Investigating Human Fatigue Factors – A Tale of Two Accidents

Katherine Wilson, Ph.D.
Human Performance and Survival Factors Division
National Transportation Safety Board*
USA

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Dr. Katherine A. Wilson is a Senior Human Performance Investigator with the Office of Aviation Safety at the US National Transportation Safety Board, joining the NTSB in 2008. She recently served as the human performance investigator for the Virgin Galactic SpaceShipTwo accident in Mojave, California, and has supported numerous domestic and international accident/incident investigations. She holds a Ph.D. in Applied Experimental and Human Factors Psychology and a M.S. in Modeling and Simulation, both from the University of Central Florida. She has over 15 years of experience studying crew resource management in aviation and healthcare, and holds a private pilot certificate.

The 24/7 nature of aviation means that fatigue will always be a consideration in accident investigations. Fatigue is a condition characterized by increased discomfort with lessened capacity for work, reduced efficiency of accomplishment, and loss of power or capacity to respond to stimulation, and is accompanied by a feeling of weariness and tiredness (FAA Pilot Safety Brochure "Fatigue in Aviation." Publication # OK-07-193). A group of international human performance experts conceded “fatigue…is the largest identifiable and preventable cause of accidents in transport operations.” The adverse effects of fatigue on human performance have been demonstrated in scientific research and accident and incident investigations.(1) These effects include slowed response time, reduced vigilance, and poor decision making. No one is immune and fatigued aviation personnel put themselves and others at risk. However, the ability to collect and analyze data to conclusively identify fatigue as a causal/contributing factor in accidents is challenging as fatigue can be subtle and there is no “blood test” to provide a positive-negative indicator. Investigators must not only determine if persons involved were experiencing fatigue at the time of the accident but also whether their actions were consistent with the known fatigue-related performance decrements.

Over the last decade, tools and techniques for investigating fatigue have evolved, and the number of potential data sources useful to evaluate fatigue in an operator have increased. This paper will highlight the “nuts and bolts” of fatigue investigation in the context of two accident investigations in which the US NTSB, an independent agency, collaborated with the operators, Federal Aviation Administration (FAA), and Bureau d’Enquêtes et d’Analyses pour la Sécurité de l’Aviation Civile (BEA) in accordance with the provisions of Annex 13 to the Convention on International Civil Aviation. Specifically, UPS flight 1354, an Airbus A300 that crashed on approach to Birmingham-Shuttlesworth International Airport, Birmingham, Alabama, and a Eurocopter AS350-B2 helicopter operated by Sundance Helicopters on a sightseeing trip that crashed near Las Vegas, Nevada.

What do we look for?

Before delving into the case studies, it is important to understand what investigators look for to determine whether fatigue played a role in an accident. There are 5 factors that can lead to a fatigued state that are considered in each accident investigation: 1) circadian factors; 2) time since awakening; 3) quantity of sleep; 4) quality of sleep; and 5) sleep disorders.

Circadian factors are those factors affecting an individual's normal circadian rhythm, such as a schedule inversion/rotation or crossing multiple time zones. Humans naturally follow a diurnal schedule, and the primary circadian trough is about midnight to 0600, with the window of circadian low generally occurring between 0300 and 0500. However, shift work and long distance flights across multiple time zones can disrupt this sequence. While research suggests that it is possible to shift one's circadian clock about 1 hour per day, the ideal conditions required are difficult to obtain and the shift is often less. Further, personal obligations often result in the shift worker reverting to a diurnal schedule when off duty thus negating any circadian shift that may have occurred.

Time since awakening refers to the number of hours the individual has been awake since a last major sleep opportunity of 3 hours or more. On average, individuals need 7-9 hours of sleep per night to feel rested upon awakening(2), resulting in 15-17 hours of wakefulness each day. Research quantifying performance impairment associated with sustained wakefulness found that performance remains relatively stable throughout the time that coincides with a normal waking day, but that prolonged wakefulness of 17 hours can result in measurable performance impairment (comparable to having a blood alcohol concentration of 0.05 percent).(3) Other research suggests that being awake for 18 hours can decrease performance by 30%. An NTSB safety study found that flight crewmembers involved in accidents made more procedural errors, tactile decision errors, and errors of omission when awake for more than 12 hours compared to crewmembers awake less than 12 hours.(4)

Quantity of sleep is the number of hours slept during each major sleep period in the days preceding an accident. A minimum of three nights sleep activity should be documented but data should be collected for as back as is considered to be reliable from the source. An individual's normal sleep patterns should also be documented to determine the number of hours needed to be wake rested. Knowing the 'normal' amount of sleep is very important to investigators as it allows a comparison to be made between the number of hours slept and the individual's normal sleep requirements to quantify acute and chronic sleep debt. Just 2 hours of sleep loss can result in reduced performance and alertness.

