CHAPTER 3

A Method for Applying Fatigue Science to Accident Investigation

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The detrimental effects of fatigue on the safe operation of vehicles or the execution of critical tasks in transportation systems (e.g., monitoring pipeline systems or maintaining vehicles) have been well established. However, estimates of the percentage of transportation accidents attributed to fatigue has varied greatly, and much of that variability can be attributed to the methods used to investigate and document accident causes or risk factors. In addition, using research findings in accident investigation can be very difficult, and establishing that fatigue played a role in an accident illustrates very well the challenges of relating research to practice. In this chapter we will discuss how fatigue research has informed accident investigation and how findings from accidents and incidents can guide future research and policy decisions. The chapter will (a) establish the seriousness of the fatigue problem in transportation accidents and incidents; (b) provide insights into the difficulties associated in determining whether fatigue is a contributing or causal factor in an event; (c) describe, in detail, a methodology that can be used to identify fatigue factors in accident investigation; and (d) illustrate how accident investigations where fatigue is well documented can inform the research community and lead to design and policy changes that will mitigate fatigue and help improve transportation safety.

Many discussions of transportation fatigue begin by citing the wide range of estimates of the percentage of transportation accidents attributed to fatigue. Much of the variability in those estimates can be attributed to the methods used to investigate and document accident causes or risk factors. Fortunately, as the researchers in this volume show, there is a large body of scientific research on sleep, shiftwork, and fatigue that can inform an investigation about what factors lead to a state of fatigue and how fatigue affects performance. Unfortunately, relating findings from research conducted in a laboratory or a simulator to the unique circumstances of a transportation accident can be very difficult. Furthermore, the wide range of individual differences in sleep patterns and the effects of sleep loss on performance make it difficult to know whether aggregate findings are applicable to individual cases. As Coury, Ellingstad, and Kolly (2010) pointed out, "most major transportation accident investigations involve uncertainties in

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cause, complexities in avenues of inquiry, multiple stakeholders, and the absence of an obvious solution path" (p. 2).

Recognizing the need to improve and standardize accident investigation techniques with respect to fatigue, the National Transportation Safety Board (NTSB) set out to establish robust and reliable methods and procedures for assessing fatigue in accidents and incidents. NTSB believed that such methods could pay dividends at both the individual level (e.g., diagnosing and treating obstructive sleep apnea in a driver who has had a lane departure incident) and the broader organizational level (e.g., tracking the effectiveness of a fatigue risk management system [FRMS]).

A recent motorcoach accident investigated by NTSB (2012b) illustrates well the challenges facing accident investigators. In this accident, a motorcoach carrying 32 passengers, traveling southbound on an interstate highway from a Connecticut casino to New York City, ran off the road, struck a guardrail, then overturned on its side and collided with two 8-inch-diameter steel sign support poles, tearing most of the roof from the bus body. Fifteen passengers were killed and 17 passengers and the driver received injuries ranging from minor to serious. When the investigation was completed, NTSB concluded that

> the driver was impaired by fatigue at the time of the accident due to sleep deprivation, poor sleep quality, and circadian factors; and his lack of evasive braking or corrective steering action as the bus drifted off the roadway was consistent with fatigue-induced performance impairment. (NTSB, 2012b, p. 74)

NTSB went on to state that "the probable cause of the accident was the motorcoach driver's failure to control the motorcoach due to fatigue resulting from failure to obtain adequate sleep, poor sleep quality, and the time of day at which the accident occurred" (NTSB, 2012b, p. 75).

The investigative effort required by NTSB to reach such conclusions about the accident was substantial and not straightforward. The driver survived the accident, and during his interview 3 days later, he reported sleeping 7 to 9 hr per day in general and in the days leading up to the accident (including naps on the bus while on duty). The driver also reported that the accident was caused by a truck that struck the motorcoach just before it departed the roadway.

In an effort to verify the driver's statement, investigators searched for corroborating evidence. Research shows that sleep patterns can be an indicator of fatigue; consequently, the investigators set out to reconstruct the driver's sleep patterns in the days prior to the accident. When investigators began to obtain sleep history data, another picture emerged, contradicting the driver's original statements. Investigators were then required to seek out additional evidence to either support or refute the driver's self-report.

Cell phone records showed that in the days leading up to the crash, the driver had been using his cell phone during the times he reported sleeping. In addition, the driver had also rented a car during those periods, and when his phone records were cross-referenced to the vehicle's location data, the data showed that the driver was not at home when he reported being asleep. Based on phone and rental car data, investigators were able to estimate the driver's sleep opportunities during the hours leading up to the accident to be 4 hr or less. The estimate was based on evidence showing that the only periods of inactivity when the driver could have slept were during layovers in the casino parking lot. This analysis led investigators to suspect that the driver was fatigued. Medical records and interviews with the driver also indicated that the driver was susceptible to obstructive sleep apnea (OSA). Finally, there was no physical evidence of contact between the motorcoach and another vehicle. Witnesses driving in the vicinity of the crash also confirmed that there were no other vehicles near the motorcoach when it went off the road.

This motorcoach crash illustrates very well the complexities and uncertainties in an accident investigation and the numerous sources of evidence that must be gathered to obtain a comprehensive picture of, and confirm the presence of, human fatigue. In this accident, investigators used (a) interviews with the driver, (b) interviews with coworkers and other witnesses, (c) work schedules from the employer, (d) driver logbooks and notes, (e) surveillance videos and logs from the casino, (f) driver cell phone records, (g) electronic highway toll system data, (h) rental car telematics data, and (i) medical records. All the evidence gathered was driven by the underlying principles from established fatigue research and was used to determine which fatigue-related factors were present in the accident. This process allowed the investigators to conclude the driver was fatigued. A more detailed discussion of the methodology used by NTSB to relate evidence gathered during the investigation to fatigue research will occur later in this chapter.

Safety-Oriented Investigations

The approach to fatigue discussed in this chapter is an integral part of a safety-oriented investigation. The primary goal of a safety-oriented investigation is to identify safety issues related to an accident. To achieve that goal, investigators are concerned with identifying underlying causes and contributing factors that point to risks in a system that can be removed or mitigated. Consequently, the standard of proof will be determined by the nature of the safety issues under consideration and the evidence necessary to support the positions to be taken to resolve the safety issue. As Coury has pointed out (Coury et al., 2010; Coury, Kolly, Gormley, & Dietz, 2008), safety issues identified in a major transportation accident are a specific type of *principal issue* that helps determine the investigative tasks that must be accomplished and defines the investigative evidence needed to draw conclusions.

Safety-oriented accident or incident investigations can also be used to track and document fatigue issues over time as part of an FRMS. Such monitoring of a specific population can provide useful insights into at-risk tasks or occupations and provide data necessary to evaluate the efficacy of countermeasures. Several agencies and organizations have created processes over the past decade to investigate and document fatigue factors in accidents and incidents (Gabree, Johnson, & Comperatore, 2012). In 2003, the Federal Railroad Administration published a technical bulletin that describes procedures to be followed by field inspectors investigating headquarters-assigned accidents for fatigue (Federal Railroad Administration, 2003). In 2011, three international aviation organizations—the International Civil Aviation Organization (ICAO), the International Air Transport Association, and the International Federation of Airline Pilots' Associations—collaborated to create an FRMS Implementation Guide for Operators, which lists a "process for investigation of safety occurrences that aims to identify safety deficiencies rather than apportioning blame" (ICAO, 2011, p. 3) as one of 10 building blocks of an FRMS. The investigation methodology outlined in the ICAO Implementation Guide is very similar to the methodology described in this chapter.

Several organizations have, as part of their FRMS, implemented fatigue reporting systems for the purpose of identifying and mitigating potential fatigue precursors, such as challenging schedules, sleep disorders, or poor sleep environments (Nesthus, 2011; Powell, 2011). In some cases, the occurrence of operator fatigue itself is defined as an event that merits reporting, with associated checklists that ask operators to provide information about duty and rest history, factors that may have contributed to their fatigue, indicators that they were experiencing fatigue, and suggestions for mitigation. Operators who choose to self-report incidents are often given the opportunity to do so anonymously to provide more incentive for operators to share information about risks in their environment. The results of such safety-oriented investigations lead to localized measures to address fatigue in the work environment and can also inform government, industry, and the research community of gaps in knowledge about fatigue issues and the need for more data about the effects of fatigue on performance.

The goals of a safety-oriented investigation are distinctly different from a criminal or insurance investigation, where the primary concern is apportioning blame and establishing who was responsible for death, injury, and damage. The emphasis in criminal investigations is typically on gathering evidence to determine culpability and, in some cases, support criminal charges and/or civil liability. Although the ultimate goals of the different investigations may vary, those who work on criminal or insurance claim investigations may also find some value in the methodology and evidence documentation techniques discussed in this chapter.

Before presenting the NTSB fatigue investigation methodology, the chapter will begin by placing fatigue in a historical context, including a brief historical perspective about fatigue in accident investigation. Then the chapter will turn to a discussion of a fatigue accident investigation methodology, outlining the procedure while using recent NTSB accidents to illustrate the use of the investigative methods and referring to relevant fatigue-related research.

Finally, we will discuss how accident investigations where fatigue is well documented can inform the research community and lead to design and policy changes that will mitigate fatigue and help improve transportation safety.

History of Fatigue in Major Transportation Accidents

Recognition that fatigue can play a part in a major accident dates back to the early 20th century. One of the most widely known early accidents involving fatigue occurred on the morning of June 22, 1918, in Ivanhoe, Indiana, when an empty Michigan Central Railway troop train of 20 empty Pullman cars ran into the back of the Hagenbeck-Wallace Circus

train (Lytle, 2010). The collision and ensuing fire killed 86 of the circus performers and injured 127. At the time, this was the deadliest rail accident in U.S. history (only to be surpassed just 3 weeks later on July 9, when two passenger trains collided head-on in Nashville, Tennessee, killing 101 people and injuring 171).

The locomotive engineer of the troop train survived and admitted to witnesses that he had fallen asleep at the controls; however, Michigan Central Railway attorneys would not allow the engineer or fireman to testify before any investigating body (both employees were facing criminal charges). As in a modern accident investigation, investigators turned to other, secondary evidence to support the conclusion that the engineer was asleep when the accident occurred (Lytle, 2010; "Rear End Collision," 1918):

- Railway records and witness statements showed that the troop train ran a red stop signal,
- The troop train crew failed to respond to the flares and signals indicating that the circus train was stopped on the tracks,
- Testimony by the circus train's flagman (who had been setting the flares and signals on the tracks behind the circus train) that there was no engineer in view at the locomotive window when the train went past his location, and
- The troop train engineer's comments to witnesses immediately after the accident that he had "dozed off."

The accident was also one of the earliest railway investigations conducted by the U.S. federal government. The investigation was conducted by the U.S. Interstate Commerce Commission (ICC) in conjunction with the Indiana Public Service Commission for the purpose of using the results of the investigation to improve railway safety. Federal involvement occurred as a result of the Accident Reports Act of May 6, 1910, which made the ICC responsible for railroad accident investigations (Coury et al., 2010). The ICC, the first independent U.S. government regulatory agency, was established by the Interstate Commerce Act of 1887 and was primarily involved in regulation of the railroad industry in the United States until it was abolished in 1994. During its tenure, the ICC was tasked with investigating certain accidents for the purpose of increasing safety and, in 1911, began to issue, often in the form of memoranda to the ICC, reports of those investigations.

