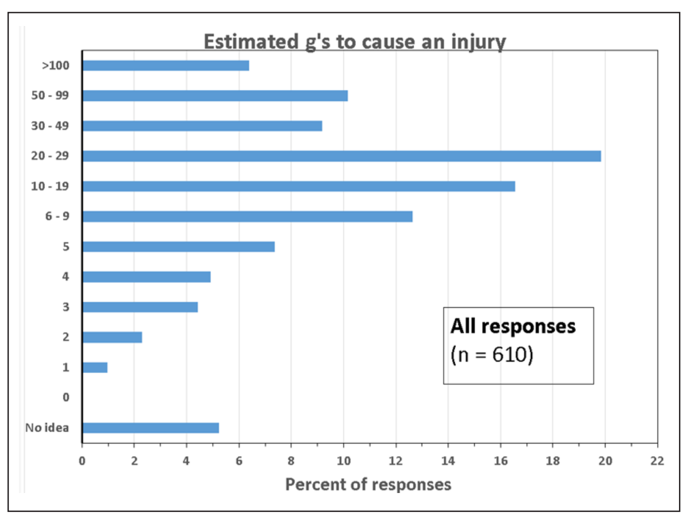

Figure 4
Respondent estimates of how many g's would be required to cause a bodily injury.

estimated 4 g's, and 45 indicated 5 g's. A total of almost 46% of all respondents thought the value was between 10 and 50 g's; 62 respondents felt the value was between 50 and 99 g's, and 39 felt it was greater than 100 g's. Of those who "completed physics," less than 8% felt the value was 5 g's or less whereas almost 22% of "no physics class" estimated the value to be < 5 g's. This question was intended to get a general feel for what respondents felt about how many g's were needed to cause a bodily injury; no specific injury or injury type was indicated in the question. Obviously, the estimate range is injury-specific and a function of age, gender, and other biomechanical and physiological parameters.

Figure 5 presents the results of two Likert scale questions: 1) "I think I have a good understanding of what 1 g, 2 g's, 3 g's, etc., means"; and 2) "I think most people have a good understanding of what 1 g, 2 g's, 3 g's, etc. means."

It is interesting to note that overall individuals tend to rank their personal level of understanding higher than their perception of other individuals' level of understanding. In general, very few participants (22) felt they "strongly agreed" with this statement; only 38 agreed with this statement. About 36% were neutral on the topic, and almost 54% of respondents disagreed or strongly disagreed. When asked to estimate the level of understanding for others, only two individuals "strongly agreed" and 17 "agreed"; individuals felt almost 60% of others had limited understanding of g's.

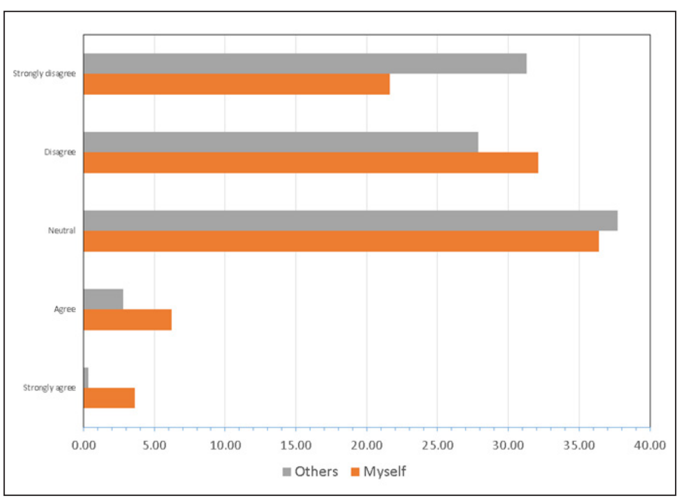

Figure 5
Responses (all 610 participants) to the question: "I think I have a good understanding of what 1 g, 2 g's, 3 g's, etc. means" (myself) and "I think most people have a good understanding of what 1 g, 2 g's, 3 g's, etc. means" (others).

There were no obvious influences of age group with two exceptions. Of the 46 respondents who were 65 years of age or older (7.5% of respondents), "I have no idea" responses were more common percent-wise versus the younger age groups. Also, almost all of the 65+ responders disagreed/strongly disagreed that they understood what 1 g, 2 g's, 3 g's, etc. means. Regarding gender, females were less likely to agree/strongly agree that they understood what 1 g, 2 g's, 3 g's, etc. means versus males. Of those who agreed/strongly agreed that they regularly read scientific magazines and/or watched science educational or documentary programs, there was a tendency for such individuals to agree/strongly agree that they understood what 1 g, 2 g's, 3 g's, etc. meant at a higher level versus those who did not read or watch science-based media. This was also true of engineering/science majors versus other college majors.

Discussion

Overall, the results indicate that most individuals have a limited understanding of what g's are all about. College-educated persons who completed a college-level course in physics tend to do better, but the "improvement" is not drastic. It is concerning that many individuals may believe that we don't experience much above 2-g activities in our daily lives and that some believe normal walking is associated with 0 g's. This is not necessarily surprising in that most individuals outside a few fields, such as specialized engineering/physics areas (mechanical engineering, aerospace, injury event reconstruction, biomechanics, and similar disciplines), don't deal with g's outside of what they see and hear in popular culture (which may not be very frequent).

For most individuals, this limited understanding of g's is probably not a major issue in their day-to-day lives. However, this can be a significant problem in the legal system when jurors are asked to weigh evidence that involves forces presented as g's. In a personal injury case, the defense attorney may say "only 3 to 4 g's were experienced by the claimant" (implying: therefore, no injury). The plaintiff attorney alternately states: "But my client experienced three to four times the force of gravity!" (therefore: injury). Obviously, this can be very confusing to jurors, especially without any understanding of what g-force values mean and what one experiences (or doesn't) in daily life.

A solution to this problem is for the expert(s) who cite forces in terms of g values to also reference various ADLs to provide a framework for jurors to understand the facts of the case and hopefully arrive at a rational decision. Any referenced ADLs should, in fact, be real activities of daily living as experienced by regular people doing "regular" activities and not necessarily include activities such as boxing punches, football helmet-to-helmet hits, etc. One possible exception may be in blunt head trauma cases. Another may involve individuals who are active in a specific activity or line of work. For example, it may be useful and relevant to cite the forces associated with lifting objects for a person who works on a loading dock — for that person, "lifting" is, in fact, an "activity of daily living."

It should be noted that some experts may cite certain ADLs as somehow modeling or representing a specific injury situation. For example, an expert may opine that falling backward into a chair somehow models a rear-end collision. ADLs are "normal" activities and not intended to model any injury situation. ADL forces and the involved time frames of such "voluntary" motions do not translate into "injury models." In general, it is a misuse and misapplication of ADLs to say that a specific injury did or did not occur (specific causation) just because the associated ADL g values are "low."

Summary and Conclusion

Referencing ADLs to provide an understandable reference of what g values are about is useful to jurors and others seeking to rationally understand what g-force values say and don't say. The results of this study indicate that most individuals have a limited (and often incorrect) understanding of g forces; referencing ADLs can minimize such problems.

The selected ADLs should be relevant to the case and not significantly exceed the levels of forces involved. Most of us walk from point A to point B, stand up, and sit down, experience vehicle braking, go up and down stairs, etc. Most of us understand what ADLs are in terms of personal experiences. Without such ADL references, jurors and others can be misled (sometimes purposefully) by statements from either side (defense and/or plaintiff) regarding a specific situation such as injury causation. Without such ADL references, the chances of analyzing a given situation (or weighing evidence) may be high in terms of reaching the wrong conclusion.

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Distracted Driving: Determining Cell Phone Usage from Forensic Cellular Records

By Mark McFarland, PE, DFE (NAFE 1186M)

Abstract

This paper presents an analysis of an alleged texting-while-driving collision case involving cellular call records. The plaintiff's expert, unfamiliar with cellular networks, made serious errors in interpreting the cellular records, which resulted in a mischaracterization of the defendant's cell phone usage at the time of the collision. Thus, the plaintiff's expert could not support his opinion that the defendant was using her phone at the time of the collision. The expert made three critical mistakes interpreting the cellular records — mistakes that are commonly made by analysts who are unfamiliar with the design and operation of cellular phone networks. This paper explains the common mistakes and faulty assumptions behind them. The proper analysis methods of a qualified engineer with an understanding of cellular networks are also presented.

Keywords

Auto collision, base station records, call detail records, CDR, cell phones, cell phone usage, cellular records, distracted driving, mobile phones, mobile phone records, forensic engineering

Introduction

According to the National Highway Transportation Safety Administration (NHTSA), more than 3,500 people were killed on U.S. highways as a result of distracted driving in 2021[1]. Additionally, the National Institute for Occupational Safety and Health (NIOSH) states that in 2020, 13% of all motor vehicle traffic crashes in the United States involved distraction[2]. These crashes have been attributed to novice and experienced drivers alike[3]. Distracted driving is defined as any activity that diverts a driver's attention from driving, which includes cell phone usage[1]. Cell phone distractions are especially dangerous because sending/reading a text or checking social media updates can take a driver's eyes off the road for several seconds.

Forty-eight states have text messaging bans in place for all drivers[4]. These restrictions help to limit a driver's distractions when operating a motor vehicle. When an automobile collision occurs, a driver may claim that the motorist who crashed into him was texting at the time of the collision and was distracted. If proven true, additional penalties may exist for the texting driver. For example, the plaintiff may be able to sue the defendant for negligence.

There are two main sources of evidence engineers and analysts may use to determine if a driver was texting at the time of a collision: records from the cellular carrier and the cell phone itself. Cellular carrier records are commonly referred to as call detail records (CDRs).

This paper analyzes the assumptions and methods of two experts in a particular case. The plaintiff's expert found the defendant driver was using her phone at the time of the collision; the defense expert found she was not. This case demonstrates how an expert's assumptions and methods affect conclusions — and why it is so important to retain qualified engineers with a background in cellular networks to review forensic cellular records.

Case Background

A motor vehicle collision occurred involving a delivery truck and a car. The delivery truck driver (defendant) who caused the collision was employed by a national auto parts store (for the sake of this paper, we will call this company "ABC Auto Parts"). She was making a delivery in an ABC Auto Parts truck to one of the company's retail stores. The delivery driver was found to be at fault for the collision; therefore, she was responsible for the damage. Additionally, the motorist she crashed into (plaintiff) claimed that ABC's driver was texting at the time of the collision. Given this claim, the plaintiff also sought to sue ABC Auto Parts and their driver for negligence.