Quality of sleep, or how well the individual slept, can further help investigators understand an individual's fatigued state. It should be determined whether the individual's sleep was fragmented (e.g., multiple sleep periods in a given 24 hours) and/or disturbed (e.g., awakenings during a sleep period). Factors that can influence quality of sleep include environmental reasons such as noise, light, and phone calls, medical reasons such as heartburn or headache, and internal reasons such as life stressors.

Sleep disorders and medical factors, including physical and mental disorders, and medications can impair sleep and lead to a fatigued state. Physical and mental disorders can include pain, urinary frequency, neurological disease (e.g., Parkinson's, dementia), cough/shortness of breath, and psychiatric disease. Medications for conditions such as depression, hypertension, osteoporosis, and seizures (among others) can also interfere with an individual's sleep. Finally, sleep disorders, including sleep apnea, restless leg syndrome, and narcolepsy can result in a restless night's sleep and a fatigued state. The most common sleep disorder, sleep apnea, affects 10-20% of the adult population.

The data needed to examine these factors should be collected from as many sources as possible. Key evidence sources include, but are not limited to, interviews with the individual operator or those that have knowledge about the individual, work schedules/logbooks, cellular telephone records, audio/video/data recordings, other time-stamped records (e.g., hotel records, company badge access), and medical records. However, there are challenges to collecting such data such as operator availability, memory limitations, perishable evidence, time-stamp irregularities (time zone differences, non-calibrated clocks) and legal hurdles, that must be considered.

Once the data are collected, they must be organized and analyzed to determine whether the operator was fatigued at the time of the accident. If it is determined that the operator was fatigued, it then must be determined whether the actions taken by the operator that led to the accident are consistent with the known performance decrements of fatigue. If the operator's actions are consistent with being fatigued, fatigue likely caused or contributed to the accident. While fatigue is the focus of this discussion, other factors may also be causal or contributory to the accident sequence, such as workload, training inadequacies, or previous operator performance deficiencies, to name a few, that should be considered.

Two case studies will be presented next in which fatigue was determined to have a role in the accident.

A tale of two accidents. What role did fatigue play?

UPS flight 1354

On August 14, 2013, about 0447 central daylight time (CDT), UPS flight 1354, an Airbus A300-600, crashed short of runway 18 during a localizer nonprecision approach to runway 18 at Birmingham-Shuttlesworth International Airport (BHM), Birmingham, Alabama, fatally injuring the captain and first officer (see Figure 1). At the time of the accident, dark night visual meteorological conditions prevailed at the airport, however, variable instrument meteorological conditions with a variable ceiling were present on the approach north of the runway. The flight had departed from Louisville International Airport-Standiford Field (SDF), Louisville, Kentucky, about 44 minutes before the accident.

Figure 1. UPS flight 1354 wreckage.

As the pilot flying (PF), the captain was responsible for monitoring the airplane systems and flight path, and as the pilot monitoring (PM), the first officer was responsible for monitoring and cross-checking the PF. The takeoff, climb and cruise phases of the flight were normal and the crew completed all required checklists. The flight was cleared direct to BHM which the crew entered into the flight management computer (FMC). While established at their cruising altitude, the first officer tuned in the ATIS and reported to the captain that runway 18 was in use at BHM. Shortly thereafter, the captain briefed and set up the approach per UPS procedure using the Profile Approach Briefing Guide.

When descending to 3,000 feet, BHM approach control directed the flight crew to turn 10 degrees right to join the localizer. Both crewmembers recognized that the localizer was captured. However, about this time, the first officer failed to "clean up" the approach in the FMC which required her to remove the direct to BHM so that only the localizer approach to runway 18 was available. Because she did not complete this step, a route discontinuity was present in the FMC. The flight crew failed to recognize the route discontinuity in the FMC for the remainder of the flight which did not allow the FMC to capture the computer-generated flight path, also known as the profile, for vertical guidance to the runway. When the automation did not capture the profile, the captain reverted to vertical speed mode to descend towards the runway, however, he did not communicate this to the first officer. About 1 minute before the airplane impacted trees, the first officer stated "let's see you're in…vertical speed…okay" to which the captain stated "…yeah I'm gonna do vertical speed. Yeah he kept us high." The airplane was descending at 1000 feet per minute (fpm) which was increased to 1500 fpm shortly thereafter, but again was not verbalized by the captain.