The investigation of the circus train accident by the ICC found that the troop train engineer had left home at 5:00 p.m. and taken a train to his duty station in Kalamazoo, Michigan, where he took over as engineer on the troop train at 8:00 p.m. The accident occurred at approximately 4:00 a.m. the next morning, almost 12 hr after the engineer had left home, and there was no evidence that he had obtained adequate sleep prior to leaving home or to coming on duty (Lytle, 2010). Two days after the accident, the Associated Press reported that one of the Michigan Central Railway attorneys issued a statement explaining that the troop train engineer was asleep due to illness and indicated that the medication taken by the engineer for a kidney ailment had contributed to the engineer's fatigue (Associated Press, 1918). This was an important finding, suggesting that fatigue from sleep loss could be exacerbated by prescription drug use. These findings led the ICC to conclude that the engineer had fallen asleep and "from this cause, fail[ed] to observe the stop indication of automatic signal 2581, and the warnings of the flagman of the circus train, and to be governed by them" (ICC, 1918).

Not only did this accident contain many of the elements of concern to a modern investigation of fatigue—sleep loss, work schedules, and drug effects—it also led to recommendations that foresaw the need for technological interventions to mitigate fatigue effects. In a review of the accident, *Railway Signal Engineer* concluded,

> This collision is another example of that class of accidents which a modern system of signaling is powerless to prevent. It has been repeatedly pointed out in reports of other accidents investigated by this bureau that the only known way to guard against such accidents is the use of some form of automatic device which will assume control of the train whenever the engineman fails to obey the stop indication of a signal. ("The I.C.C. Report," 1918, p. 356)

Such a conclusion preceded, by 90 years, the U.S. Rail Safety Improvement Act of 2008, which called for the implementation of positive train control technologies that would intervene when a train runs a stop signal.

Fatigue was also recognized by other modes of transportation as a factor in accidents. Even in the early days of aviation, fatigue was identified as an important concern to pilot performance. In fact, fatigue was included as a factor in a government-sponsored report outlining the methods for classifying and comparing military and civilian aviation accidents. The report, produced by the National Advisory Committee for Aeronautics (NACA) in 1928, was the first time an official U.S. government group attempted to both rationalize accident investigation and define terms to be used in the classification of underlying causes and contributing factors, especially as they related to pilot errors (Coury et al., 2010; NACA, 1928). NACA was created in 1915 by president Woodrow Wilson and was to become the National Aeronautics and Space Administration (NASA) in 1958. In its report, NACA presented a method for analyzing aviation accidents and defining terms used to assign cause or identify contributing factors. Causes and contributing factors were characterized in terms of personnel (pilots, supervisors, and others), materiel (aircraft components and handling characteristics), and miscellaneous (e.g., environmental factors). This treatment of pilot performance offered a new approach to accident investigation by providing definitions for pilot errors and including them in a three-part representation of aviation accident causes that mapped immediate causes of the accident to underlying causes.

Fatigue was characterized as one of the physical and psychological causes underlying pilot error, and it was treated as a temporary disease or defect "which is remediable and one which may not be expected to repeat itself with undue frequency in the individual concerned" (NACA, 1928, p. 570). This was the first time in aviation that fatigue was integrated into an official government approach to accident investigation and data analysis. In fact, the NACA reports were landmarks in aviation accident investigation by establishing an official, government approach that put forth a method and standardized language that could be applied to all types of aviation accidents.

The importance of fatigue in accident investigation was not restricted to transportation. Heinrich (1931, 1941) was one of the first to identify fatigue as a factor in workplace accidents and to place its importance in the context of an accident model. Working in industrial safety as a representative of Travelers Insurance Company, Heinrich studied many industrial accidents to determine the causes and factors leading to major injuries. Unlike his predecessors, and in contrast to the focus on classifying causes and factors (as in the NACA approach), Heinrich proposed a model to explain *why* accidents happened and was the first to claim that an accident was the result of a sequence of events (Coury et al., 2010).

Heinrich depicted an accident as the ordered sequence of five factors: ancestry and social environment, fault of the person, unsafe act and/or mechanical or physical hazard, accident, and injury (Heinrich, 1941). Heinrich considered fatigue as a cause of an unsafe act by a person. In his description of causes of unsafe acts, he treated fatigue as a personal proximate subcause, where *proximate* referred to a cause or subcause directly related to the accident and the cause of the injury. Fatigue was characterized by Heinrich as one of a number of "Bodily Defects" in that it "is the inevitable result of continued exertion—either mental or muscular" (Heinrich, 1941, p. 284).

Heinrich's approach to fatigue was important because it implied the two important questions always facing investigators: (a) Was the person fatigued? and (b) Did the fatigue contribute to the accident? By treating fatigue as an unsafe act of a person, his approach placed it squarely in the causal chain of events. What was also very interesting about Heinrich's approach is his admission that there were no direct tests of fatigue. From a contemporary perspective, however, Heinrich's definition of fatigue was a broad one, encompassing both physical and psychological fatigue. Subsequent research showed that these two types of fatigue are very different and must be considered separately in any assessment of human performance.

Early Descriptions of Human Fatigue in NTSB Reports

The earliest cases of fatigue documented by NTSB date back to the mid-1960s, when the NTSB was established as an independent agency. There is little documentation on record for these earliest cases; however, the brief narratives that accompany the coded accident information for fatigue-related aviation accidents that took place in the 1960s and 1970s suggest that acute sleep deprivation or long periods of continuous duty were the main factors considered when designating pilot fatigue as a probable cause. Quotes from those early narratives include "no sleep during previous 24 hours" (ANC67D0048), "17 hours flight time in last 24 hours; 4 hours sleep" (FTW67A0113), and "pilot stated he was tired, up all night and day before" (MIA70D0054). (Accident reports are available from NTSB's Aviation Accident Database at http://www.ntsb.gov/_layouts/ntsb.aviation/index.aspx.) In the 1980s, NTSB published several major reports concerning railroad, maritime, truck, and bus accidents in which operator fatigue was determined to be a causal factor. Several of these accidents—such as the 1988 Thompsontown, Pennsylvania, freight train collision (NTSB, 1989); the 1986 Brinkley, Arkansas, bus/truck collision (NTSB, 1987); and the 1985 grounding of a ferry near Mona Island, Puerto Rico (NTSB, 1986)—were characterized by their operators' extreme sleep deprivation. However, the reports also mention sleep disorders, poor sleep quality, unpredictable work and rest schedules, extended duty periods, and monotonous work environments as factors that led to operators' fatigued conditions.

The investigation of the American International Airways DC-8 that collided with terrain a quarter of a mile from the approach end of the runway at the U.S. Naval Air Station in Guantanamo Bay, Cuba, in August 1993 was a landmark case for NTSB. That case marked the first major aviation accident investigation report in which operator fatigue was identified as the probable cause of the accident (NTSB, 1993). Prior to this investigation, fatigue had been listed as a contributing factor but never as the cause of a high-profile aviation accident. The investigation was also unique in that NTSB requested assistance to ensure that fatigue was adequately investigated and documented in this accident. The assistance came from members of the NASA Ames Research Center Fatigue Countermeasures Program led by Dr. Mark R. Rosekind (who, incidentally, would be appointed 17 years later by President Obama to be the 40th member of NTSB and provides the preface to this volume). An appendix to the Guantanamo Bay investigative report authored by the NASA team proposed a systematic approach to examine fatigue factors in an accident investigation, an approach that formed the basis of the methodology that has been employed since to evaluate the role that human fatigue plays in accidents and incidents (Rosekind et al., 1994).

Importance of a Valid Way to Determine Fatigue

Historically, fatigue has been notoriously difficult to define and operationalize. From decades of experimental research, we know that when people are sleep deprived, their sleep latencies will be shorter and their performance on cognitive tasks will degrade. Yet, those studies have also shown that people do not provide reliable or precise estimates of their fatigue or performance when they are sleep deprived (Belenky et al., 2003). Nor has science yet discovered a reliable biological marker for fatigue or sleep deprivation.

However, because fatigue-related performance errors in a transportation system have been shown repeatedly to lead to catastrophic events, it is vital to develop a means to estimate when a human operator is likely to be (or likely to have been) fatigued. In the absence of a direct measure of fatigue, investigators must rely on indirect or secondary measures to help estimate whether an individual was likely fatigued and whether any fatigue-related errors he or she made contributed to the accident. And, because no single measure is usually sufficient to indicate fatigue, the investigator must rely on a set of indicators that can be cross-validated with known fatigue effects (Price, 2005). Without such a methodology, the importance of fatigue-related factors in an accident cannot be determined.

NTSB HUMAN FATIGUE INVESTIGATION METHODOLOGY

To address the need for a valid and reliable way to determine the role of fatigue in an accident, NTSB developed a methodology based on current scientific knowledge about fatigue and based on its investigators' experience working with complex transportation accident investigations. The investigation of the previously mentioned American International Airways DC-8 accident in 1993 paved the way for development of an accident investigation methodology, and the increasing importance, and frequency, of fatigue in major transportation accidents led NTSB to emphasize the need for a methodology that could be used for all forms of transportation.

Any investigation focused on fatigue must address two fundamental questions:

1. Was the operator fatigued at the time of the accident?
2. Did the operator's fatigue contribute to the accident?

Answering these two questions are the two key steps in determining whether human fatigue contributed to an accident or other event. The first question requires a comprehensive examination of multiple factors to establish whether the operator was in a fatigued state at the time of the accident. The second question relies both on scientific research to determine whether the operator's performance was consistent with the known effects of fatigue and on an analysis to determine whether his or her performance contributed to or caused the accident. There is a very important distinction between the two questions because the mere presence of fatigue does not immediately imply that fatigue was a contributing factor in the accident.

Yet, the first step alone can provide useful information about safety risks in the entire transportation system. For example, an investigation may determine that the cause of an airplane crash was an engine failure, but the fact that the pilot was using a sedating antihistamine or had an undiagnosed sleep disorder at the time of the crash can provide important insight into latent risks in the system that may not have been previously considered. Therefore, there is value in documenting the time of day, operator work and sleep data, and certain health-related data in *all* events, even in those situations where no clear human-related causal findings can be established. From a research perspective, the data collected during an investigation may serve as an important control or comparison group for future epidemiological research.

For the sake of clarity, the vehicle operator will be the focus of the discussion. However, this approach may be applied to any human involved in the system at the time of the event, including maintainers, dispatchers, controllers, and others. Furthermore, a focus on the vehicle operator does not mean that fatigue-related factors resulting from management and organizational policies and practices are excluded from investigation.

NTSB's human fatigue investigation methodology is summarized in Figures 3.1 and 3.2. The methodology begins with the first step (Figure 3.1): Establish whether the operator was in a fatigued state at the time of the accident. The importance of this step is evident, but the challenge facing an accident investigator makes this step critical although, at times, very difficult. The methodology focuses on those indices of fatigue that can establish the presence of fatigue.

STEP 1: WAS THE OPERATOR FATIGUED?