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The plaintiff's lawyers hired an expert to review the defendant's CDR. The plaintiff's expert determined from the CDR that ABC's driver was using her cell phone at the time of the collision. Likewise, the ABC Auto Parts' counsel hired an expert to review the same cellular records. The defendant's expert determined that ABC's driver was not using her cell phone at the time of the collision. Both experts examined the same CDR yet came to different conclusions.

Both experts cannot be right. As it turned out, the plaintiff's expert had no background or understanding of the design or operation of mobile cellular networks. His conclusions were based upon unfounded assumptions and incorrect methods. This undermined the plaintiff's negligence claim against ABC Auto Parts. That is why a background in cellular network design and operation is necessary to provide an accurate and reliable analysis of CDRs.

About Cellular Call Detail Records

Cellular CDRs are essentially cellular carrier phone records. Obtained from cellular carriers with a subpoena from a lawyer, they are basically logs of transactions (calls, texts, data, etc.) contained in spreadsheets. It is not possible for forensic engineers to obtain the records on their own authority, although individual cellular customers may request their own records.

The records typically contain information on voice, message, and data transactions for a given phone number. In the CDR, a "call" can be a telephone call (voice transaction) or an SMS message (texting transaction). Each voice and message transaction in the record typically includes a time stamp (in the UTC time standard), call direction (incoming or outgoing), the number that initiated the call, the number that received the call, location information, and other cellular network information. This can include the base stations (or towers), sectors, and switches used to route the call. Entries are added to a user's call record whenever a call or text is sent or received. Data transactions can be entered separately.

Some of this information is only available if the call was routed over a long-term evolution (LTE) cellular network. Calls routed over an internet protocol (IP), Wi-Fi network, or the public switched telephone network (PSTN) may include different information.

CDRs are not archived by the carriers indefinitely. Most carriers retain the full records for a period of up to two years. After that, limited records may be available. Billing information from the CDRs is typically retained for longer periods of time.

The CDRs are often provided in spreadsheets, and many people are proficient in analyzing spreadsheet data. However, without sufficient knowledge of cellular networks, it is unlikely that the CDR spreadsheet data could be interpreted correctly. Although these records may appear self-explanatory, analysts without a strong understanding of the design and operation of cellular networks can make critical mistakes in interpreting CDRs. These mistakes — and the poor methods that accompany them — do not yield proper understanding or facts. In fact, in this case, the plaintiff's expert issued a total of three reports: an original report, a revised report (to correct the first mistake), and a second revised report (to correct the second mistake). These mistakes and poor methods are described in detail below.

Three Common Mistakes

Although competent with analyzing spreadsheet data, the plaintiff's expert had no background in cellular network design or operation. The three mistakes the plaintiff's expert made are common among inexperienced cellular analysts. These mistakes are discussed below along with the impact they had on the case.

Three common mistakes people make when analyzing CDRs are:

1. Time zone conversion errors.
2. Attributing handoffs (or handovers from one base station to another) to indicate phone activity initiated by the user.
3. Attributing increased data usage to the phone user.

Time Zone Conversions

The CDR entries include a time stamp indicating when an activity occurred. Because of the complexity of timekeeping on nationwide cellular networks, the cellular carriers may store time stamps in one common time standard, such as Universal Time Coordinated or UTC, which is also called Universal Coordinate Time and Coordinated Universal Time. It is the basis for local times worldwide. UTC is similar to Greenwich Mean Time (GMT) and is referred to as "Zulu" time in military settings. UTC is a fixed time standard at zero degrees longitude (the Prime Meridian). UTC does not observe Daylight Savings Time (DST).

To properly evaluate the records, the time stamps must be translated from UTC to the local time zone where the crash took place (in this case, Central Daylight Time or CDT). When the plaintiff's expert did the conversion, he didn't account for DST in the local time zone. He reported:

> *The defendant's cellular records show an outgoing call that started at 6:43:25 PM and lasted until 6:43:53 PM for a duration of 28 seconds. These facts indicate that the defendant was on her cell phone at the time of or immediately before the crash.*

However, the CDR shows that this outgoing call occurred one hour after the crash at 7:43 PM CDT (00:43 UTC). Thus, the conversion from UTC to CDT is [-5] hours. Stated another way, the CDT time zone offset is UTC-5. The plaintiff's expert did not account for DST in the time conversion. Instead, he mistakenly used UTC-6 for the offset.

To correctly convert from UTC to local time zones, four items are required:

1. The UTC time stamp.

2. The local time zone (e.g., Eastern, Central, Mountain, Pacific).

3. The local date.

4. Whether the local time zone is affected by DST.

It is important to note that not all localities observe DST, and the dates when DST begins and ends each year change. To avoid mistakes, analysts can use appropriate computer functions or libraries that perform the conversions automatically.

As a result of this mistake, the plaintiff's expert issued his first revised report in which he corrected his error. In this report, he committed another error, which is described below.

Misunderstanding Handoffs

In the plaintiff's expert's next report, once again he concluded that the defendant was on the phone at the time of the collision. This time, he based his opinion on the fact that the CDR showed there were multiple handoffs between the mobile phone and the neighboring base stations just before the collision.

Handoffs occur when a cell phone switches from one base station, sector, or channel to another in order to stay connected to the cellular network[5,6]. Handoffs are also referred to as "handovers." Base stations are also referred to as "towers" in colloquial language. The plaintiff's expert stated these frequent handoffs occurred because the defendant was on her phone and that her phone usage caused the handoffs to occur. He wrote:

> *The defendant's cellular records show that her phone switched base stations several times just before the crash. These facts indicate that the defendant was using her cell phone at the time of or immediately before the crash.*

The plaintiff's expert did not account for the fact that a mobile cell phone autonomously switches among base stations to maintain the best connection to the network — even when it's not in use. Thus, mobile cell phone connections are handed-off among base stations, sectors, and even communication channels without any input from the user. Handoffs occur when a mobile phone moves out of range from one base station or sector and into range of another[5,6]. These handoffs can occur frequently when a mobile phone traverses the service borders of base stations or sectors. Handoffs occur even when the phone is not in use. For a handoff not to occur, the phone would have to be turned off or put in airplane mode.

Information in the CDR showed that the collision occurred in an area along the border between two base stations. Frequent handoffs, as those shown in the CDR, should be expected. The phone's user has no control over the handoffs. Additionally, handoffs among base stations, sectors, and channels occur even when a phone is not in use[5,7].

It was incorrect for the plaintiff's expert to attribute the frequent handoffs that occurred just before the collision to the defendant's phone use. Handoffs provide no evidence of phone use, as they occur autonomously — even when a phone is not in use. Once again, the plaintiff's expert could not support his opinion that the defendant was on the phone at the time of the collision. His methods did not result in knowledge or facts.

Misattributing Data Throughput

The CDR also contains information on data throughput — that is, how much data is transferred to and from the phone at given times. Sources of data throughput include user data, such as phone calls, messages, web browsing, streaming services, emails, etc., and control data. Control data includes channel assignments, power level assignments, quality-of-service metrics, etc. Control data are also used to facilitate handoffs.

In the third revision to his report, the plaintiff's expert again concluded that the defendant was on her phone at the time of the collision. This time, he attributed his conclusion to the fact that the CDR showed there was an increase in data throughput (or data usage) just before the collision. He reported:

> *The defendant's cellular records show a fourfold increase in data throughput prior to the accident. Both the bytes up (transmit) and bytes down (receive) data increased. These facts indicate that the defendant was using her cell phone at the time of the accident.*

Although the CDR did show an increase in data throughput just before the collision, it cannot be attributed to the phone user. Just as with handoffs, data usage can increase autonomously without any input or activity from the user.

Data throughput consists of two types of data: user-initiated data and network-initiated data[8].

User-initiated data result when the phone user interfaces with the phone and sends or receives data. Examples of user-initiated data include sending emails, texts, or multimedia messages; surfing the web; and posting messages, photos, or videos on social media.

Network-initiated data include information sent over the network's control channels. Control channels are special radio channels used by the phone and the base stations to establish and maintain a reliable connection. When the control channels are active, network-initiated data are being transferred, and data usage will increase. Additionally, this data usage can increase even when the phone is not in use. The phone user has no control over the network-initiated data. The control channels send and receive information without any input from the user. In fact, this process is transparent to the user[8,9].

The defendant's cellular carrier did not differentiate between user-initiated data throughput and network-initiated data throughput in the CDR. Many carriers do not. Data is data, regardless of its source. As a result, it was not possible to distinguish the two data sources. Therefore, the data throughput listed in the CDR could not be attributed to the defendant. In fact, the cellular provider stated that it:

> *[D]oes not retain records that can definitively show whether a transaction was a customer-initiated or network-initiated data transaction.*

Additionally, mobile phone apps can transfer data without any input from the user, increasing data throughput. This can occur when certain apps are running on a phone in either the foreground or background. For example:

- Google Maps can transfer data to and from the user without any user input when it's being used for navigation. This activity will increase data throughput.
- Streaming apps, such as iHeart Radio, Spotify, or Apple Music, will increase data throughput without any input from the user.
- A phone's email app could download a message to the phone with a large attachment, increasing data throughput — without any input from the user.

These are just a few examples of how different apps can autonomously increase a user's data throughput.

To distinguish the user-initiated from the network-initiated data would require an examination of the phone itself along with the CDR. Even then, it may not be possible to attribute all data transactions.

Conclusions

Although the CDRs are supplied in spreadsheets, it is important that reviewers of these spreadsheets have a solid understanding of cellular networks.

When reviewed by a qualified forensic engineer with a solid understanding of cellular networks, the following conclusions can be made about the information in the defendant's CDR:

- No voice phone calls took place immediately preceding or at the time of the collision.
- No text messaging took place immediately preceding or at the time of the collision.
- The handoffs that took place preceding the

collision occurred autonomously and do not indicate any type of phone activity by the defendant.

- The increased data throughput that occurred preceding the collision cannot positively be attributed to the defendant and do not indicate any type of phone activity by the defendant.

- The CDR provides no evidence that the ABC Auto Parts delivery truck driver was distracted by her cell phone.

This case study demonstrates the importance of retaining a forensic engineer knowledgeable in cellular network design and operation to review forensic call detail records. This constitutes the most reliable method to ensure accurate and reliable analysis of the records.

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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**.

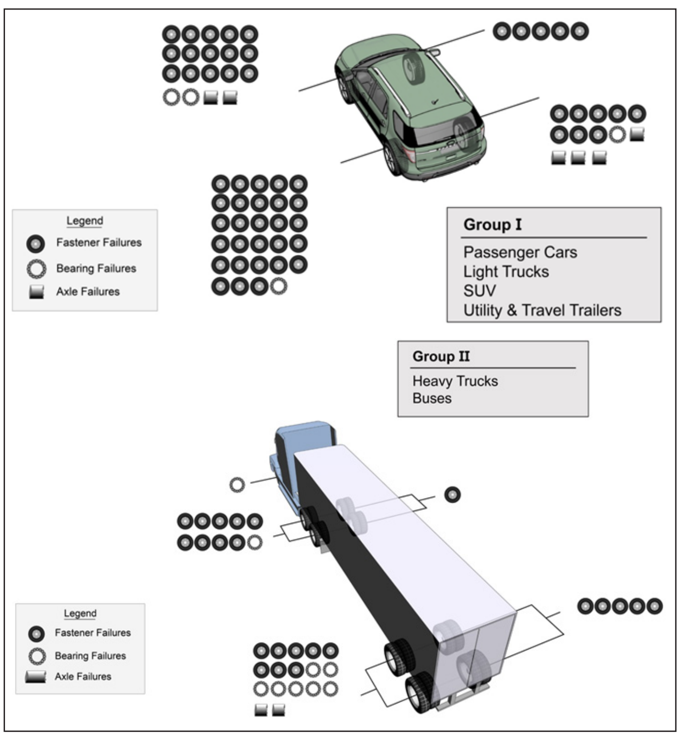

Figure 1
Summary of 100 wheel separation investigations. Group II includes tractor trailer combinations and single heavy trucks.

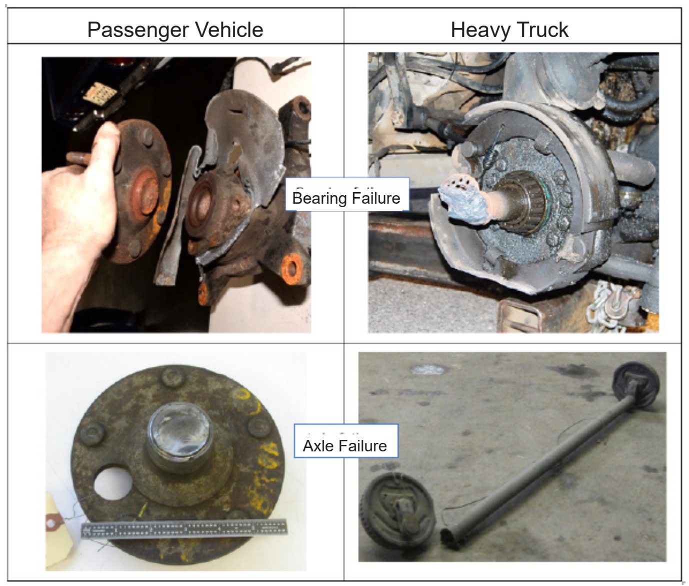

Figure 2
Examples of bearing and axle failures on passenger vehicles and heavy trucks.

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.

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

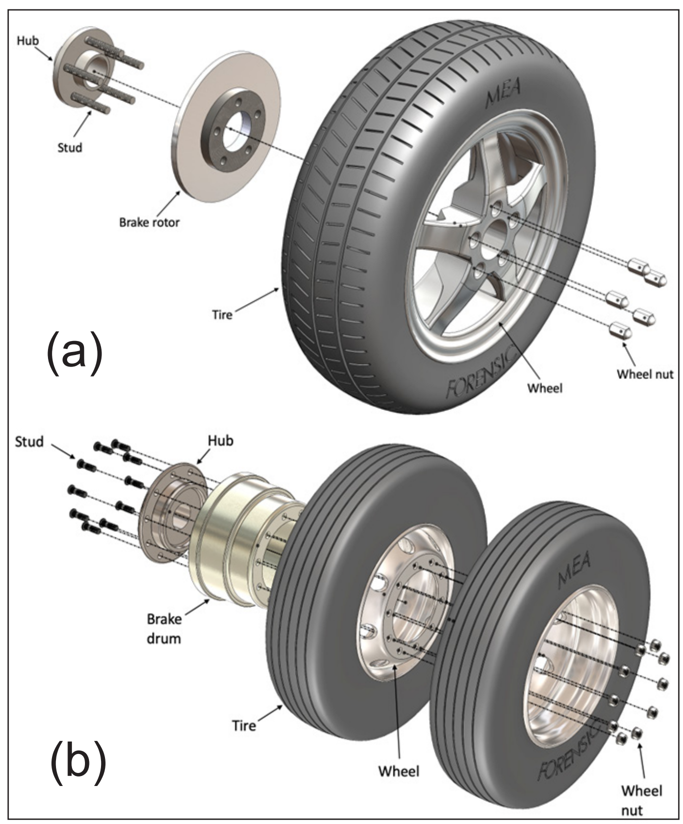

Figure 5
Axle end terminology for (a) Group I (passenger cars, light trucks, SUVs and utility and travel trailers) and (b) Group II (heavy trucks and buses).

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

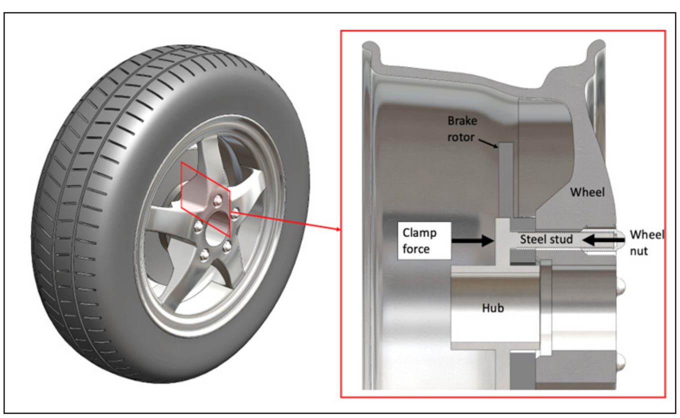

Figure 6
The wheels and brake drum are clamped to the hub between five studs and nuts.

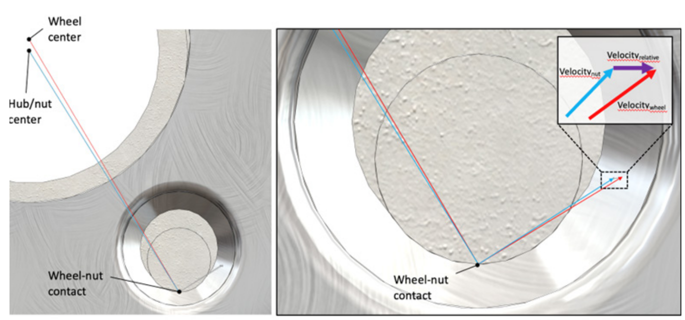

Figure 7
A left side wheel. Wheel turns counterclockwise in this view. Left: Axle weight causes axle to move down relative to wheel when relative motion between wheel and hub are permitted. Right: When wheel and axle are not concentric, there is a small relative velocity vector between the wheel and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

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 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**.

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.

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.

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

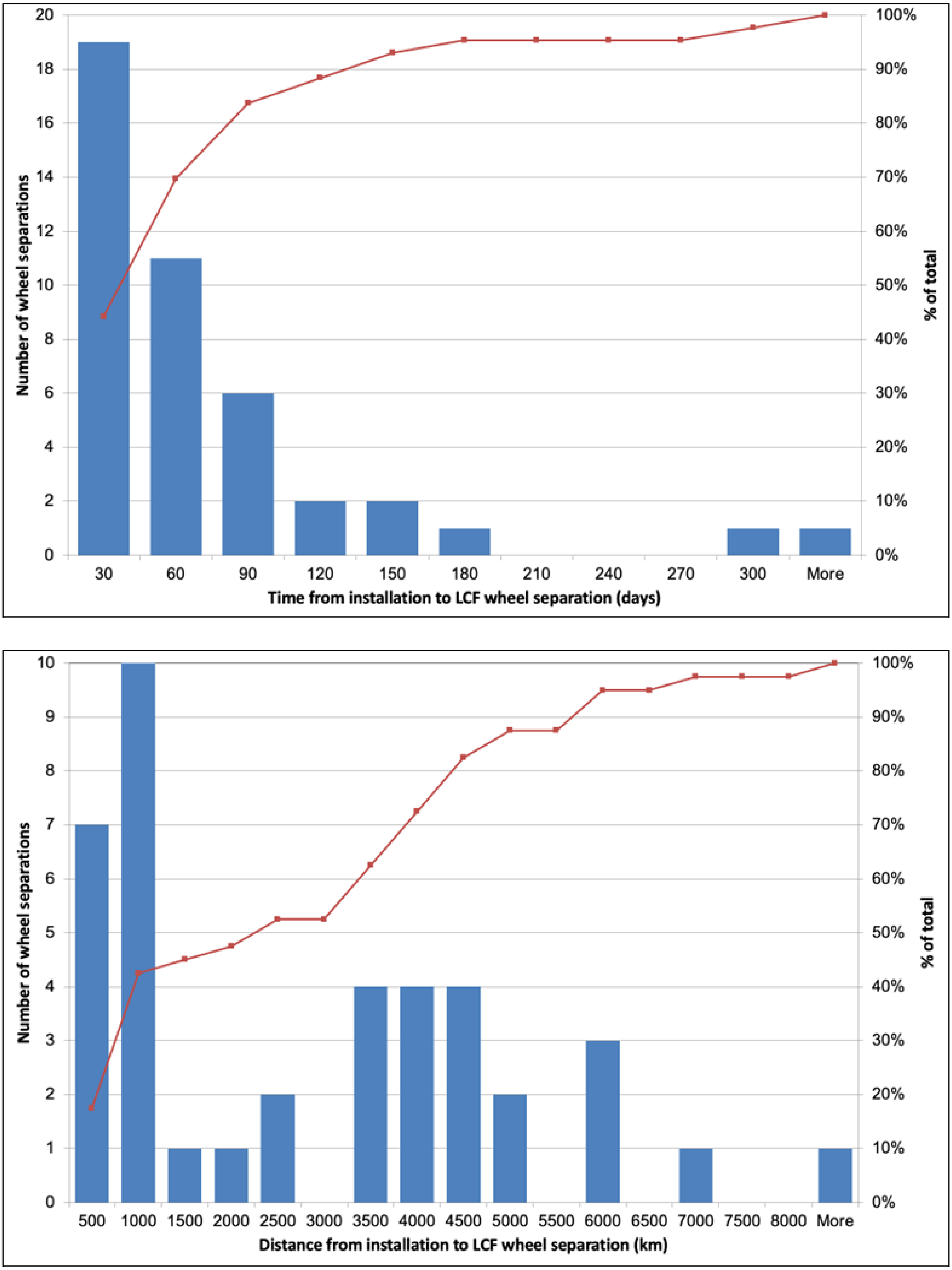

Figure 9

Time from installation to separation in LCF type wheel separations.