Research and practical experience point to two major areas for documenting fatigue factors in an investigation: sleep/wake history and operator health. Evidence gathered in these areas can shed light on multiple important risk factors for fatigue. For example, a

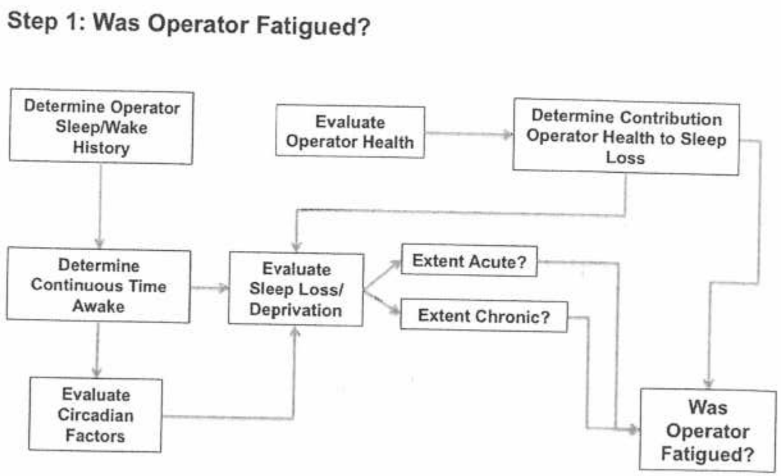

Figure 3.1. *Step 1 in the National Transportation Safety Board human fatigue investigation methodology to determine if the operator was fatigued.*

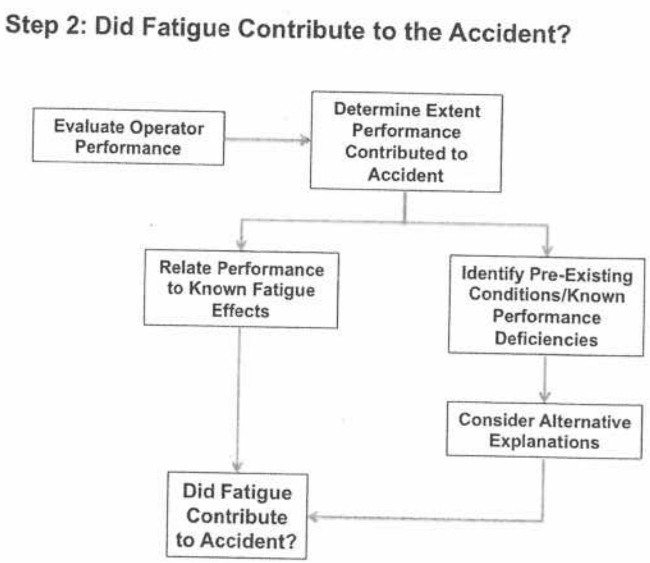

Figure 3.2. *Step 2 in the National Transportation Safety Board fatigue investigation methodology to determine if fatigue was a contributing factor in the accident.*

sleep/wake history can provide information about acute or chronic sleep deprivation, circadian factors, and how long an operator was awake at the time of the event. Evidence gathered about operator health can inform the investigators' knowledge about sleep disorders, or other health issues that may affect sleep and wakefulness, and can also provide information about the use of sedating drugs or medications.

Sleep/Wake History

Documenting sleep, or the lack thereof, is the most important element in determining whether an operator was fatigued at the time of an accident. It is important to look at multiple sources of evidence in recreating the operator's sleep/wake history leading to the accident, as different sources may yield different information. The need to consider multiple sources of evidence was evident in the motorcoach accident discussed in the introduction whereby the driver reported obtaining a certain amount of sleep, but other sleep-related data gathered by the investigators indicated a distinctly different pattern of sleep and wake periods. The first part of this section will describe the methods an investigator may use to document an operator's sleep/wake history, as shown in Figure 3.1. Once that history has been established, an investigator may use that information as the basis of evaluating several factors, such as sleep deprivation, circadian factors, and time awake.

Documenting sleep/wake history. There are many factors that may affect both the availability and the reliability of sleep/wake history data, including whether the operator survived the accident, the mode-specific policies and practices for documenting duty periods, and the availability of evidence from family, coworkers, and recorded data. We begin our discussion with the methods used to document sleep and wake times when the vehicle operator survives the accident.

If an operator survives (and consents to an interview), he or she may be able to provide evidence that is not available from any other source, especially information about sleep quality and subjective sleepiness at the time of the event. Interviews with other individuals close to the operator, such as family members, coworkers, dispatchers, supervisors, physicians, or witnesses who saw the operator on the day of the accident, can also provide important information. Operator interviews should focus on recreating, in detail, the 72 hr (or more, if the operator can remember) prior to the event, including sleeping, working, and all other activities. One approach an investigator may take is to ask the operator to free-recall as much as possible about his or her activities, working backward from the time of the accident or forward from several days before the accident (or both). Some investigators choose to fill in a log or a time grid as an aid to ensure that there are no gaps in the operator's report.

Specific information to obtain includes the following:

- Times the driver awoke/went to sleep each day
- Times, durations, and locations of any naps
- Step-by-step recounting of activities, including times and durations
- Times and occasions of seeing or talking to people

- Times and durations of meals
- Time and amount of any drug ingestion, including alcohol
- Time and dosage of any medications taken, including prescription and over-the-counter
- Sleep/activity times for typical workdays and nonworkdays
- Variances in sleep habits in the days leading to the accident compared to typical patterns
- Presence of external factors (e.g., noise, light, phone calls) that may have interfered with sleep
- Operator assessment of subjective sleep quality, overall and in the days leading to the accident
- Subjective rating of sleepiness at the time of the accident

Although direct operator interviews are very valuable, it is also very important to document multiple sources of evidence and secondary sources of data that can be used to cross-validate and verify the answers provided by the operator. Again, the motorcoach accident discussed earlier provides a very good example. In that case, cell phone records and rental car location data conflicted with the periods of sleep reported by the driver. Consequently, any time-based documentation may assist in determining the sleep/wake history for an individual.

The following types of records often include time-based data:

- Cell phone records
- Work schedules
- Operator logbooks
- Key-card usage from hotels or workplaces
- Paper or electronic toll records
- Continuous positive airway pressure (CPAP) device data
- Hotel check-in/check-out records, hotel phone usage, wake-up call requests
- In-vehicle data, audio, or video recordings
- Other audio/video recordings, such as surveillance videos

As one might expect, the availability and accuracy of time-based data can vary, not only across transportation modes but within modes and within individual investigations as well. For example, cell phone and vehicle recorder data may be regularly synchronized to a master clock; however, other clocks, such as those in security videos, may be free-running. In order to construct an accurate timeline of sleep/wake patterns, all time-stamped data must be synchronized with a common master to facilitate comparisons among various sources of evidence.

Using all available sources of sleep/wake data, an investigator may then create a comprehensive master log of operator activity, such as the example shown in Figure 3.3. The times provided by different sources often conflict at least slightly, so investigators must seek additional sources, or use their judgment to resolve discrepancies. Once conflicts have been resolved, it is useful to create a graphic to visualize the sleep/wake patterns or

Time (EST)	Activities	Location
Wednesday, March 9		
9:00 p.m.	Arrive for duty, World Wide Travel terminal	Brooklyn, NY
9:15 p.m.	Depart terminal	Brooklyn
10:00 p.m.	Pick up passengers; depart en route to Mohegan Sun	Flushing, NY
Thursday, March 10		
Time (EST)	**Activities**	**Location**
1:00 a.m.	Arrive Mohegan Sun casino, drop off passengers, and move motorcoach to parking lot	Uncasville, CT
1:20–3:15 a.m.	Sleep in bus (self-reported)	Parking lot
5:15 a.m.	Pick up passengers	Bus lobby entrance
5:30 a.m.	Depart Mohegan Sun en route to New York	I-95 south
8:58 a.m.	Return World Wide Travel terminal	Brooklyn
10:00 a.m.–4:00 p.m.	Sleep (self-reported)[a]	Residence
9:30 p.m.	Arrive for duty, World Wide Travel terminal	Brooklyn
9:45 p.m.	Depart terminal	Brooklyn
10:30 p.m.	Pick up passengers; depart en route to Mohegan Sun	Flushing
Friday, March 11		
Time (EST)	**Activities**	**Location**
1:56 a.m.	Arrive Mohegan Sun, drop off passengers	Uncasville
~2:00 a.m. – 6:00 a.m.	Sleep in bus (self-reported)	Parking lot
~6:30 a.m.	Depart Mohegan Sun en route to New York	I-95 south
~9:50 a.m.	Arrive World Wide Travel terminal	Brooklyn
11:00 a.m.–4:00 p.m.	Sleep (self-reported)[b]	Residence
6:15 p.m.	Arrive for duty, World Wide Travel terminal	Brooklyn
7:40 p.m.	Pick up passengers; depart en route to Mohegan Sun	Bowery, New York City, NY
10:36 p.m.	Arrive Mohegan Sun, drop off passengers	Uncasville
10:54 p.m.	Drive to casino parking lot	Parking lot
11:46 p.m.	Drive from parking lot to casino for lost item	Bus lobby entrance
11:55 p.m.	Return to casino parking lot from bus lobby entrance	Parking lot
~11:55 p.m.–3:17 a.m.	Sleep on bus	Parking lot
Saturday, March 12		
Time (EST)	**Activities**	**Location**
3:17 a.m.	Receive incoming cell phone call (32 seconds)	Parking lot
3:19 a.m.	Pick up passengers	Bus lobby entrance
3:48 a.m.	Depart Mohegan Sun en route to New York	I-95 south
5:38 a.m.	Accident	I-95, near New York City

[a]The driver's cell phone was in use multiple times between 10:15 a.m.–12:03 p.m. Additionally, a 24-second incoming call occurred at 3:39 p.m.
[b]The driver's cell phone was in use numerous times during this period, with the longest period of non-use between 11:38 a.m.–12:17 p.m. (39 minutes).

Figure 3.3. Sample master log of operator activity.

the "sleep opportunities" if the actual sleep times are unknown. An example of such a sleep/wake history graph from the New York motorcoach crash is shown in Figure 3.4.

The graph is based on multiple sources of data. As previously discussed, evidence from the driver's cell phone records and additional cell phone "tower data" (that is, information about the location of the cell phone towers accessed when the phone was in use) showed that the cell phone was in use at several locations in both New York City and

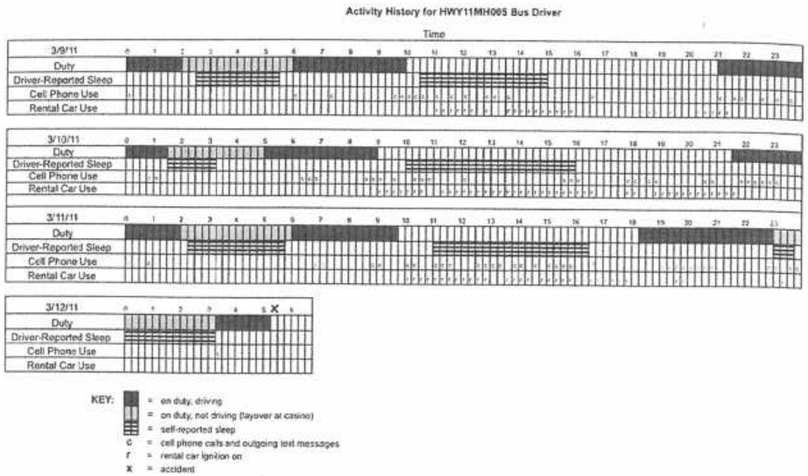

Figure 3.4 Sleep/wake history graph of recent activity history for the driver in the March 12, 2011, New York motorcoach accident.

Nassau County, New York. When the cell phone and rental car location data records were synchronized, then considered alongside a witness report of seeing the driver and the vehicle in Nassau County on one of the driver's off-duty periods, the data indicated that the driver was not at his home sleeping during his self-reported sleep periods. Figure 3.4 clearly shows that the driver's actual daily sleep opportunities in the days leading to the accident would have been limited to short periods of approximately 4 hr or less, including the layover at the casino before starting the accident trip. It is worth noting that in many investigations, the operator's self-report is consistent with the objective evidence. However, the New York motorcoach example underscores the need to look at multiple sources of evidence in order to determine the most accurate picture of an operator's sleep/wake history. Indeed, no single source of fatigue evidence should be used to conclude the presence of fatigue factors in an accident without confirmation from other evidence sources.

When the operator is not available. Documenting sleep and wake times when an operator does not survive the accident, is incapacitated, or refuses to cooperate with the investigation is more dependent on secondary sources of evidence. Interviews with those close to the operator, including the operator's spouse, other family members, and coworkers, become even more vital to the investigation, as does any documentation of duty periods, sleep/wake patterns, and activities. As previously mentioned, the accuracy and reliability of secondary data sources can vary considerably between transportation modes as well as within a mode.