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.

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.

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.

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.

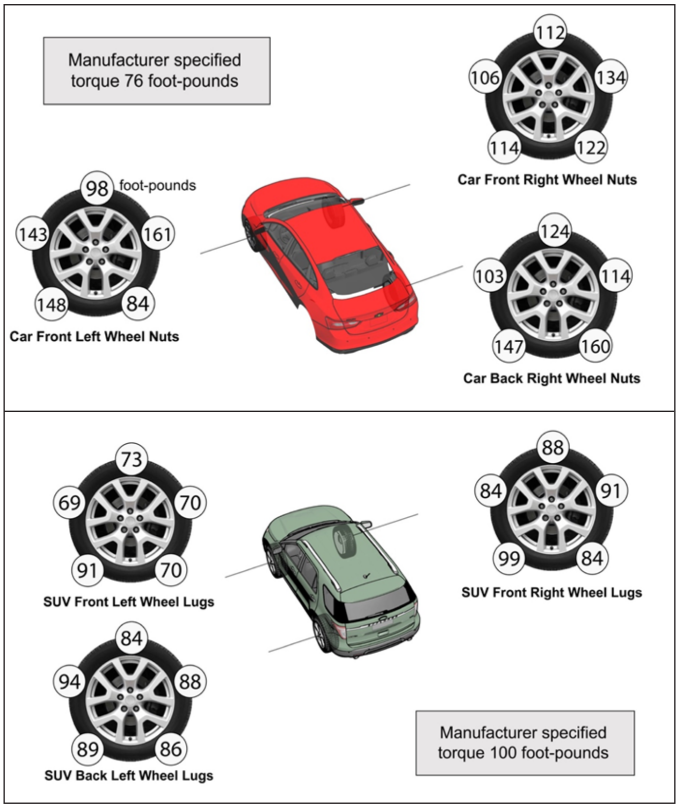

Figure 11
Top: Torque audit on a passenger car.
Bottom: Torque audit on an SUV.

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

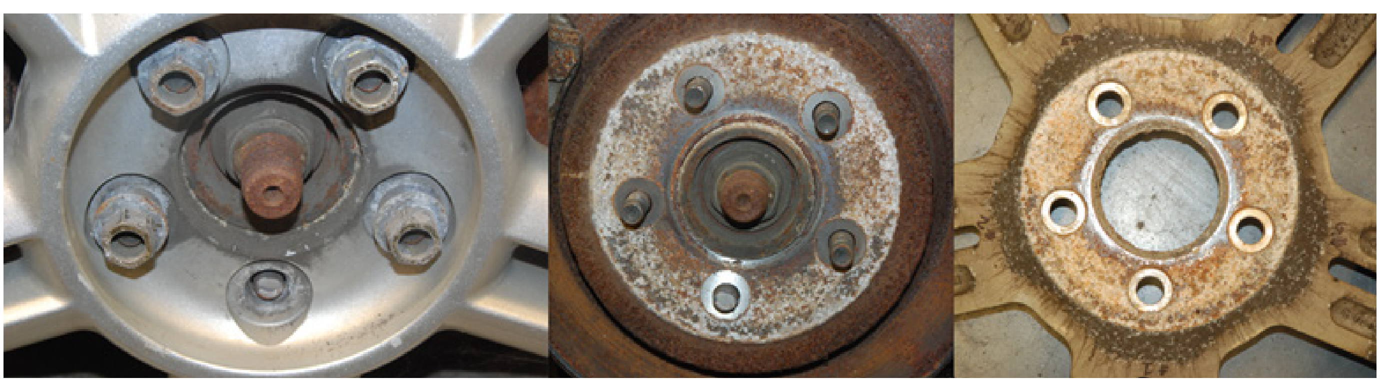

Figure 12
Left: One stud fatigue fracture on SUV right rear wheel. Middle and left: Corrosion and dirt on interfaces
(the five shiny rings around the stud holes correspond to circular recesses around the wheel stud holes).

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

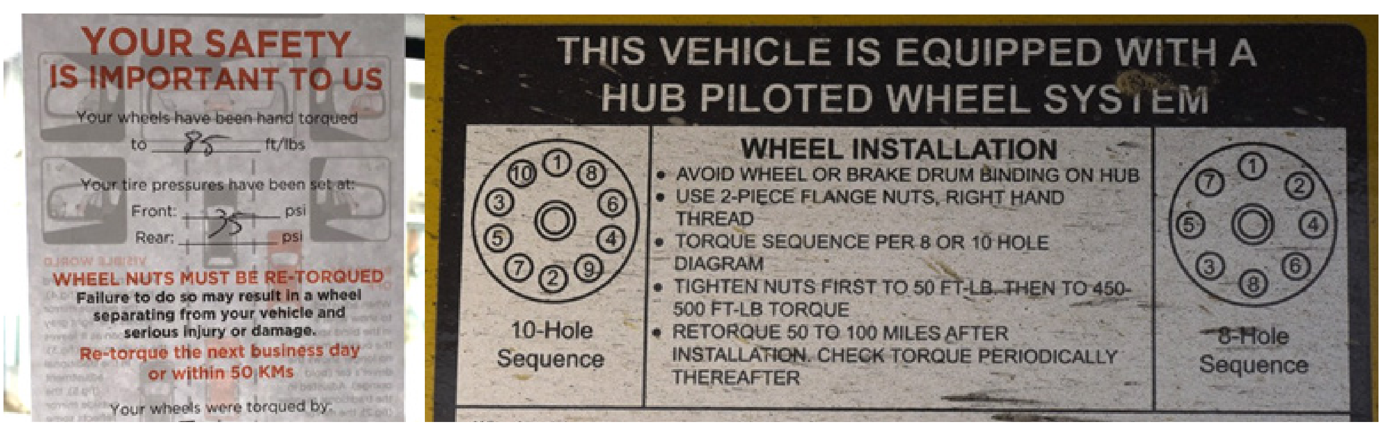

Figure 14
Left: One day, 50 km re-torque reminder for an SUV. Right: 50 to 100 mile re-torque placard on a commercial trailer.

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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FE Evaluation of Pedestrian and Worker Fall Incidents — the Evolution of Analysis Techniques and Safety Requirements

By Christopher B. Shiver, PE, DFE (NAFE 661S)

Abstract

Fall injury and fatality claims and legal cases involving ordinary pedestrians as well as employees/contractors at work sites have increased dramatically over the course of the author's 43-year engineering career. As a result, forensic engineers are frequently being contacted by insurers and attorneys to analyze these incidents. The need is to determine probable cause(s) and ascertain as to whether location features were designed, constructed, installed, manufactured, and/or maintained in accordance with the standard of care, including requirements specified in applicable codes and standards. The proper contemporary analysis techniques for these incidents are addressed in this paper as well as what constitutes proper basis for establishing a standard of care for involved installations and/or equipment. It will also expand on and update information provided in approximately two dozen past NAFE papers on various aspects of fall incident analysis, most of which are more than 10 to 30 years old.

Keywords

Forensic engineering, pedestrian, walkway, slip, trip, fall, stair, ramp, handrail, guard

Introduction

Pedestrian and worker access features that enable walking, ascending, or descending are a widespread part of the built environment in buildings, facilities, and public spaces, resulting in significant potential for hazardous incidents. The standard of care, including legally enforceable code and ordinance requirements for installation and maintenance of those features, has evolved significantly with a trend toward more stringent specifications, especially in the last 30 years. These standards and requirements are based on elimination of features that are generally considered to be trip, loss-of-balance, and/or fall hazards. Evaluation of claims or allegations of an injury being potentially related to a deviation of one or more access features from those standards of care requires knowledge on how those features are constructed and maintained, what specific standards are applicable, and how deviation of a feature from those standards could have been a factor in a specific incident. This paper addresses these issues and presents a few summarized case studies.

Access Features

Walkways or surfaces originally installed without elevation changes (not necessarily level) are the most common type of pedestrian or worker access feature. Of particular significance are doorways, including thresholds and landing areas on either side. For significant elevation changes, ramps and/or stairs are most commonly utilized. In many cases, handrails or guards (guardrails) are necessary on the sides of stairs and ramps to assist pedestrian stability, help identify the elevation change, and/or protect against falls from heights.

An often ignored or forgotten pedestrian access feature is proper illumination of other built features (both indoors and outdoors), especially at night. Another area of increasing concern for pedestrian access and safety are paved surfaces intended primarily for vehicle traffic, which could also be reasonably expected to be used by pedestrians, especially in parking areas. Of special concern are walkways and elevation change features provided primarily or solely for workers on commercial, industrial, and construction sites. At those restricted locations, falls from significant heights are a major concern.

The issue of walkway surface traction for proper pedestrian safety is of great importance. However, due to the scientific complexities of this issue, it is more properly the

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subject of separate papers devoted to that topic[1,2,3,4,5,6,56]. Therefore, this paper mentions means for documenting pedestrian access features in cases where a slip is claimed, but does not address surface slip resistance evaluation or standards of care.