An example of using secondary sources to determine sleep/wake patterns when an operator does not survive is illustrated well in the investigation of the crash of Continental Flight 3407, in Clarence Center, New York (NTSB, 2010). In that accident, a commercial air carrier crashed into a residence in Clarence Center while on approach to Buffalo-Niagara International Airport at about 10:17 p.m. on February 12, 2009. The two pilots, two flight attendants, and 45 passengers aboard the aircraft and one person on the ground were killed, and the airplane was destroyed.

NTSB determined that the probable cause of the accident was the captain's inappropriate response to the activation of the stick shaker (a device that warns a pilot of an impending wing aerodynamic stall through vibrations of the control column), which led to a stall from which the airplane did not recover (NTSB, 2010). NTSB also listed as contributing factors to the accident the crew's failure to monitor the aircraft's airspeed, the crew's failure to adhere to sterile cockpit procedures (a rule that prohibits nonessential activities during critical phases of flight), the captain's failure to effectively manage the flight, and the airline's inadequate procedures for airspeed selection and management during approaches in icing conditions. With respect to fatigue, NTSB concluded that the pilots' performance was likely impaired because of fatigue, but the board members disagreed about the extent of their impairment and the degree to which it contributed to the performance deficiencies that occurred.

Investigators examined a wide variety of evidence to build a picture of the crew members' training, work and rest history, medical status, performance history, and performance on the day of the accident. With respect to fatigue-related factors, investigators used interviews with family members, interviews with coworkers, cell phone records, airline work schedules, the cockpit voice recorder, and the flight data recorder. In spite of this thorough review of available information, there were periods in the 72 hr before the accident in which activities of the crew were not known.

In the end, investigators documented that in the days leading up to the accident, the captain was on a trip rotation away from home. His actual sleep times were not known, but his known activities indicated that his sleep opportunities may not have afforded him enough time for 8 hr of continuous sleep during the days leading to the accident. The first officer appeared to obtain adequate sleep at her home on the nights of February 9 and 10 and slept on airplanes while commuting and in a crew room during the 24 hr leading to the accident flight. Her sleep on the airplanes and in the crew room totaled approximately 9 hr in the 24-hr period before the accident. In the case of the Clarence Center accident, as will be discussed later in this chapter, the fatigue-related issues for the crew concerned potential sleep quality issues rather than the length of the sleep opportunities.

Evaluating sleep/wake history information. Once an investigator has assembled the best possible representation of the operator's sleep/wake history, he or she may use that information to determine whether the operator may have been sleep deprived, whether the operator was awake for an excessive period of time prior to the event, and the potential effects of circadian factors. Each of these will be discussed in turn.

Sleep deprivation. To assess sleep loss or deprivation, actual sleep lengths may be compared to the person's basal sleep needs. Although individual needs may vary, it is generally believed that adults need 7 to 8 hr of sleep per night to avoid being fatigued the next day (National Heart, Lung, and Blood Institute, 2005). Ideally, investigators should ask operators or their family members about the operator's sleep patterns when they are not on duty or when they not constrained by external work or family demands. In practice, however, it may be difficult to obtain a precise estimate of an individual's sleep needs, especially if the individual regularly engages in shiftwork or is chronically sleep deprived (Carskadon & Roth, 1991). Ultimately, using the best available information, an investigator should estimate any deficits between the operator's basal sleep need and actual sleep obtained for several days leading to the accident in order to consider whether he or she was affected by acute or chronic partial sleep deprivation.

Sleep deprivation is often described in two ways: acute sleep deprivation and chronic partial sleep deprivation. *Acute sleep deprivation* typically refers to an individual's sleep deprivation in the 24 hr preceding the event. Laboratory studies suggest that a one-night sleep restriction must be fairly extreme before significant performance impairment is evident. Some epidemiological research has shown that drivers who reported getting five or fewer hours of sleep in the previous 24 hr had an almost threefold increase in risk for an injury crash (Connor et al., 2002); however, in laboratory studies, performance decrements are generally not seen after one night unless time in bed is restricted dramatically to 3 hr or fewer (Belenky et al., 2003; Roehrs, Burduvali, Bonahoom, Drake, & Roth, 2003). *Chronic partial sleep deprivation* refers to the cumulative effects of sleep deprivation over multiple days. Laboratory research has clearly shown that even minor sleep reductions, when carried over multiple days, can have detrimental effects on performance (Belenky et al., 2003; Van Dongen, Maislin, Mullington, & Dinges, 2003). The additive sleep deprivation is often referred to as a sleep debt. Although it was once believed that one to two full nights of sleep could erase a sleep debt, more recent research has shown that individuals may be more susceptible to the effects of subsequent sleep deprivation after having experienced recent chronic sleep deprivation (Banks, Van Dongen, Maislin, & Dinges, 2010). Consequently, documenting an operator's sleep and wake times for several days prior to the event is valuable when evaluating the likelihood that an operator was fatigued at the time of the accident.

Time awake/time on task. An individual's time awake, or time since last sleep, is also a predictor of fatigue and performance and is inextricably related to sleep lengths. Although time on task or "on duty" is of great concern to regulators, and research has shown a nonlinear increase in crash risk with increasing driving time, particularly when driving periods extend beyond 8 to 9 hr (Belenky, Hanowski, & Jovanis, 2013), fatigue researchers have also argued that in general, time since awakening is a better predictor of fatigue and fatigue-related performance impairment (Dawson & McCulloch, 2005). Prolonged wakefulness has been associated with impairments in simple reaction time and in more complex cognitive functions. For example, Zhou et al. (2010) found that individuals who have been awake for longer than 17 hr show significant declines in neurobehavioral performance tasks that involve vigilance and mental math. Authors of another study found that after 18 hr of continuous wakefulness, laboratory subjects showed a progressive deterioration in performance on a psychomotor vigilance task (Doran, Van Dongen, & Dinges, 2001).

Assuming that he or she has obtained reliable data concerning the operator's sleep/wake history, an investigator may estimate time awake simply by counting the hours since the most recent wake time, keeping in mind that the time since the most recent "anchor sleep" may be more meaningful than the time since a brief nap. Additionally, be aware that extended wake periods that extend into the time of day known as the circadian trough or "window of circadian low" (Cohen et al., 2010) are particularly problematic.

Circadian factors. There are two key issues to understanding the potential effect of circadian factors on human performance. The first, and most evident, is whether the event happened during a circadian low point, when human performance is degraded and sleepiness is greatest. The primary circadian trough is approximately midnight to 7:00 a.m., and especially 4:00 a.m. to 7:00 a.m., and a secondary, less well understood trough, sometimes referred to as a "postlunch dip" occurs at approximately 3:00 p.m. to 5:00 p.m. (Goel, Van Dongen, & Dinges, 2011).

The second issue involves determining whether the operator suffered from circadian dysrhythmia from crossing multiple time zones or due to rotating, inverted, or variable work/sleep schedules. Travel across multiple time zones requires adapting one's circadian cycle to new light/dark cues. Sleep is more difficult, and it may take several days before one's circadian rhythm is synchronized to the new geographic location. For operators who regularly cross multiple time zones, such as pilots, it can be difficult or impossible to fully adapt. Shift workers who work night or rotating schedules face similar challenges, and the term *social jet lag* has been used to refer to the circadian dysrhythmia associated with those schedules (Wittmann, Dinich, Merrow, & Roenneberg, 2006).

Although there are numerous strategies that shift workers and those who cross multiple time zones can use to mitigate the negative effects of circadian shifts, it is difficult to completely erase the effects. Shorter sleep lengths and sleepiness during waking periods are common among those populations (Graeber, Lauber, Connell, & Gander, 1986; Tepas & Carvalhais, 1990).

From an investigative perspective, a thorough documentation of the operator's sleep and activity schedule going back several days is crucial. Such documentation will provide valuable information about whether the individual was engaged in a conventional diurnal schedule or not, and information gathered from interviews may shed light on how well the individual may have adjusted to any time zone or schedule shifting that took place in the days or weeks leading to the event.

The New York motorcoach crash illustrates well three notable issues with respect to circadian factors. First, the time of day when the accident occurred—approximately 5:37 a.m.—fell during the period in the circadian cycle when subjective sleepiness is most pronounced and when human performance is most degraded (Van Dongen & Dinges, 2005). Second, the driver's work schedule was inverted, and research has shown that inverted work schedules are associated with shortened sleep lengths, higher subjective wake-time sleepiness, and degraded performance (Richardson & Malin, 1996). Furthermore, the driver self-reported that his sleep patterns followed a more traditional diurnal pattern during his off-duty periods. The result of such dramatic change to his sleep/wake schedule would likely have induced a state of circadian dysrhythmia that can lead to difficulty sleeping and performance impairment. Third, the driver's work schedule was rotated backward by approximately 3 hr the day before the accident. His schedule indicated that he was beginning his work shift at approximately 9:00 p.m. on March 8, 9, and 10 and that he was sleeping between approximately 2:00 a.m. and 6:00 a.m. during his layover periods. On March 11, the day before the accident, he began his work shift at 6:15 p.m., and his layover period at the casino was between 11:00 p.m. on the night of March 11 and 3:00 a.m. on the morning of March 12. Although this 3-hr backward rotation is minor in comparison to the large sleep/wake rotations the driver engaged in between his workdays and nonworkdays, such rotations have been associated with sleep reductions as well (Walsh, Schweitzer, Sugerman, & Muehlbach, 1990).

Sleep Quality

Where does sleep quality fit in? Undoubtedly, sleep quality is important to understand, and it is heavily related to other factors, such as circadian factors and health. High job demands and low job control are established predictors of low sleep quality (Van Laethem, Beckers, Kompier, Dijksterhuis, & Geurts, 2013). It is also likely that sleep quality is affected by environmental factors, such as noise or uncomfortable sleeping environments. As stated earlier in the chapter, from the perspective of a safety investigation, the primary focus should be on the amount of sleep obtained by an operator in the days leading to the event. If the individual's sleep was disrupted, or if the quality of the sleep was affected by time of day, psychosocial work characteristics, or health issues, the net effect is less sleep.

In the Clarence Center investigation, the evidence indicated that both the captain and first officer had off-duty periods that afforded adequate sleep periods. However, both pilots regularly commuted to their Newark, New Jersey, reporting base from long distances. The captain lived in Florida and the first officer lived in Washington State. Both routinely deadheaded (that is, commuted as an airline passenger) from their home states to their base in New Jersey, and neither had a dedicated "crash pad" or apartment that they used for sleeping away from home. Instead, they used couches in a crew room to obtain rest before the accident flight. Sleeping in the crew room was officially prohibited by the airline, and there was a policy that said that the lights must remain on at all times. Nonetheless, pilots used it for this purpose. The investigators were concerned that these commutes and sleeping arrangements did not afford good-quality sleep. On the basis of that concern, investigators gathered additional data about pilots' commuting practices at the airline.

The data showed that approximately two thirds of the accident airline's pilots identified themselves as commuters, and many pilots' homes were hundreds of miles or more from their reporting base in Newark (Table 3.1). However, the airline's chief pilot stated that he did not know the number of commuting pilots at the airline. Further, although the airline had a commuting policy, that policy was mainly designed to ensure that pilots were able to arrive at their base and report for duty on time and did not reference ways to mitigate fatigue resulting from commuting. As a result of its investigation, NTSB recommended that the Federal Aviation Administration (FAA) require airline operators to address fatigue risks associated with commuting, including identifying pilots who commute, establishing policy and guidance to mitigate fatigue risks for commuting pilots, using scheduling practices to minimize opportunities for fatigue in commuting pilots, and developing or identifying rest facilities for commuting pilots (NTSB, 2010). Commuting pilots is the kind of safety issue that investigators may uncover in an investigation that indicates a potential fatigue risk in the system. Unlike a criminal investigation, whereby the evidence must prove culpability or liability, this type of safety-related investigation has to obtain only enough evidence to show that the risk exists and needs to be addressed before it becomes a factor in an accident.