Codes, Standards, and Laws

The most often-cited regulations are building and egress codes, government regulations, and/or national standards, which, in most localities, are adopted (possibly with amendments) by ordinance, frequently in accordance with state law. A listing and brief description of past and current nationally prominent codes is provided in **Figure 1**[7,8,9,10,11,12,13,14,15,16,17,18,19,20].

Since 2000, either the International Building Code (IBC) or the Life Safety Code (LSC) represents the law and the standard of care for construction (and, in many cases, maintenance) of pedestrian access features in most locations within the United States. One important note about both the LSC and the IBC and their predecessors is that most of the requirements governing pedestrian access features are located in single chapters covering means of egress (MOE) and accessibility for persons with physical challenges. However, these codes also include separate chapters for differing types of occupancies that may include additional special requirements for pedestrian access features at those locations.

The key factor with all of these codes is that they are only recommended for use by their publishing organizations, though they do serve as a widely recognized standard of care. They are only enforceable as a matter of law when required by the state or municipality where a property or structure resides. In addition, the enforcing authority (frequently referred to in the codes as the "authority having jurisdiction" or AHJ) may adopt any of these codes with its own amendments or even create its own code.

For free-standing residential structures housing one or two families only (or, in some locations, a slightly greater number, such as in a row of townhouses, based on AHJ enforcement), related residential codes have developed with generally less complex — and to a certain degree less

Code Type	Code Name/Publisher Acronym	Effective Yrs	Comments
Egress	Building Exits Code (BEC) - NFPA 101	1927 to 1963	Covered only facility means of egress (MOE) features
	Life Safety Code (LSC) - NFPA 101	1966 to present	Replaced BEC to cover MOE and other fire prevention/protection and emergency features
Building	National Building Code (NBC) - NBFU/AIA	1905 to 1976	First nationally recognized building code, created by property insurers
	Unified Building Code (UBC) - ICBO	1927 to 1997	One of three U.S. regional model building codes, primarily in Western states
	Southern Standard Building Code (SSBC) - SBCC	1945 to 1973	One of three U.S. regional model building codes, primarily in Southeastern states
	Standard Building Code (SBC) - SBCCI	1973 to 1999	Update/replacement for SSBC, primarily a marketing name change
	BOCA National Building Code (BOCA) - BOCA	1950 to 1999	One of three U.S. regional model building codes, primarily in Midwestern and Northeastern states
	International Building Code (IBC) - ICC	2000 to present	Created by cooperative merging of three U.S. regional model building codes
Residential	One- and Two-Family Dwelling Code - CABO	1971 to 2000	Cooperative effort of three U.S. regional building code organizations, for houses
	International Residential Code (IRC) - ICC	1998 to present	Successor to CABO code for one- and two-family dwellings
Disabled Access	ADA Standards for Accessible Design	1991 to present	Based on U.S. federal legislation and regulations, mandatory for many public facilities
	American National Standard A117.1 - ANSI	1961 to present	Represents a design professional standard of care but only limited adoption by law or codes
Maintenance	BEC and LSC	1927 to present	Has general maintenance requirement specific to MOE
	International Property Maintenance Code (IPMC) - ICC	2000 to present	Provides maintenance requirements for all properties
	International Fire Code (IFC) - ICC	2000 to present	Provides construction and maintenance requirements for MOE and other fire safety features

Figure 1

Codes for pedestrian walkway features (means of egress). Note: Prior to 2000, the three Model Building Code organizations published some MOE maintenance requirements in their building codes and/or in separate codes.

stringent — requirements, including for pedestrian access features. Regulations and standards associated with pedestrian routes provided for access by persons with mobility impairments may also apply, depending on the type of facility and local authority requirements. Requirements for maintaining pedestrian features in a safe/usable condition also exist, depending on local authority adoption of available codes or their own specific requirements.

An important building code concept is "grandfathering" where the code that was mandated by the AHJ at the time of construction continues to apply to the structure or property up to the present day — even if newer code editions have more stringent requirements for pedestrian access and other features than exist at that property. Typically, if the structure or property undergoes a significant renovation, has a change in occupancy (usage or function), or if the AHJ deems that a particular feature not meeting the most current code requirements must be updated for public safety, then the newer requirements come into effect.

Unique to the Life Safety Code are differing requirements for new construction versus renovations where existing features (especially stairs and ramps) are left in place or are themselves repaired or improved. The LSC provides that these existing features may retain their original dimensional properties if they meet somewhat less stringent specific requirements. This is permitted because attempting to rebuild a feature (such as a staircase or ramp) with greatly differing dimensions may not be practical without major demolition and reconstruction in many buildings. Determining the actual construction (and/or major renovations) date(s) for a particular property can frequently be obtained online through the appropriate property tax assessor's office from design drawings prepared for the facility construction or renovation — or from the AHJ.

For the special case of protecting workers from falls at locations where they are employed that include out-of-the-ordinary potential access hazards, the primary force of law are the federal Occupational Safety and Health Administration regulations[21,22,23,24,25,26,27] as well as regulations from other agencies governing specific types of industries. Many states have also adopted additional provisions for worker safety. There are also two American National Standards[28,29] that provide standard of care provisions. Some of these ANSI provisions have been adopted by OSHA or other governing authorities for both permanent-type workplaces and construction sites, respectively.

An important explanatory reference for interpreting code provisions regarding pedestrian access features is the companion handbooks provided with the more recent editions of the LSC by the National Fire Protection Association (NFPA)[30]. Most editions of the LSC also include Annex A explanatory material, which provides non-mandatory advice or further details on the basis of certain code requirements. In addition, a useful standard of care reference for design professionals with regard to pedestrian access features (including some features not necessarily addressed by codes) has been published and updated for more than 80 years by the American Institute of Architects[31]. ASTM International first published its *Standard Practice for Safe Walking Surfaces*[32] nearly 30 years ago. However, it is not typically referenced in codes/ordinances (except for explanatory/informational reference in the LSC) or necessarily well known outside the engineering community. Therefore, it may not necessarily be accepted as a standard of care for some properties or jurisdictions.

Evaluation of Access Features

When assessing any access area alleged to have been involved in a pedestrian injury incident, it is important first to identify all of the access features that potentially could have been a factor in the described sequence of events. This is followed by determining how each of those features can be assessed objectively for comparison to applicable standards. As part of this initial assessment, the overall incident area and the individual features should be photographed. It may be helpful to photographically and/or video-graphically recreate the probable views of the reported pathway of the incident claimant/plaintiff based on the report of that person and any witnesses.

If possible, the incident area should be viewed and documented in lighting conditions similar to those reported. For outdoor inspections, the weather conditions at the time of the incident may need to be considered, including water flow or icing conditions. If there is significant delay between the dates of incident and inspection, then determine if there is any photographic evidence or online views of the area closer to the time of the incident for analysis of modifications or changes to the physical features.

Of particular importance is whether the property owner/manager has modified any of the pedestrian features of interest — either in response to the incident or for other reasons. Additionally, outdoors it can be important to document the location of the pedestrian access feature(s) claimed to have been involved in the incident relative to both adjacent building exits and also any marked ADA access features. Note: For measurements of details, such as stair treads, risers, and rail features, the author recommends that parameters be recorded with an accuracy of $\pm^{1}/_{16}$ inch. This is of sufficient precision to compare parameters to typical code requirements. Workmanship limitations for the construction of most pedestrian access features is such that greater precision is typically meaningless. In cases involving complex dimensional details, three-dimensional imaging/scanning may also be useful. Any walking surface instability, damage, or deterioration and its cause should also be documented in detail.

Flat Walkways

With "flat" walkways, the primary details to document are any elevation changes as well as clear width. Sloped surface grades and lengths between grade changes should be recorded. Additionally, document heights or profiles of any abrupt elevation changes, including doorway thresholds or trim strips between differing floor surfacing materials (for these types of investigations, a carpenter's or machinist's profile gauge may be useful), as shown in **Figures 2** and **14**.

A specific type of abrupt elevation change often found in parking decks — and the subject of a number of trip claims — are expansion joints with or without covers. Of particular interest, especially in outdoor decks and walkways, are abrupt elevation changes at joints or fractures in surfaces that appear to have occurred after construction.

When measuring elevation change heights, it can be important to document the vertical change at multiple points along the walkway width because variations are frequent. It's important to document surrounding conditions that appear to have possibly contributed to the elevation change initiation or progress (e.g., trees and roots adjacent to sidewalks). Specifically for sidewalks, if appropriate for the site, a small diameter probe rod may be useful for detection of voids or differing bearing strength soils beneath areas where differential settlement appears to have occurred (use appropriate safety practices if underground utility features may be present).

Figure 2
Use of profile gauge to measure elevation change details.

For elevation changes at or close to doorways, important details include size of landing areas on either side of the door or doorway, height of those landings relative to each other and the door threshold, width of the landings relative to the doorway width, and swing or slide details for the door(s). The type of floor or walkway surfacing materials should also be documented. A tool that may be particularly useful on sloping surfaces or for documenting any type of elevation change (especially over longer distances) is a laser-type leveling or scanning instrument for accurately establishing the difference in elevation between two or more locations.

Stairs

For stairways (including single steps or risers), it is most crucial to document the depth of each tread and height of each riser, typically at multiple points across the width of the stairway. The LSC and its associated Handbook, in Annex A for the stairway requirements, provides useful guidance on how to determine those parameters, including for stairs where overlaps, tread slopes, or soft surface materials are present. In most cases, the author has found that a steel carpenter's square combined with a short carpenter's level are the most efficient and accurate means for obtaining these measurements, though other references specify potentially effective alternative methods[33,34,35]. Curbs are a special case — basically a single riser step — and the documented parameters should include the height (including any variations over its length), any damage or deterioration, and any added coloring or other visual enhancement.

For stairways, the presence or absence of handrails and/or guards should be documented, keeping in mind that, depending on the stair age and configuration, they may not be required, required on one side only, required on both sides, or even required at intermediate locations for wide stairs. Handrail and guard height must be measured as accurately as possible above the leading edge of treads (nosing); the LSC Handbook illustrates this as the height above the imaginary sloped line that connects each tread nose. For this measurement, a combination of a ruler or tape and a 4-foot carpenter's level is best (a graduated level is ideal). The distance the rail extends beyond the topmost and bottommost risers on a staircase may also be of importance.

Other critical handrail dimensions involve determining if it has continuous "graspability" and include the cross-sectional profile/dimensions of the rail (another potential application for a profile gauge), the clearance between the rail and any adjoining wall or other surfaces, and how the rail supports and balusters are connected. The LSC Handbook has a good discussion and illustrations on graspability and these other rail details.

Whether they occur on stairs, ramps, or a level height, several details are critical for claims involving a person that fell over or through a guard system or lost balance and fell due to a loose or failed guard or handrail. This includes spacing between balusters as well as the details on how the rail system is or was anchored to the walkway or ground, walls, and posts. Failed handrail or guard system evaluations may be complicated by expedited post-incident repairs and possibly even disposal of removed hardware. This may necessitate reliance on photographs, statements, and repair documents — or even similar exemplar rail systems at the same property. Further details on evaluating guards/guardrail systems involved in incidents are also available[36,37,38,39].

Documenting the presence or absence of features that visually delineate the tread and riser boundaries/edges on stairs can be of importance in many cases. It is not uncommon for the original incident claim or later disclosure to allege that visibility of those features contributed to the occurrence. Photography focused on objectively documenting the visual contrast between those features (or lack thereof) can be most helpful.

Evaluations of pedestrian features should consider whether a particular feature that was alleged to have been a factor in an incident can be readily perceived by persons[40]. Another issue with some stairways is the stability of the treads or tread surfaces, especially as they age. Some stair treads may deteriorate, and, in some metal staircases with inserted wood or concrete treads, the supports or fasteners may loosen, resulting in treads that shift under a user's weight (**Figure 3**). Therefore, in cases where it was alleged that a user lost balance due to movement of the staircase or treads, careful examination of the entire structure (including the treads) for signs of damage, deterioration, or non-rigid conditions is critical. Carpet-covered stairs can pose additional visualization and footing challenges, particularly if the carpet fit is loose. Those details should also be documented.

Figure 3
Concrete stair tread attachment to steel frame.

Ramps

For ramps, the most critical dimensional property is the slope, including the consistency of that slope from top to bottom and side to side. Slope can be properly measured with either a mechanical-type instrument or an electronic "smart level"-type instrument. When using many electronic instruments, it is critical to set or calibrate the zero slope value using a reference known level surface, in accordance with the manufacturer's instructions, and to document that process.

Ramp clear width is also an important parameter. For ramps, as with stairways, the presence or absence of handrails and/or guards/guardrails (including combinations of both) as well as their dimensional details are important. The same dimensional parameters should be measured for rail systems on ramps as for those on stairs. Some ramps with open sides (whether or not rails are present) may also have curbing or other boundaries whose presence, height, and width should be documented.

An increasingly widespread type of exterior ramp is a curb ramp, which provides for elevation change access across a curb. They are of two types: ramps formed or cut into the curb and sidewalk (standard type) or extended (built-up) curb ramps that are built out from a curb onto the lower elevation paving (**Figure 4**). Curb ramps

Figure 4
Combination standard and extended curb ramp.
Lack of side flares on the extended portion presents
a trip hazard to pedestrians approaching laterally.

that are not delineated by rails or other barriers to prevent pedestrian cross traffic must have sloping side flares, so measurement of those side flare dimensions and slopes is of the utmost importance. When measuring ramp slopes, it is essential to document the direction and magnitude of the maximum slopes. As with stairs, the documentation of the visual contrast between ramp features (especially on curb ramps) is an important part of any inspection. Further guidance on design of curb ramps — and the sidewalks they are a part of — is provided in a federal government informational publication[41].

Illumination

In many fall injury claims, there may be an allegation that inadequate lighting prevented the injured party from visualizing the pedestrian pathway, especially at elevation changes. This can be a potential factor indoors (potentially at any time) or outside — usually for incidents occurring in twilight or nighttime conditions. The engineering investigator should recommend that the inspection include an illumination study, if there is any reason to believe that lighting conditions may become a factor in a fall incident claim or case.

The first step in evaluations where illumination was potentially a factor is to determine (as much as possible) the factors present at the date and time of the incident that would have affected the light intensity (both natural and artificial) on the pedestrian access features of interest. The goal with this initial research is to prepare for an inspection during conditions that replicate the incident lighting conditions as closely as possible.

The first factor to consider includes the number, type, and location of all artificial luminaires (including which were actually illuminated at the time of the incident) that could have affected the light intensity in the subject area. Of great interest is any shadowing of that light produced by permanent or movable physical features in the area or, in some cases, pedestrian or vehicle traffic. Outdoors, shading by trees and shrubs may need to be considered as a factor, including seasonal effects on foliage. Natural lighting, including lighting through windows, doorways, and skylights, must also be considered.

For natural lighting conditions during the day time, the sun angle and elevation (as well as any cloud cover) may need to be considered for the specific incident date and time. For night time or during twilight (the time before sunrise or after sunset when some solar illumination of the sky is still present), any sunlight effects as well as lighting from the moon need to be considered. There are a number of reputable online sources that will provide both sun and moon data (sky locations for each as well as lunar phases and percent illumination) at any given date and time at a specific GPS location or address[42]. Further available online is daily/hourly weather data for regions, based on the closest National Weather Service station[43]. Use of a professional-quality, properly calibrated illuminance meter (in accordance with the manufacturer's instructions), which can be placed on walkway surfaces, is critical for these types of evaluations.

Special Work Site Considerations

In addition to normal pedestrian features found at publicly accessible locations, industrial, commercial, and construction work sites limited to authorized workers typically have additional hazards for access. These can include elevated platforms with access stairs, ladders, or ramps (including stair/ladders that don't conform to the normal building code dimensional limitations) constructed of metal or fiberglass/plastic solid material or gratings. Although typical trip, slip, and fall hazards may be present at these locations, one of the most prevalent concerns is a fall from height.

At any location where a fall has occurred, evaluation of fixed fall protection features (if any), such as guardrails, gates, and ladder cages, should be performed. A federal government advisory document provides further guidance for evaluation of these types of features[44]. Where fixed fall protection is absent or appears inadequate, the evaluation should include provisions made for providing the workers with fall prevention and arrest equipment, including harnesses and lanyards. Provision of adequate strength lanyard anchor points can be a critical part of these types of evaluations, as are the employer's policies, procedures, and training provided to the workers regarding accident prevention and use of personal protective equipment[45,46].

In some cases, appropriate warning signage may be mandated or necessary. For some work sites — especially construction and demolition sites — the presence of permanent or temporary floor, wall, and/or roof openings may require special designs or protection provisions for fall prevention (**Figure 5**)[47]. A special case for work sites involves workers falling off of heavy vehicles or mobile machines, including construction site machinery, locomotives, airplane access equipment, etc.[48]. Additional considerations are necessary for worker protection during use of temporary scaffolding or other similar access hardware at construction sites[49].

Figure 5
Temporary floor opening at construction site requiring fall prevention features, such as covers or barricades per OSHA and ANSI requirements.

Another category of special cases, which may or may not technically involve a work site, affects situations and equipment for recreational activities. For example, activities such as natural surface or wall climbing, high diving, hunting and fishing, and amusement parks may have standards established through association groups or standards organizations, such as the American National Standards Institute, ASTM or Underwriters Laboratories (UL)[50,51].

Site Evidence Considerations

In many cases, the physical evidence may have been altered or destroyed following the incident. There are many instances where a property owner/manager, upon discovering that an incident has occurred, may have decided that improving, repairing, or even replacing pedestrian access features of interest is necessary. When a potential client first calls regarding possible retention for a case, it is advisable to query them regarding the site evidence conditions. Important actions may include a timely proper legal request regarding preservation of the evidence and prompt scheduling of an inspection (if needed) to avoid loss or spoliation of evidence. A further consideration for scheduling is to determine if weathering and pedestrian or vehicle traffic is likely to alter the pedestrian access features if an inspection is delayed.

When evaluating cases where some or all of the critical evidence has been altered or destroyed, photographs and witness statements (if available) can be evaluated to see if clear indications of feature compliance/deviation in regard to the relevant codes or standards can be determined. In some instances — where photographs are provided showing the intact evidence conditions — then a photogrammetric study may actually enable determination of key dimensions. Such a study may be enhanced by a site visit to measure intact features (shown in the provided photographs), which can be used as dimensional references. At some properties — where seemingly identical features are still in place or at locations other than where the incident occurred (e.g., apartment complex walkways, ramps and staircases) — these exemplars may be useful for acquiring dimensional and layout details when the actual subject features are no longer present.

Determination of Access Features Acceptability or Deficiency

After performing a thorough study of access features at a reported incident location, it is important to identify what codes, standards, and/or laws define the requirements and/or standard of care for construction and maintenance of those features, based on when the structure was built or renovated. **Figure 6** provides a listing of most of the

Code	Flat Walkways	Stairs
BEC/LSC	No abrupt level change >¼" and < 4" since 2000 ed. 1:2 bevel on changes >¼" and <½"	Risers <7 to 8" Treads >9-11" Variations: <$^{3}/_{16}$" or $^{3}/_{8}$"
IBC	No abrupt level change <4" since 2000 ed.	Risers <7" Treads >11" Variations: <$^{3}/_{8}$"
IRC	No specific parameters	Risers <7¾" Treads >10" Variations: <$^{3}/_{8}$"
RMCs*	Abrupt level changes typically not addressed	Risers <7¾ to 8" Treads >9" Variations: "uniform" or <$^{3}/_{16}$" or $^{3}/_{8}$"
ADA	No abrupt level change >½", since 1980 1:2 bevel on changes >¼" and <½" since 1986	Stairs are not allowed in ADA accessible routes.

Figure 6
Key code parameters for certain pedestrian walkway features (means of egress).
*RMCs refer to the three regional model codes as well as the AIA NBC in effect in portions of the United States before 2000 (see **Figure 1**).

widely recognized and adopted codes and standards in the United States. A key concept when utilizing the building and egress codes is understanding what constitutes the means of egress, since these codes cover those indoor and outdoor features at buildings and facilities.