Table 3.1. Geographic Distribution of Colgan Air Pilots Based at Newark Liberty International Airport (EWR), Newark, New Jersey.

Distance From Newark (in statute miles)	*Number of Pilots*	*States Represented*
Less than 100	45	Connecticut, New Jersey, New York, Pennsylvania
100 to 199	13	Maryland, Massachusetts, New York, Pennsylvania, Rhode Island
200 to 399	29	Maine, Massachusetts, New Hampshire, New York, North Carolina, Pennsylvania, Virginia
400 to 999	20	Florida, Georgia, Illinois, Iowa, Michigan, Ohio, South Carolina, Tennessee, West Virginia
1,000 or more	29	California, Colorado, Florida, Louisiana, Minnesota, Nevada, Texas, Utah, Washington

Source: National Transportation Safety Board (2010, p. 48).
Note: Geographic distances from EWR were determined using the pilots' address on record with the Federal Aviation Administration. The number of statute miles was based on straight-line distances between zip codes.

Operator Health

There are numerous health-related conditions that can affect sleep quality, sleep quantity, and sleepiness during waking periods, such as insomnia, OSA, restless legs syndrome, and narcolepsy. Other medical conditions, such as gastroesophageal reflux disease (GERD), chronic pain, and alcoholism, also have known negative effects on sleep. In addition, multiple drugs, medications, and drug interactions can affect sleep or wakefulness.

Perhaps the most notable sleep disorder with respect to transportation safety is OSA. OSA, a condition in which an individual obstructs his or her own airway while sleeping, resulting in interruptions in breathing and nonrestful sleep, is widely recognized as a significant risk factor in transportation accidents because it is very common (Young, Peppard, & Gottlieb, 2002, reported approximately 7% of the overall population), especially among people who are obese, and is often undiagnosed (Resta et al., 2001). For example, accident data have shown that OSA can be a significant risk factor in driving; a driver with OSA is 6 to 7 times more likely to be in a crash than a driver without OSA (Teran-Santos, Jiminez-Gomez, Cordero-Guevara, & Cooperative Group Burgos-Santander, 1999).

Guidelines put forth by a joint task force of the American College of Chest Physicians, American College of Occupational and Environmental Medicine, and the National Sleep Foundation (Hartenbaum et al., 2006) set screening recommendations for commercial drivers with possible or probable OSA. For example, the task force recommended an in-service evaluation and a 3-month maximum conditional certification for drivers that fall into any one of the following five major categories:

1. Sleep history suggestive of OSA (snoring, excessive daytime sleepiness, witnessed apneas)
2. Two or more of the following:
   a. Body mass index (BMI) ≥35 kg/m^2
   b. Neck circumference greater than 17 inches in men, 16 inches in women
   c. Hypertension (new, uncontrolled, or unable to control with less than 2 medications)
3. Epworth Sleepiness Scale Score (ESS) greater than 10
4. Previously diagnosed sleep disorder; compliance claimed but no recent medical visits/compliance data available for immediate review (must be reviewed within 3-month period); if found not to be compliant, should be removed from service (includes surgical treatment)
5. Apnea/hypopnea greater than 5 but less than 30 in a prior sleep study or polysomnogram and no excessive daytime somnolence (ESS less than 11), no motor vehicle accidents, no hypertension requiring two or more agents to control

The Federal Motor Carrier Safety Administration Medical Review Board (MRB) has subsequently recommended OSA screening for all drivers with a BMI over 30, among other criteria. For drivers with a BMI equal to or greater than 33, the MRB recommends that drivers be conditionally certified for 1 month pending the findings of a sleep study.

OSA has been found to be an important issue in a number of recent NTSB investigations. The driver of the motorcoach in the New York crash exhibited physical and medical characteristics that are indictors of susceptibility to sleep disorders. In another recent motorcoach accident, the driver was being treated for OSA, and his sporadic use of his CPAP sleeping device in the days leading up to the accident, combined with other fatigue-related factors, led NTSB to conclude that the driver was fatigued (NTSB, 2009). In this accident, a motorcoach carrying 52 passengers ran off the road near Mexican Hat, Utah; struck a guardrail; drove down an embankment; then rolled over, killing nine passengers and injuring all the other passengers and driver. Fatigue issues associated with OSA have also been cited in NTSB investigative reports of marine and railroad accidents (NTSB, 2009, 2011).

Documenting operator health evidence. To determine if sleep disorders or other medical factors (e.g., disease or drug use) are an issue in an investigation, multiple sources of information should be evaluated. Key sources include interviews with the operator, interviews with the spouse or family members, interviews with the operator's personal physician or medical examiner, fitness examination records, personal health records, pharmacy records, and postaccident toxicology analysis. Depending on the investigation, some of these records may be particularly difficult or impossible to obtain without operator permission or subpoena authority due to privacy considerations and legal protections.

During an interview, the following questions can help to elicit information about health conditions that affect sleep or wake-time alertness:

- Do you have difficulty falling asleep or staying asleep?
- Have you ever told a doctor about how you sleep? If so, why, when, and what was the result?
- Do you snore when you sleep (or have you been told that you do)?
- What drugs/medications do you use regularly, and did you take any in days prior to the accident?
- Do you have any medical concerns that affect your sleep (e.g., chronic pain, GERD, etc.)?
- Do you ever feel sleepy or nod off during the day or during work?
- How is your health in general?

Keep in mind that some operators may not be aware of health issues or may conceal them if they fear criminal prosecution or loss of employment. Other physical and medical indicators can also provide useful information about potential health-related issues:

- Review of operator's toxicological results for substances that may affect sleep or alertness; examples include alcohol, tranquilizers, sedative-hypnotics (e.g., sleep aids), and certain popular antihistamines, such as diphenhydramine
- Operator's height, weight, and neck circumference measurements made during an interview or from medical records
- Operator's medical or pharmacy records or any drugs or medicine found at the accident site
- Postaccident operator evaluation by physician who specializes in sleep medicine

Other Factors: Environment, Task, and Organization

In terms of determining whether an individual was influenced by fatigue at the time of an event, his or her sleep/wake history and health are the most important factors to consider. However, an investigator should also consider environmental, task, and organizational factors. It is rare that any of these factors alone lead to a state of severe fatigue in the absence of sleep loss, circadian factors, or health issues; however, an understanding of each of them can provide important insights in an investigation of fatigue factors. For example, certain environmental or task factors can exacerbate preexisting fatigue and lead to fatigue-related performance decrements. Organizational factors may give clues about workplace polices or cultural factors that foster the development of operator fatigue. Finally, an understanding of these factors may provide valuable information about how future risk may be mitigated.

Environmental and task factors. Several environmental and task factors relevant to transportation operations have been associated with increases in sleepiness and reductions in performance, including monotonous driving conditions (Larue, Rakotonirainy, & Pettitt, 2011; Thiffault & Bergeron, 2003), extreme high- or low-workload conditions (Åkerstedt, Fredlund, Gillberg, & Jansson, 2001; Grech, Neal, Yeo, Humphreys, & Smith, 2009), and dim lighting (Phipps-Nelson, Redman, Dijk, & Rajaratnam, 2003). To document environmental and task factors, investigators should interview the accident operator or coworkers about the job in general and about the specific tasks conducted on the day of the accident. Direct observation of the work environment, if feasible, can also provide valuable insights. For example, in the November 2004 collision between two transit trains in Washington, D.C., investigators looked at all aspects of fatigue and found that task factors created an environment in which the operator was susceptible to fatigue-related errors (NTSB, 2006). The collision occurred when a nonrevenue train (that is, one not carrying passengers) that was paused in a tunnel rolled backward down a grade and collided with the revenue train that was traveling behind it. The physical evidence showed no signs that the operator applied the brakes or took any other measures to stop the train as it rolled backward down the grade for about 78 s and ultimately struck the revenue train.

When investigators looked at the activity history of the operator, they determined that his opportunity for uninterrupted sleep in the 38 hr prior to the accident was limited to about 5 hr. Additionally, investigators learned that the operator had been experiencing GERD in the month leading to the accident, which may have affected sleep quantity and quality.

With respect to task factors, the investigative report noted that during the accident trip, the train operator's task demands were relatively low. He was operating during off-peak hours, a time when the system moves fewer trains and the time between revenue trains is greater. Additionally, because the train was not in service as a revenue train, the operator did not need to attend to passengers, make public address announcements, stop at stations, or operate the doors.

During test rides in the control cab of an exemplar train, investigators noted that the operating compartment of the train, even while the train was moving, was generally comfortable and quiet, particularly when the master controller was in the coast setting. Safety board investigators further noted during their test rides that a train rolling back remains relatively quiet and free of unusual sounds, creating minimal rocking or vibration and only a subtle physical sensation of movement. Under these conditions, there were no obvious external cues that would have been a deterrent to an operator's reduced alertness.

NTSB concluded that the low task demands and unremarkable operating environment during the accident trip were conducive to the train operator's becoming disengaged from some critical train operations and that the cause of the collision was his failure to apply the brakes due to his reduced alertness.

Organizational factors. When investigating organizational factors, investigators should, at a minimum, determine whether the organizational leaders are aware of, and adhering to, fatigue-related regulations and guidance, such as the rules that govern hours of service and the medical fitness of operators. Ideally, an organization will be following all established rules and will also have FRMSs in place that include science-based work schedules, fatigue-risk mitigation training for employees, and screening and treatment of sleep disorders.

To document organizational factors, an investigator may request company policies, handbooks, or labor contracts. Additionally, he or she can interview employers, coworkers, or dispatchers about scheduling practices and absenteeism policies and fatigue-related training. Investigators may also be able to observe whether workplaces provide access to fatigue countermeasures, such as nap rooms or caffeinated beverages.

Organizational factors that affected operator fatigue played a key role in the February 18, 2007, Embraer ERJ-170 runway overrun in Cleveland, Ohio. When interviewed by investigators, the captain reported that he felt well rested on the day before the accident but that he was unable to sleep that night and received only 45 min to 1 hr of sleep. The captain did not advise his employer about his fatigue or remove himself from duty and explained he felt he would be terminated if he took this action. The captain had received a written warning a month prior to the accident about having too many "unexcused absence occurrences," including a case in which the captain attempted, unsuccessfully, to call in fatigued. The written warning indicated that future absence occurrences (including fatigue calls that were not considered to be "company induced") could result in termination. Ultimately, NTSB identified as contributing factors in the accident "the captain's fatigue, which affected his ability to effectively plan for and monitor the approach and landing" and "the company's failure to administer an attendance policy that permitted flight crewmembers to call in as fatigued without fear of reprisals" (NTSB, 2008, p. 67).

When Fatigue Is Difficult to Determine

Unfortunately, not all accidents have sufficient data to adequately characterize sleep/wake history and/or health issues. This situation was especially true in an accident involving a collision between a truck and an Amtrak passenger train near Miriam, Nevada, on June 24, 2011 (NTSB, 2012a). At about 11:19 a.m., a truck-tractor pulling two side-dump trailers struck an Amtrak train at an active grade crossing on U.S. Highway 95. The flashing lights at the grade crossing were activated, and the gate was in the down position. The collision destroyed the truck-tractor and two passenger railcars. The train came to a stop without derailing; however, a fire ensued, engulfing two railcars and damaging a third railcar. The accident killed the truck driver, the train conductor, and four train passengers; 15 train passengers and one crewmember were injured. Evidence showed that as the truck approached the grade crossing, the driver applied the brakes, but the truck was unable to stop in time.

NTSB determined that the probable cause was the truck driver's delayed braking and the failure of the truck company to adequately maintain the brakes on the accident truck. Based on the evidence, investigators were able to rule out several possible explanations for the driver's delayed braking, including the performance of the grade crossing warning system, alcohol and drug use, medical incapacitation, and the ability of the driver to see the grade crossing warning system. Investigators considered in detail three possible explanations for the driver's delayed braking: fatigue, distraction from using a cell phone, and distraction from pain associated with a medical condition. In doing so, they interviewed the driver's girlfriend, coworkers, and family members and reviewed logbooks, cell phone records, employment records, and medical records.

The evidence showed that the driver generally worked 5 days per week, 11 to 12 hr per day, and during the 2-month period for which driver logs were available, his shifts started about 2:30 a.m. The day of the accident was his 4th day on duty. The driver lived in a camper across the street from his work reporting location during the week and traveled to stay with his girlfriend on the weekends. According to the driver's girlfriend, he typically went to bed by 5:00 p.m. on work nights and awoke at 2:00 a.m. Cell phone records indicated that the driver did not use his two cell phones from approximately 6:30 p.m. to 2:00 a.m. during the 3 days before the accident. Had the driver been in bed during these periods, he would have had the opportunity to sleep approximately 7.5 hr each day, which is within the range that is considered "normal" human sleep. The driver had no risk factors for sleep disorders; however, his sleep quality may have been affected due to difficulty in falling or staying asleep in the early evening hours (Lavie, 1986), his shifting sleep schedules between his work and off-duty days (on his days off, the driver typically went to bed at 9:00 p.m. and awoke at 10:00 a.m.), or pain due to a recent episode of Achilles tendonitis.

The driver reportedly slept 13 hr per night on his days off while sleeping less than 7.5 hr per night during the workweek, indicating that he may have regularly accumulated a sleep debt and used his off days to recover by obtaining extra sleep. The accident driver also traveled for long periods of time on the same route almost every day through a desert environment, driving conditions that have been associated with reductions in vigilance and alertness (Larue et al., 2011). The air conditioning in his truck was apparently broken, and the weather was hot, which may have created a condition that could exacerbate any preexisting fatigue. However, the other possible explanations for the driver's delayed braking—distraction from using a cell phone and distraction from pain associated with a medical condition—could also explain the driver's performance.

This accident and the Continental Flight 3407 accident provide clear examples of the challenges investigators face in gathering fatigue-related evidence when operators are fatally injured. They also illustrate the challenges associated with establishing the link between an operator's fatigued state and the sequence of events that lead to an accident, a topic to be discussed in more detail in the next section.

STEP 2: DID FATIGUE CONTRIBUTE TO THE ACCIDENT?

Once an investigator has determined that an operator was in a fatigued state at the time of the accident, the next step is to determine if the operator's fatigue contributed to the accident. This step also has two important parts to it (Figure 3.2). First, the investigator must determine if the operator's behavior or performance was a causal or contributing factor to the accident. If the operator contributed to the accident, then the investigator must determine if the operator's behavior or performance was consistent with the known effects of fatigue and consider whether alternative explanations may account for the operator's performance. It is beyond the scope of this chapter to discuss how causal and contributing factors are determined in an accident; however, the topic has been treated by a number of researchers concerned with human performance and accident investigation (Coury et al., 2010).

Fatigue has been shown to affect a wide range of human performance, including vigilance and executive attention, psychomotor and cognitive speed, and working memory (Goel, Rao, Durmer, & Dinges, 2009). To relate those performance factors to fatigue, the investigator begins by using available evidence to determine whether the operator's performance was deteriorating prior to the accident. Research tells us that answers to the following questions can provide evidence of fatigue-related effects:

- Did the operator overlook or skip tasks or parts of tasks?
- Was there steering or speed variability?
- Did the operator focus on one task to the exclusion of more important information?
- Was there evidence of delayed responses to stimuli or unresponsiveness?
- Was there evidence of impaired decision making or an inability to adapt behavior to accommodate new information?

There are a variety of information sources that can be used to evaluate operator performance, including the following:

- In-vehicle recorders, such as cockpit voice recorders, cockpit data recorders, air traffic control recordings, marine voyage recorders, rail recorders, engine control modules, forward-facing (common in rail) or operator-/passenger-facing videos (increasingly common in motorcoaches)
- External recorders, such as roadway/traffic cameras, security cameras, witness audio/video recordings
- Operator interview
- Witness/coworker/passenger/crew interviews
- Wreckage inspection (e.g., for evidence of brake use)
- Crash scene inspection (e.g., for evidence of evasive maneuvers, speed at impact)

The availability of this evidence can vary dramatically depending on the investigation. For example, in an air carrier accident, data from the cockpit voice recorder and flight data recorder may yield hours' worth of detailed pilot performance information. In some motorcoach crashes, bus passengers have been able to provide detailed accounts of drivers nodding off, video cameras mounted in the coach can provide views of the roadway and the driver, and data from the engine control module can provide useful data about speed, throttle, and brake usage. By contrast, in most fatal small plane crashes, there is very little evidence about pilot performance in the moments leading to a crash, and it can be very difficult for investigators to determine whether pilot performance was a factor.

In the Mexican Hat motorcoach accident, for example, there was clear evidence of fatigue-related driver performance. In that accident, the motorcoach ran off the road where the roadway curved to the left. The motorcoach was equipped with interior, rear-, and front-facing video cameras that captured both the view out the front windshield and of the driver. Video analysis showed that at the time of the accident, the motorcoach was traveling at 88 mph. Video analysis of the driver showed that he was slow to respond when the motorcoach began to run off the road; in fact, the vehicle traveled 350 feet along the guardrail and onto the embankment before the driver was seen to react in the video with steering input. In the miles leading up to the accident, passengers repeatedly asked the driver to slow down and reported that he had driven off the road and swerved back onto the road. The NTSB report summarized the accident sequence as follows:

> (1) the driver was fatigued and in a diminished state of alertness at the time of the accident; (2) the driver was speeding and neglected to establish an appropriate speed for the upcoming curve; (3) the driver's response to the road departure was delayed; and (4) given that delayed response, the driver had almost no opportunity to regain control of the vehicle. (NTSB, 2009, p. 38)

These accidents represent situations whereby the operator's fatigue can be directly related to performance. However, the mapping of fatigue factors to performance may not be straightforward, for a number of reasons. First, there may be competing explanations for an operator's performance. In the Amtrak/truck collision in Miriam, Nevada, there were two other possible explanations for the driver's delayed braking: distraction from his cell phone and a chronic medical condition. Evidence showed that the driver routinely used his handheld cell phone for talking, texting, and Internet usage while driving. On the day of the accident, during his approximately 8 hr of driving, he made 30 outgoing voice calls, took one incoming voice call, sent one text message, checked voicemail four times, and used the Internet three times. The driver would sometimes allow incoming calls to go to voicemail, and he often checked voicemail within minutes of receiving the call. Although the last outgoing call placed by the driver was a 16-s call initiated 47 min before the accident, the driver received an incoming call at 11:17:28 a.m., 2 min prior to the accident, which was unanswered and went to voicemail. Investigators considered the possibility that the driver may have been attempting to retrieve the voicemail in the moments leading to the accident; however, cell phone records would not have documented an attempt to retrieve the voicemail or to place another call unless the connection had been completed.

The driver was also suffering pain from preexisting medical conditions. The driver had a long history of back pain stemming from a serious injury that took place several months before the accident. Additionally, the driver was diagnosed with Achilles tendonitis about one month before the accident. He was instructed not to work for 1 week, but his driver logs indicate that he continued to work. Cell phone records indicate that the driver called four orthopedic clinics in the 3 hr preceding the accident. One of the clinics reported receiving a call from him on the morning of the accident.

None of the potential explanations for the driver's delay was sufficient enough for NTSB to consider it as part of the probable cause, but the accident report did note in its conclusions that "possible reasons for the driver's delayed braking include fatigue, distraction from using his hand-held cell phone, and distraction from pain associated with his medical ailment" (NTSB, 2012a, p. 49). In terms of our methodology, there was insufficient secondary evidence or indicators to convincingly conclude that fatigue was a factor in this accident.

In addition, there can be evidence of other types of human performance deficiencies that can account for the observed performance errors and degradation in the accident. In the case of the Continental Flight 3407 accident, the pilots failed to detect the impending onset of the stick shaker and responded improperly to the stick shaker warning when it activated, which ultimately led to the accident. Although investigators noted that such errors, and other workload management errors made by the crew, could be consistent with fatigue, those errors have also been observed in pilots who are not fatigued. Evidence from the cockpit voice recorder indicated that the pilots were conversational and engaged throughout the flight. Additionally, some of the errors made by the captain during the accident flight were consistent with his pattern of performance failures during upgrade training and recurrent testing, which he had experienced throughout his flying career. Interviews with the airline's training instructors revealed that the captain continued to have problems with aircraft control. For example, a simulator instructor for the airline stated that during unusual-attitude training, the captain was "very rough" on the controls and had somewhat overcontrolled the roll axis (NTSB, 2010, p. 117).

Competing explanations for observed operator behavior and preexisting conditions complicate Step 2 of the NTSB methodology. Although there is considerable research relating fatigue factors to human performance, the challenge facing an accident investigator is using available evidence to support a position that relates the fatigue factors identified in Step 1 to the known behavior of the operator and the vehicle. Often, the investigator must consider a number of human performance issues before any conclusions can be drawn about the effects of fatigue in an accident. As Coury et al. (2010) point out in their discussion of accident investigation methods, there may be many interactions among different human performance issues in a major transportation accident, and it is these interactions that make such investigations so complex and difficult. To understand these interactions requires an iterative approach, whereby human performance issues, such as fatigue, generate specific questions about the accident, and it is those questions that determine the requirements for evidence gathering. When there are multiple, competing explanations that involve unquantifiable and often contradictory information, the solution path through the resolution of human performance issues may be uncertain. The investigator may pursue multiple investigative paths before finding the correct one.

An investigator's conclusions about the effect of fatigue on operator performance will be based on considerable knowledge and expertise and an ability to relate research to practice. In a safety-related accident investigation, this knowledge and expertise is crucial, because the investigator will have to construct an explanation that best fits the evidence and that can bear scrutiny from the multiple stakeholders involved in the investigation. However, as seen in the Continental Flight 3407 accident, there does not need to be a direct relationship between fatigue and human performance in order to identify a potential safety issue related to fatigue risk. The risk associated with crews' commuting long distances could result in fatigue due to inadequate sleeping conditions and circadian dysrhythmia from crossing multiple time zones. Consequently, the risk may be high enough for new policy and practices to be implemented to mitigate the potential effects of fatigue.

DISCUSSION AND CONCLUSION

Fatigue is a critical issue in transportation and can be a contributing factor in major transportation accidents. The fatigue accident investigation methodology presented in this chapter has illustrated how a structured approach, based on fatigue research, can be used to investigate the role of fatigue in a major transportation accident. The methodology focuses on two fundamental steps in evaluating the effects of fatigue in an accident: first, determining if the operator was in a fatigued state and, then, determining if the operator's fatigue contributed to the accident.

This two-part, sequential approach (as shown in Figures 3.1 and 3.2) is applicable to both research and accident investigation. As previously discussed, researchers have long acknowledged that the presence of fatigue will not automatically produce operator errors, resulting in a system failure. In fact, the challenge facing both researchers and accident investigators is to determine if and when the presence of fatigue will have a detrimental effect on human performance and result in deterioration in system performance. As Perrow (1984) pointed out some time ago, transportation systems involve a complex coupling between people and technology, and it is the interaction among the components of a system that is the source of system failure.