The 2024 edition of the LSC defines the "means of egress" as a continuous and unobstructed way of travel from any point in a building or structure to a public way. It further defines the "public way" as a street, alley, or other similar parcel of land essentially open to outside air deeded, dedicated, or otherwise permanently appropriated to the public for public use and having a clear width and height of not less than 10 feet. The LSC Annex A Explanatory Material additionally explains the means of egress includes courts and yards — and that reaching the public way means persons can move away from a building unimpeded, including in crowded conditions. It should be noted that older code editions had more limited means of egress scope definitions. If the evaluation potentially involves compliance of pedestrian access features within what appears to be a pathway designated for ADA accessibility, then the definitions and descriptions of an "accessible route" as provided in the ADA accessibility regulations and standards are of great importance.

Flat Walkways

For indoor same level walkways, the current codes typically require flat level conditions without abrupt level changes, unless a compliant ramp or stairs is used — **Figure 6** provides details for each code. The LSC Annex A additionally provides a commentary discussing how small changes in elevation should be avoided due to increased occurrence for missteps due to the difficulty in visualizing them — and advising on how to increase their visualization if their construction is unavoidable. Since many of these small abrupt elevation changes in outdoor walkways are attributable to pavement condition changes, a critical factor (in many cases) may revolve around whether property maintenance requirements adopted into law by the AHJ requires the property owner to maintain walkways in a safe condition. Where adopted, the International Property Maintenance Code (IPMC) holds the property owner responsible for maintaining walkways, stairs, ramps, driveways, and parking spaces in a proper state of repair and safe condition.

Stairs

Stair treads and risers have had dimensional limits dating back to the earliest codes; however, those restrictions have generally (though not always) become more stringent over time — **Figure 6** provides details for each code. Some of the earlier codes also contained an archaic provision believed to be dated back to the 17th century for stairs, requiring the dimensional sum of the height of two adjacent risers and the depth of the tread in-between to be between 24 and 25 inches. However, this formula has generally been found to have little use in consistently reducing hazardous stair configurations (as explained in the LSC Handbook), and the advent of the IBC resulted in its final removal from the nationally recognized codes.

One important provision for stair treads equipped with attached full or partial depth walking surfaces coverings or finishes (a good example is wooden or concrete stairs with a leading edge or nosing metal plate installed) is that these features maintain a true level tread surface without any added trip hazard. Another evolving set of requirements to be aware of are those for the allowable curvature of tread leading edges (nosings) and overhangs between adjacent treads. The codes also have requirements dealing with whether or not open risers are permitted on certain types of staircases. Additionally, the codes have special dimensional requirements for winding or spiral type stairs, though these are generally considered more hazardous than standard stairs per the LSC Handbook.

Another major evolving set of requirements in the codes has been those requiring the use of handrails on stairs and their dimensional parameters. Depending on which code and edition is referenced, handrails have always been required on at least one side of a staircase, except for some low height flights. In earlier codes, handrails were required to be between 30 to 34 inches above the tread leading edges (in line with the riser). Starting in the 1980s, anthropomorphic studies caused the LSC to lead the way in raising that range — ultimately to the current 34 to 38 inches with allowance for the top rails of 42-inch-high guards with acceptable graspability to also serve as handrails.

Another evolving requirement in the codes involves details for graspability of handrails. Required in some codes for at least 40 years are rail cross-sections, which permit a wide range of hand sizes to exert a power grip with the fingers wrapped around and under the rail. The LSC Handbook provides useful diagrams illustrating these concepts and showing varying handrail shapes/sizes and their acceptability for use — notably, "2 x 4" or larger size lumber is not considered acceptable.

Over time, the codes have added and then tightened a requirement for handrail clearances to adjacent walls and how handrail supports should be configured to prevent interference with grasping. The codes also have varying and increasing requirements for how far handrail coverage must extend beyond the top and bottom ends of a staircase — and when and where additional intermediate handrails are required for wide stairs. For example, the LSC currently requires that new handrails continue at least 12 inches beyond the top riser in a level position and sloping down at least one tread width beyond the bottom riser. It also requires that a sufficient number of handrails be installed such that there is at least one within 30 inches of any staircase pathway, especially in the means of egress pathway.

Uncorrected deterioration or damage to stairways and handrails (for rails, see further discussion below under "Guards or Guardrails" section) that results in either dimensional changes that affect code compliance or user instability fall into the same category as discussed above regarding maintenance requirements for flat walkways. Where enforced, the IPMC requirements specifically mandate that property owners/and managers keep stairs and rails in a proper state of repair and safe condition.

Ramps

The maximum allowable value for the critical ramp parameter, slope, has become increasingly more stringent over time. In some of the earliest codes, the slope was allowed to be as steep as 1 in 6, whereas the most current codes require a slope no steeper than 1 in 12 (the current LSC allows existing ramps to be not steeper than 1 in 8, and the current IBC & International Residential Code allow ramps that are not part of the means of egress to be not steeper than 1 in 8).

The Building Exits Code (BEC) and older LSC editions allowed for differing ramps slopes based on the overall elevation change for the full ramp. Ramp slope can be of particular importance for exterior ramps that were wet at the time of an incident, since increasing slope will typically lower the effective slip resistance. As with stair tread and riser dimensions, older editions of the LSC and the BEC provided for differing slope limits, depending on the required width for an egress ramp.

Ramp handrail requirements are generally similar to those for stairs in any given code edition. It is important to understand that handrails can also help to delineate that the sometimes subtle elevation change of a ramp slope is present, potentially increasing user awareness. For curb ramps, rails are typically not required unless side flares are not provided (**Figure 4**), in which case rails or some other physical barrier or indication of the dropoff from the walkway onto the ramp may be mandated.

Where side flares are provided with a ramp, the typical code requirement is (and has been) that the slope not exceed 1 in 10. Deterioration of ramp surfaces is addressed similarly by the applicable maintenance code (including the IPMC where implemented) as a type of walkway surface. Extended (or built-up) curb ramps, in particular, are susceptible to edge damage where their material is at its thinnest, which can result in abrupt change in elevation trip hazards (**Figure 7**).

Guards or Guardrails

Within the building and egress codes, there has been a fairly consistent requirement that any level walking surface with an edge dropoff more than 30 inches (may differ in some locales) above the surrounding grade or level is required to have a guard system to inhibit pedestrian falls. The typical minimum required height for the top rail of these guard systems has been 42 inches. However, for stairs, differing code editions have permitted lower height guard and handrail combinations. And, in some codes, an open side guard requirement is based on the number of risers.

Evolving over time have been the provision and dimensional requirements for the intermediate rails, balusters, or other barriers that prevent persons (especially children) from falling through an intact guard system. Current requirements typically mandate that openings within guard systems be no greater than 4 inches with exceptions for certain types of installations. This is based on minimizing the risk of a child's head passing through or becoming entrapped in the barrier.

Figure 7
Extended curb ramp edge material loss potential trip hazard.

Important for guards and handrails — particularly where a fall incident is alleged to have occurred due to a rail system failing — are the strength requirements for these installations. These can also apply in cases where a handrail or guard/handrail combination on a stair or ramp is alleged to have flexed excessively while being used for balance. These strength requirements have generally evolved and become more stringent over time with quite a bit of variation between different codes, especially in earlier editions.

The earlier codes typically only had a basic top rail single point load resistance requirement whereas, when the IBC's requirements are enforced, the handrail or guard top rail must withstand a concentrated load of 200 pounds, a uniform load of 50 pounds per linear foot, and the intermediate portions of the systems must withstand a concentrated load of 50 pounds with a further reference to ASCE 7[52]. The International Code Council (ICC) also prescribes methodologies used by certified labs testing manufactured guard systems in AC 174[53]. Generally, complete analysis of a guard system or handrail support failure may involve structural engineering analysis and/or component (evidence or exemplar) testing for comparison to the applicable code loading requirements.

Many rail system failures are caused by weakness at the points where the system components are connected to the building structure. These weaknesses may be due to design, installation, and/or maintenance deficiencies. As with other pedestrian access features, the AHJ's property maintenance provisions would apply. If the IPMC is enforced, then it has a specific section requiring that the load-bearing capacity of rail systems be maintained by the property owner/manager.

Illumination

Dating back for at least 60 years, the various building and egress codes have required that walking surfaces be illuminated to a minimum level of 1.0 foot-candle (fcd). There are some exceptions (primarily related to performance venues) that are allowed to have specified reduced illumination levels while a performance is occurring. Recent editions of the LSC have increased the required value for stairs to 10 fcd. Maintenance of these illumination levels is generally required by the applicable codes. In some locales, older housing codes permitted illumination based on usage of a minimum wattage incandescent lamp.

Summary

The final determination to be made in any access features evaluation is whether or not any deficiencies identified may have been a probable or possible cause for a specific alleged injury incident. In some incidents — where the injured pedestrian can specifically identify a pedestrian access feature where they tripped or lost balance — examination of that feature (including dimensional, stability, presence/absence of critical components and illumination studies as appropriate) may be sufficient to establish whether or not design, installation, or maintenance deficiencies were probable causes or contributors to the incident. In more complex cases — and particularly if the injured person is unable or unavailable to provide sufficient detail on which portion of a pedestrian path was involved in a fall — a more sophisticated analysis of the incident dynamics may be necessary.

There also are cases in which the design or construction of pedestrian facilities may have resulted in injury due to interaction with a vehicle, where vehicle accident reconstruction expertise may be considered. For cases involving a structural failure, especially in staircases or rail systems, structural engineering expertise may be necessary. A further type of potentially complex case are those where features are provided within a commercial/industrial facility or on a construction site for worker access to equipment or machinery, and an injury occurs involving that interface.

For managed properties, an expert in the standard of care for property management practices may also be necessary. In some fall cases, expertise in human motion physics and/or human factors may be needed to scientifically address how the fall occurred and the location features factored into the fall initiation and occurrence. If these types of expertise (or other necessary specialty types of expertise) cannot be provided by the initially retained forensic engineer, then recommendations for adding additional expert(s) should be discussed with the client at the earliest possibility.

Typically, if an appropriate evidence inspection/review and evaluation of conditions found, in comparison to code requirements, does not identify any non-compliant conditions, then that determination should be provided to the client. This is particularly important in cases when retained by an attorney representing an injured pedestrian plaintiff — in many courts, an expert finding that there has been a violation of some legally established specification for pedestrian access features is necessary to prevent the case from being summarily dismissed.