Fortunately, fatigue research has progressed to the point that under certain circumstances, the mapping of fatigue effects to human performance errors can be straightforward. This was certainly the case in both the New York City and the Mexican Hat, Utah, motorcoach accidents, whereby concrete evidence of the drivers' fatigue state and clear measures of driver performance errors were found. This mapping is also aided by recent advances in evidence-gathering techniques and in new data sources (especially electronic and digital data). Cell phone records (including voice, text, and data), surveillance cameras, vehicle data and voice recorders, onboard vehicle location data, and electronic operator logs are just some of the data sources that are available for investigators to use in recreating an individual's activity patterns. The New York City motorcoach accident is an excellent example of the use of cell phone records, cellular network data, and rental car location data to construct an accurate record of the driver's pattern of sleep opportunities and wake periods, a pattern that was crucial to determining the driver's fatigue state.

The importance of indirect or secondary measures in accident investigation merits specific emphasis. Because there is no existing direct measure of fatigue, these indirect or secondary measures are needed to estimate whether an individual was likely fatigued and whether any fatigue-related errors contributed to the accident. And, because no single measure or piece of evidence is usually sufficient to indicate fatigue, the investigator must rely on a set of indicators that can be cross-validated with known fatigue effects. Without integrating these measures into a structured methodology, the role played by fatigue-related factors in an accident will be difficult, if not impossible, to determine, especially when the crew or operators do not survive the accident. The importance of

using multiple sources of fatigue evidence to confirm that the operator was in a fatigued state cannot be emphasized enough in accident investigation.

The NTSB fatigue investigation methodology also emphasizes the central role of an individual's sleep and wake history in the determination of fatigue. As seen in the first step of the methodology (Figure 3.1), the majority of the investigator's time will be spent determining the amount of sleep the operator obtained in the days and hours leading up to the accident and the pattern of sleep and wake periods during those periods. The sleep/wake history graph (Figure 3.4) is an important tool in the NTSB methodology, providing a graphical representation of the length and frequency of sleep opportunities. This graph, especially when combined with any known medical issues that can affect sleep, provides the basis for much of the analysis of an individual's fatigue state. Indeed, an investigator's assessment of the effects of other factors (such as circadian rhythms, sleep quality, and environment) will be dependent upon a thorough understanding of an individual's sleep and wake patterns. Consequently, one can only conclude that the amount of sleep is the cornerstone of any assessment of fatigue and its role in an accident.

Unfortunately, determining the role of fatigue in an accident remains a challenge. As useful as secondary measures can be in verifying sleep/wake patterns, the data are not always readily available or sufficient to conclude that an individual was suffering from the effects of sleep loss. In the Continental Flight 3407 accident, for example, there was plenty of data but not sufficient evidence to account for all of the opportunities for the crew to obtain sleep, and other evidence (e.g., flight data and cockpit voice recordings) did not reveal any indicators of fatigue. Although there were no direct indicators of fatigue in that accident, investigators did identify potential risk factors associated with long-distance commutes between home and duty station and the lack of adequate sleep facilities for commuting crew.

In addition, fatigue may be only one explanation for the observed human performance. Many decades of human factors research has shown that human error can arise from many causes, and research has identified many of the important dimensions of human performance that would account for errors and performance degradation. An accident investigator then must be cognizant of these other potential factors and take them into consideration when using the second step of the methodology (Figure 3.2) to determine if fatigue contributed to the accident. The Continental Flight 3407 accident, and the collision between the truck and Amtrak train in Miriam, Nevada, illustrated very well the potential for other competing explanations (such as training, other distractions, and medical issues) to account for the observed behavior. In both cases, the individuals being assessed did not survive; consequently, conclusions about fatigue had to be based on secondary measures for both sleep patterns and performance.

Although the discussions in this chapter have focused on the operator, there is no doubt that the performance of the entire system can be affected by fatigue in other areas. For example, fatigue-related errors made during vehicle maintenance can introduce serious risk into transportation systems. The methods described in this chapter may be applied to other safety-critical personnel in the transportation system; however, if the errors under consideration occurred weeks or months before the accident, recreating sleep/wake histories can become even more challenging than in accidents involving operator error.

Finally, as extremely useful fatigue research is to an investigator, there are still gaps in our understanding of fatigue that would benefit from additional research. For example, as recent announcements from the Food and Drug Administration (FDA) have suggested, many popular sleep aids may impair driving ability (Thomas, 2013). This knowledge has led the FDA to ask manufacturers to cut standard drug doses for women and to conduct driving performance research on new sleep drugs. However, there are many drugs that have the potential to affect sleep and waking performance. Additional research in this area has the potential both to improve consumer and transportation safety and as a resource to accident investigators in understanding the potential impairing effects of certain drugs.

A second area where more research could have widespread benefit for both accident investigators and transportation safety professionals is in the refinement and validation of fatigue biomathematical models. For many years, researchers have been developing models to predict operator alertness and performance using data such as work or sleep schedules. Recent studies have used such models to predict railroad accidents (Hursh, Fanzone, & Raslear, 2011), serious-injury road crashes (Åkerstedt, Connor, Gray, & Kecklund, 2008), truck accidents (Dorrian, Sweeney, & Dawson, 2011), and flight attendant performance (Roma, Hursh, Mead, & Nesthus, 2012). Fatigue models have already been adopted by some organizations as part of their accident documentation process (Federal Railroad Administration, 2003), and as these models continue to evolve, it is likely that more organizations will adopt them as part of their FRMS and as a tool for accident investigation.

A third area where future research is needed pertains to the continued development and evaluation of in-vehicle fatigue-monitoring technologies. As previously discussed, improvements in data (especially digital) have helped investigators construct more accurate records of an individual's sleep, wake, and activity periods. The increasing use of vehicle data recorders and video surveillance will continue to aid investigators, especially in commercial transportation, but there needs to be greater attention paid to the development and evaluation of in-vehicle technologies that can track fatigue and potentially mitigate the effects of fatigue-related performance decrements. Although there are many commercially available vehicles that already have such technologies available, little is known about their real-world performance in reducing fatigue-related accidents.

Ultimately, the goal of a safety-oriented accident investigation is to identify underlying causes and contributing factors that can be removed and/or mitigated. The NTSB fatigue investigation methodology contributes to this goal by identifying factors related to fatigue in an accident and, in addition and sometimes more importantly, the fatigue risk factors that could potentially affect system performance. For example, in the Continental Flight 3407 accident, a company policy that allowed crew to commute long distances between home and duty station without any provision for crew rest facilities was cited by NTSB as a potential risk factor for fatigue. In this accident, it was evident that management decisions had created a situation that could potentially result in crew fatigue. This conclusion from the investigation also highlights a management and policy risk factor not addressed in fatigue research. Investigations mentioned throughout this chapter and several others that came before have resulted in recommendations to regulators, companies, or others to address fatigue. Over the past several decades, NTSB has made recommendations to revise hours-of-service regulations; improve scheduling policies and practices; establish FRMS programs; institute systems for screening, diagnosing, and treating sleep disorders; and developing in-vehicle technologies that can reduce fatigue-related accidents.

The complex nature of transportation accidents also helps enlighten the research community about potential fatigue risk factors. As Coury et al. (2010) pointed out, an accident can be a test of the assumptions underlying a system or the source of new information that can help us understand causation. Perrow's (1984) characterization of a system as a complex coupling of people and technology is very applicable to transportation, and the role of fatigue in system performance can be a difficult one to determine. However, the use of a structured approach to fatigue accident investigation can both effectively use fatigue research to reach conclusions and inform the research community about the fatigue risk factors uncovered in the field.

As investigative methods continue to evolve and technologies, such as recorders, proliferate, our understanding of multiple human performance areas, including fatigue, will improve. The subsequent improvements in investigative methods will help investigators better understand the size and scope of the fatigue problem in transportation and produce results and recommendations that will better serve the transportation community. More importantly, better documentation of fatigue in accidents can facilitate evaluations of the effectiveness of current and future countermeasures and enable us to identify those countermeasures that can be most effective in addressing fatigue-related accidents and to reduce the fatalities and injuries that result from them.

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REFERENCES

Åkerstedt, T., Connor, J., Gray, A., & Kecklund, G. (2008). Predicting road crashes from a mathematical model of alertness regulation: The sleep/wake predictor. *Accident Analysis & Prevention, 40*, 1480–1485.

Åkerstedt, T., Fredlund, P., Gillberg, M., & Jansson, B. (2001). Work load and work hours in relation to disturbed sleep and fatigue in a large representative sample. *Journal of Psychosomatic Research, 53*, 585–588.

Associated Press. (1918, June 24). Engineer slept at the throttle. *Fort Wayne News and Sentinel*, p. 1.

Banks, S., Van Dongen, H. P. A., Maislin, G., & Dinges, D. F. (2010). Neurobehavioral dynamics following chronic sleep restriction: Dose-response effects of one night for recovery. *Sleep, 33*, 1013–1026.

Belenky, G., Hanowski, R., & Jovanis, P. (2013). *Expert panel report: Fatigue and commercial motorcoach/bus driver safety*. Retrieved from http://www.mrb.fmcsa.dot.gov/documents/Meetings2013/Expert%20Panel%20Recommendations%20-%2012-20-2012%20EP%20Report%20-%20version%206_mt%20revisions-2-5-13.pdf

Belenky, G., Wesensten, J. J., Thorne, D. R., Thomas, M. L., Sing, H. C., Redmond, D. P., Russo, M. B., & Balkin, T. J. (2003). Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: A sleep dose-response study. *Journal of Sleep Research, 12*, 1–12.

Carskadon, M. A., & Roth, T. (1991). Sleep restriction. In T. H. Monk (Ed.), *Sleep, sleepiness and performance* (pp. 156–167). Hoboken, NJ: Wiley.

Cohen, D. A., Wang, W., Wyatt, J. K, Kronauer, R. E., Dijk, D., Czeisler, C. A., & Kerman, E. B. (2010). Uncovering residual effects of chronic sleep loss on human performance. *Science Translational Medicine, 2*(14), 1–16. doi:10.1126/scitranslmed.3000458

Connor, J., Norton, R., Ameratunga, S., Robinson, E., Civil, I., Dunn, R., Bailey, J., & Jackson, R. (2002). Driver sleepiness and risk of serious injury to car occupants: Population based on case control study. *British Medical Journal, 324*, 1125.

Coury, B. G., Ellingstad, V. S., & Kolly, J. M. (2010). Transportation accident investigation: The development of human factors research and practice. In D. H. Harris (Ed.), *Reviews of human factors and ergonomics* (Vol. 6, pp. 1–33). Santa Monica, CA: Human Factors and Ergonomics Society.

Coury, B. G., Kolly, J. M., Gormley, E., & Dietz, A. (2008). The central role of principal issues in aviation accident investigation. In *Proceedings of the Human Factors and Ergonomics Society 52nd Annual Meeting* (pp. 99–103). Santa Monica, CA: Human Factors and Ergonomics Society.

Dawson, D., & McCulloch, K. (2005). Managing fatigue: It's about sleep. *Sleep Medicine Reviews, 9*, 365–380.

Doran, S. M., Van Dongen, H. P. A., & Dinges, D. F. (2001). Sustained attention performance during sleep deprivation: Evidence of state instability. *Archives Italiennes de Biologie, 139*, 253–267.

Dorrian, J., Sweeney, M., & Dawson, D. (2011). Modeling fatigue-related truck accidents: Prior sleep duration, recency and continuity. *Sleep and Biological Rhythms, 9*, 3–11.

Federal Railroad Administration. (2003). *Human factors circadian rhythms supplement* (FRA Technical Bulletin G-03-02). Washington, DC: Author.

Gabree, S. H., Johnson, N., & Comperatore, C. (2012). *The fatigue factor: Phase 1, assessment of organizational capabilities to identify contributory and causal fatigue effects in accident investigations*. Unpublished manuscript.