It is advisable to verbally inform each client of any conditions found that may increase the hazard or risk for pedestrians — even if that is a potentially subjective finding — so that the client can make informed decisions and take action, as appropriate. This is particularly important if the determination is for a case or claim in which the client is in a potential defense position, so that they can determine if property remediation actions to reduce or eliminate those conditions should be accomplished.

Further details on slip, trip and/or loss of balance fall evaluations, claims, and cases are available in books authored by expert witnesses (including one referenced in the LSC), although some of the code details may differ from the most current standards and regulations[54,55].

Case A — Retail Center Entry Walkway

One of the main entries for a shopping mall building included concrete exterior approach walkways providing parking area access. This pavement had been poured in sections separated by visible joints. At many of these joints, differential settlement of the adjacent paving sections had occurred, resulting in sudden vertical elevation changes that (at some locations) exceeded ¼ inch or even ½ inch. Some of the joints that had elevation changes above these values had been striped with yellow paint, reportedly to indicate potential trip hazards to pedestrians. However, other joints with elevation changes above these values had not been striped with yellow paint, and, in some cases, the unpainted joints had greater magnitude sudden elevation changes than painted joints (**Figure 8**). A pedestrian tripped and fell while reportedly passing across an unpainted joint with an elevation change ranging from $^{5}/_{8}$ to $^{3}/_{4}$ inch (**Figure 9**).

The subject walkway area was part of an accessible route, including a curb ramp from marked ADA parking spaces. Based on the documented facility construction and renovation dates, appropriate editions of the LSC and ADA facilities requirements (including a state-mandated accessibility code) applied. These required that walkway elevation changes exceeding ½ inch be accomplished with a compliant ramp. The IPMC also was in effect for this facility and required that the walking surfaces be maintained in a safe condition. The inconsistent striping of joints with trip hazards potentially increased the risk of a pedestrian tripping on the unmarked joints with abrupt elevation changes.

Case B — Residence Interior Stairway

The injured pedestrian reported falling from near the top of this staircase, which included a right angle turn accomplished with two diagonal treads. The pedestrian further reported that handrails observed during the inspection, within this corner portion of the staircase, were added by the property owner after the incident (**Figures 10** and **11**). A dimensional study of the staircase revealed riser heights well over 8 inches, tread depths less than 9 inches, variations in these features exceeding 2 inches, handrail heights varying between 31 and 42 inches, and handrail wall clearances less than 1½ inches (including for the more recently added handrails).

Based on the townhouse's original construction date and location, the IRC requirements were applicable — this was an instance where the AHJ determined that the IRC was applicable to a residential structure containing more than two dwelling units due to provided firewall separations. The measured staircase dimensions were significantly non-compliant with the riser height, tread depth, riser/tread variation, handrail height, and handrail clearance requirements. The upper portion of the staircase, including the corner, effectively had no handrail coverage at the time of the incident in violation of that code. The riser and tread dimensions and the use of the corner as

Figure 8
Mall entry walkway and curb ramp – note yellow striped joints.

Figure 9
Measurement of incident location elevation change height.

Figure 10
Townhouse staircase lower portion and corner.

Figure 11
Townhouse staircase upper portion and corner, including handrails added after incident.

part of the staircase rather than as a landing indicated that the staircase overall had been built in an overly steep configuration to fit the limited space within this townhouse. These overall conditions would not only increase the risk of a fall but would also increase the potential that a fall might result in a pedestrian tumbling down the full stairway. **Figure 12** is an example of how to present staircase inspection findings in comparison to code requirements as part of an expert report.

Case C — Public Service Facility Doorway

The main entry doorway for a walk-in business included a manufactured metal threshold installed under the swinging type standard width door (**Figure 13**). Reportedly, a patron entering the business tripped on that threshold, which evidenced several elevation change features and a maximum height above the floors on either side (which themselves were at elevations differing by approximately $^{7}/_{8}$ inch) exceeding 1½ inches. Use of a profile gauge was valuable for documenting the actual threshold dimensions (**Figure 14**). The gauge study

Figure 13
Doorway threshold insert.

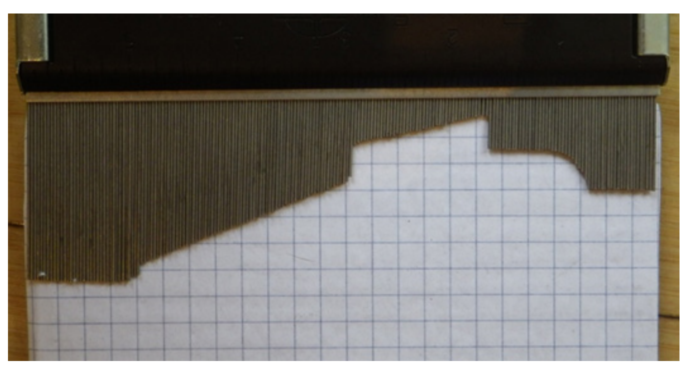

Figure 14
Threshold insert profile — each square equals ¼ inch.

Dimension	IRC Section	IRC Requirement	LSC Section	LSC Requirement	Measured	Comments
Riser Height	R311.5.3.1	<7¾	7.2.2.2.1	<7, >4	All except topmost >7 2 risers $>8^3/_8$	15 of 16 risers non-compliant with LSC, two risers major non-compliance with either code
Tread Depth	R311.5.3.2	>10	7.2.2.2.1	>11	All treads $<8^7/_8$	Major non-compliance with either code all treads
Riser Height Variation	R311.5.3.1	$<^3/_8$ all risers	7.2.2.3.6	$<^3/_8$ all risers $<^3/_{16}$ adjacent risers	Overall variation $2^3/_8$ greatest adjacent variation $2^1/_8$	Non-compliant with either code Major non-compliance with LSC at two locations
Tread Depth Variation	R311.5.3.2	$<^3/_8$ all treads	7.2.2.3.6	$<^3/_8$ all treads $<^3/_{16}$ adjacent treads	Overall variation $^3/_8$ greatest adjacent variation $^3/_8$	Compliant Non-compliant with LSC in three locations
Handrail Coverage	R311.5.6	Continuous full stair length	7.2.2.4.1	Continuous full stair length & at inside of turn	Reported/documented no handrails on or above turn	Non-compliant with either code at turn and stairs above it, non-compliant with LSC at turn inside corner
Handrail Height	R311.5.6.1	<38, >34 above nose slope	7.2.2.4.4.1	<38, >34 above nose slope	New rails on landing 31½ to 41¼	New rails non-compliant with either code
Handrail Clearance	R311.5.6.2	>1½	7.2.2.4.4.5	>2¼	Old and new rail $<1^7/_{16}$	Non-compliant with either code

Figure 12

Case Study B — Comparison of stair dimensions to applicable code requirements (all dimensions in inches).
Notes: IRC = 2003 International Residential Code; LSC= 2003 Life Safety Code (NFPA 101);
staircase "landing" is part of staircase, since it includes two separate treads with a riser in-between.

revealed that passing across the uppermost portion of the threshold in either direction would expose a pedestrian to a greater than ¼-inch abrupt vertical localized elevation change, additionally elevated above the adjacent floors by more than ½ inch.

Based on the facility construction and renovation dates, the IBC and LSC were applicable to the subject doorway. The threshold profile was not in compliance with the doorway elevation change specifications in those codes. The subject threshold presented a much more vertically aggressive profile than the author has typically observed. It was hidden from the view of pedestrians until they opened the door — even then, they could only view it from almost directly above, presenting minimal opportunity to properly view this trip hazard.

Case D — Curb Ramp Outside of a Business

At a restaurant parking area sidewalk three-way intersection, a curb ramp had been installed. A patron walking from a car toward the restaurant on the sidewalk portion extending out into the parking lot reportedly lost balance when they unexpectedly stepped onto the ramp side slope/flare (**Figure 15**). Dimensional study of the ramp indicated that the main slope was steeper than 1:10 — and that the slope of both side flares was as steep as 1:4. The ramp was part of an accessible route from marked ADA parking spaces.

Based on the documented facility construction and renovation dates, appropriate editions of the SBC, LSC, and the ADA facilities requirements (including a state-mandated accessibility code) applied. These codes required that the ramp main slope not exceed 1:12 and the side flare slopes not exceed 1:10. In addition, no portion of the ramp had any visual indication of its presence in contrast to ADA requirements for visual and tactile warning features.

Case E – Exterior Walkway Single Step at Night

An outside sidewalk that was part of an apartment building means of egress had a single step down to a

Figure 15

Curb ramp flare with excessive slope.

Figure 16
Walkway at night looking toward
single step down (indicated by arrow).

Figure 17
Primary illumination for walkway step
down (arrow) at time of inspection

crossing sidewalk where it approached the parking area. A visitor did not visualize this feature at night and lost balance, crossing it from above (**Figure 16**). Illumination during nighttime inspection was documented to differ from the time of the incident — namely that new fixtures had been added, and non-functional fixtures had been restored to service (**Figure 17**). An illumination study at the walkway level indicated that in areas shadowed by adjacent shrubs and/or the walkway elevation change that lighting levels were less than 0.13 fcd with all lighting functioning. Temporary removal of that reportedly added illumination resulted in measured lighting levels below 0.06 fcd. At the inspection, the elevation change was striped yellow, although it was documented that this striping was not present on the incident date.

Based on the documented facility construction and renovation dates, appropriate editions of the SBC and LSC applied, which required illumination of at least 1.0 fcd. The actual lighting at the time of incident was demonstrated to be less than 10% of that required level.

Conclusions

As in all fields of forensic engineering, evaluation of alleged trip or loss of balance falls should be accomplished using both scientifically based inspection and analysis techniques along with proper research to determine what established rules and standards of care properly apply to the features at the incident location. The forensic engineering expert's findings should be based on an objective comparison of the evidence to the governing standards, minimizing subjective conclusions. The expert should typically limit his or her documented findings to the details of which, if any, pedestrian access feature conditions could be identified as definitely or probably not in compliance with the applicable standards and/or which features were compliant.

Generally, the specific identification of parties who may or may not have been responsible for a particular condition or incident causation, should be deferred to the legal and/or insurance claims professionals and systems. However, it may be appropriate for the forensic engineering expert to specifically identify where the documented deficient actions or omissions by an identified engineering design professional potentially or definitely contributed to improper pedestrian access feature conditions that were a factor in an incident occurrence.

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