Goel, N., Rao, H., Durmer, J. S., & Dinges, D. F. (2009). Neurocognitive consequences of sleep deprivation. *Seminars in Neurology, 29*, 320–339.

Goel, N., Van Dongen, H. P. A., & Dinges, D. F. (2011). Circadian rhythms in sleepiness, alertness, and performance. In M. H. Kryger, T. Roth, & W. C. Dement (Eds.), *Principles and practice of sleep medicine* (5th ed., pp. 445–455). St. Louis, MO: Elsevier Saunders.

Graeber, C. R., Lauber, J. K., Connell, L. J., & Gander, P. H. (1986). International aircrew sleep and wakefulness after multiple time zone flights: A cooperative study. *Aviation, Space, and Environmental Medicine, 57*(12), 3–9.

Grech, M. R., Neal, A., Yeo, G. B., Humphreys, M., & Smith, S. (2009). An examination of the relationship between workload and fatigue within and across consecutive days of work: Is the relationship static or dynamic? *Journal of Occupational Health Psychology, 14*, 231–242.

Hartenbaum, N., Collop, N., Rosen, I. M., Phillips, B., George, C. F., Rowley, J. A., Freedman, N., Weaver, T. E., Gurubhagavatula, I., Strohl, K., Leaman, H. M., & Moffitt, G. L. (2006). Sleep apnea and commercial motor vehicle operators: Statement from the Joint Task Force of the American College of Chest Physicians, American College of Occupational and Environmental Medicine, and the National Sleep Foundation. *Journal of Occupational and Environmental Medicine, 48*(9), 34–37.

Heinrich, H. W. (1931). *Industrial accident prevention*. New York, NY: McGraw-Hill.

Heinrich, H. W. (1941). *Industrial accident prevention* (2nd ed.). New York, NY: McGraw-Hill.

Hursh, S. R., Fanzone, J. F., & Raslear, T. G. (2011). *Analysis of the relationship between operator effectiveness measures and economic impacts of rail accidents* (Report No. DOT/FRA/ORD-11/13). Washington, DC: Federal Railroad Administration.

The I.C.C. report on the Ivanhoe collision. (1918). *Railroad Safety Engineer, 11*, 354–356.

International Civil Aviation Organization. (2011). *Fatigue risk management systems: Implementation guide for operators* (1st ed.). Retrieved from http://www2.icao.int/en/FatigueManagement/FRMS%20Tools/FRMS%20Implementation%20Guide%20for%20Operators%20July%202011.pdf

Interstate Commerce Commission. (1918). *Report of the chief of the bureau of safety covering the investigation of an accident which occurred on the Michigan Central Railroad at Ivanhoe, Ind., on June 22, 1918*. In conjunction with the Indiana Public Service Commission. Washington, DC: Government Printing Office.

Larue, G., Rakotonirainy, A., & Pettitt, A., (2011). Driving performance impairments due to hypovigilance on monotonous roads. *Accident Analysis & Prevention, 43*, 2037–2046.

Lavie, P. (1986). Ultrashort sleep-waking schedule, III: "Gates" and "forbidden zones" for sleep. *Electroencephalography and Clinical Neurophysiology, 63*, 414–425.

Lytle, R. M. (2010). *The great circus train wreck of 1918*. Charleston, SC: History Press.

National Advisory Committee on Aeronautics. (1928). *Aircraft accidents: Method of analysis* (Report No. 308). Washington, DC: Author.

National Heart, Lung, and Blood Institute. (2005). *Your guide to healthy sleep* (NIH Publication 06-5271). Washington, DC: Department of Health and Human Services.

National Transportation Safety Board. (1986). *Grounding of the Panamanian-flag passenger car-ferry M / V A. Regina, Mona Island, Puerto Rico, February 15, 1985* (Marine Accident Report NTSB/MAR-86/02). Washington, DC: Author.

National Transportation Safety Board. (1987). *Trailway Lines, Inc. innercity bus collision with Rising Fast Trucking Company, Inc., Interstate Highway 40 near Brinkley, Arkansas, July 14, 1986* (Highway Accident Report NTSB/HAR-87/05). Washington, DC: Author.

National Transportation Safety Board. (1989). *Head-end collision of Consolidated Rail Corporation freight trains UBT-506 and TV-61 near Thompsontown, Pennsylvania, January 14, 1988* (Railroad Accident Report NTSB/RAR-89-02). Washington, DC: Author.

National Transportation Safety Board. (1993). *Uncontrolled collision with terrain, American International Airways; Flight 808, US Naval Air Station, Guantanamo Bay, Cuba; August 18, 1993* (Aviation Accident Report NTSB/AAR-94-04). Washington, DC: Author.

National Transportation Safety Board. (2006). *Collision between two Washington Metropolitan Area Transit Authority trains at the Woodley Park-Zoo/Adams Morgan Station in Washington, D.C., November 3, 2004* (Railroad Accident Report NTSB/RAR-06/01). Washington, DC: Author.

National Transportation Safety Board. (2008). *Runway overrun during landing, Shuttle America, Inc., doing business as Delta Connection Flight 6448, Embraer ERJ-170, N862RW, Cleveland, Ohio, February 18, 2007* (Aircraft Accident Report NTSB/AAR-08/01). Washington, DC: Author.

National Transportation Safety Board. (2009). *Motorcoach run-off-the-road and rollover, U.S. Route 163, Mexican Hat, Utah, January 6, 2008* (Highway Accident Report NTSB/HAR-09/01). Washington, DC: Author.

National Transportation Safety Board. (2010). *Loss of control on approach, Colgan Air, Inc., operating as Continental Connection Flight 3407, Bombardier DHC-8-400, N200WQ, Clarence Center, New York, February 12, 2009* (Aviation Accident Report NTSB/AAR-10/01). Washington, DC: Author.

National Transportation Safety Board. (2011). *Collision of tankship* Eagle Otome *with cargo vessel* Gull Arrow *and subsequent collision with the* Dixie Vengeance *tow, Sabine-Neches Canal, Port Arthur, Texas, January 23, 2010* (Marine Accident Report NTSB/MAR-11/04). Washington, DC: Author.

National Transportation Safety Board. (2012a). *Highway–railroad grade crossing collision, US Highway 95, Miriam, Nevada, June 24, 2011* (Highway Accident Report NTSB/HAR-12/03). Washington, DC: Author.

National Transportation Safety Board. (2012b). *Motorcoach run-off-the-road and collision with vertical highway signpost, Interstate 95 Southbound, New York City, New York, March 12, 2011* (Highway Accident Report NTSB/HAR-12/01). Washington, DC: Author.

Nesthus, T. E. (2011, May). *Comparison of aviation industry fatigue reporting forms as established in fatigue risk management systems (FRMS).* Paper presented at the annual meeting of the Aerospace Medical Association, Anchorage, AK.

Perrow, C. (1984). *Normal accidents.* Princeton, NJ: Princeton University Press.

Phipps-Nelson, J., Redman, J. R., Dijk, D. J., & Rajaratnam, S. M. (2003). Daytime exposure to bright light, as compared to dim light, decreases sleepiness and improves psychomotor vigilance performance. *Sleep, 26,* 695–700.

Powell, D. (2011, September). *Fatigue reporting forms and the role of the fatigue safety action group.* Paper presented at the 2011 FRMS Forum, Montreal, Canada.

Price, J. M. (2005, September). *A review of the evidence investigators use in determining operator fatigue.* Paper presented at the 2005 International Conference on Fatigue Management in Transportation Operations, Seattle, WA.

Rear end collision on Michigan Central. (1918). *Railway Safety Engineer, 11,* 217–219.

Resta, O., Foschino-Barbaro, M. P., Legari, G., Talamo, S., Bonfitto, P., Palumbo, A., Minenna, A., Giorgino, R., & De Pergola, G. (2001). Sleep-related breathing disorders, loud snoring and excessive daytime sleepiness in obese subjects. *International Journal of Obesity and Related Metabolic Disorders, 25,* 669–675.

Richardson, G., & Malin, M. (1996). Circadian rhythm sleep disorders: Pathophysiology and treatment. *Journal of Clinical Neurophysiology, 13,* 17–31.

Roehrs, T., Burduvali, E., Bonahoom, A., Drake, C., & Roth, T. (2003). Ethanol and sleep loss: A "dose" comparison of impairing effects. *Sleep, 26,* 981–985.

Roma, P. G., Hursh, S. R., Mead, A. M., & Nesthus, T. E. (2012). Flight attendant work/rest patterns, alertness, and performance assessment: Field validation of biomathematical fatigue modeling (Report No. DOT/FAA/AM-12/12). Washington, DC: Federal Aviation Administration.

Rosekind, M. R., Gregory, J. B, Miller, D. L., Co, I. L., Lebacqz, V., & Brenner, M. (1994). Examining fatigue factors in accident investigations: Analysis of Guantanamo Bay aviation accident. In *National Transportation Safety Board Aviation Accident Report: Uncontrolled collision with terrain, American International Airways; Flight 808, US Naval Air Station, Guantanamo Bay, Cuba; August 18, 1993, NTSB/AAR-94-04* (pp. 133–141).Washington, DC: National Transportation Safety Board.

Tepas, D. I., & Carvalhais, A. B. (1990). Sleep patterns of shiftworkers. *Occupational Medicine, 5,* 199–208.

Teran-Santos, J., Jimenez-Gomez, A., Cordero-Guevara, J., & Cooperative Group Burgos-Santander. (1999). The association between sleep apnea and the risk of traffic accidents. *New England Journal of Medicine, 340,* 847–851.

Thiffault, P., & Bergeron, J. (2003). Monotony of road environment and driver fatigue: A simulator study. *Accident Analysis & Prevention, 35,* 381–391.

Thomas, K. (2013, August 13). To judge sleep aids, U.S. looks at drowsy driving in the morning. *The New York Times.* Retrieved from http://www.nytimes.com/2013/08/14/business/to-judge-sleep-aids-us-looks-at-drowsy-driving-in-the-morning.html?pagewanted=all&_r=0

Van Dongen, H. P. A., & Dinges, D. (2005). Circadian rhythms in sleepiness, alertness, and performance. In M. H. Kryger, T. Roth, & W. C. Dement (Eds.), *Principles and practice of sleep medicine* (4th ed., pp. 435–443). Philadelphia, PA: Elsevier.

Van Dongen, H. P. A., Maislin, G., Mullington, J. M., & Dinges, D. F. (2003). The cumulative cost of additional wakefulness: Dose-response effects on neurobehavioral functions and sleep physiology from chronic sleep restriction and total sleep deprivation. *Sleep, 26,* 117–126.

Van Laethem, M., Beckers, D. G. J., Kompier, M. A. J., Dijksterhuis, A., & Geurts, S. A. E. (2013). Psychosocial work characteristics and sleep quality: A systematic review of longitudinal and intervention research. *Scandinavian Journal of Work, Environment and Health, 39,* 535–549.

Walsh, J. K., Schweitzer, P. K., Sugerman, J. L., & Muehlbach, M. J. (1990). Transient insomnia associated with a 3-hour phase advance of sleep time and treatment with zolpidem. *Journal of Clinical Psychopharmacology, 10,* 184–189.

Wittmann, M., Dinich, J., Merrow, M., & Roenneberg, T. (2006). Social jetlag: Misalignment of biological and social time. *Chronobiology International, 23,* 497–509.

Young, T., Peppard, P. E., & Gottlieb, D. J. (2002). Epidemiology of obstructive sleep apnea: A population health perspective. *American Journal of Respiratory and Critical Care Medicine, 165,* 1217–1239.

Zhou, X., Ferguson, S. A., Matthews, R. W., Sargent, C., Darwent, D., Kennaway, D. J., & Roach, G. D. (2010). Interindividual differences in neurobehavioral performance in response to increasing homeostatic sleep pressure. *Chronobiology International, 27,* 922–933.

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