About 30 seconds before impact, the first officer made the appropriate 1000 foot callout and the captain responded "alright ah DA [decision altitude] is twelve ah hundred." Neither crewmember recognized that the flight was descending at 1500 fpm, which exceeded the stabilized approach criteria below 1000 feet of a maximum of 1000 fpm descent. At this point, a go around should have been executed. The first officer confirmed the DA and the captain stated "two miles" which coincided with the distance to the runway when the DA should be crossed. About this same time, the first officer should have made the approaching minimums and 5 seconds later the minimums callout; neither callout was made and the flight crew did not recognize that the flight descended below minimums. About 8 seconds before impact with trees, the crew received a sink rate alert and 4 seconds before impact stated they had the airport in sight. The first point of impact with trees was about 6,387 feet north of the runway 18 threshold.

Postaccident examination found no evidence of any structural, engine, or system failure or anomaly occurring prior to impact, and the airplane met all FAA regulations and the manufacturer's recommended maintenance program. Therefore, the investigation focused on the flight crew. A review of company records revealed that the flight crew had adequate experience and was properly trained for the flight. While the investigation also focused on the flight crew's workload and expectation of weather conditions, the information presented in this paper will focus on flight crew fatigue.

Data used to determine whether the flight crew fatigue was causal or contributing to the accident, data was gathered through interviews, company records, hotel records, cellular telephone records, and information retrieved from six personal electronic devices found in the crewmembers' personal possessions (see Figure 2).

Figure 2. Images of UPS 1354 flight crew's personal electronic devices.

The captain had been off duty for 7 days prior to returning for duty the day before the accident. There was nothing from the previous day's schedule that was unusually demanding, and it did not result in an extended duty day or reduced rest period the day before the accident. In addition, he took steps to be fit for duty and to mitigate the effects of fatigue when flying during the overnight hours, by napping prior to returning to duty and securing a sleep room at the UPS facility during his two duty periods before the accident. Although he had an adequate sleep opportunity the day before the accident, daytime sleep can be less restorative than nocturnal sleep. He had also previously reported to colleagues that he had a difficult time adjusting when returning to night flying.

The first officer had a 62-hour scheduled layover prior to returning for duty the day before the accident. During the period, the first officer visited a friend in a nearby city and reverted to a diurnal schedule. On the subsequent nights leading up to the accident flight, a review of data from the first officer's mobile devices revealed that she did not have ample sleep opportunity to obtain adequate rest prior to resuming duty and returned to duty with an estimated 3 hour sleep debt. The first officer was aware of her fatigued state as evident in text messages retrieved from her cellular phone (see Figure 3); at the end of this duty period, she was estimated to have a 9 hour sleep debt. During her 14 hour and 30 minute layover the day before the accident, she had less than a 5 hour and 30 minute sleep opportunity due to electronic device usage and unknown activities outside of her hotel room.

8/12/13 19:29:38	outgoing	Im getting sooo tired
8/12/13 19:35:30	outgoing	And its time i get ready
8/12/13 21:22:58	outgoing	 Hey, bak in the ol office, and im sleepy as a # :)
8/13/13 0:26:48	outgoing	Waitin on van
8/13/13 11:06:56	outgoing	Hey just dual fmc[7] failure last nite, thats always nice on ur ' first' nite ;)
8/13/13 11:07:09	outgoing	Just ol school navin
8/13/13 11:16:36	incoming	Oh yeah...that's great when ur tired as hell. I was snoozing by 830 but up at 5 to come to work. I'm still tired today. We are to old for that #. Lmao
8/13/13 11:18:26	outgoing	U got that rite, i fell asleep on every damn leg last nite- n rfd now, got here at 6 am n bed by 645 ish , now #[8] up, slept like 4 # hrs.... Van isnt till 8 tonite so hoping i will nap again this afternoon
8/13/13 11:19:29	incoming	Yeah u can get a nap in this afternoon. Grab some lunch and hit the bed again
8/13/13 11:20:31	outgoing	Thats da plan: sleep eat sleep eat sleep eat- works nice diet wise ha

Figure 3. Text messages sent by UPS 1354 first officer.

At the time of the accident, the flight crew had been on duty about 8 hours and 30 minutes. The captain had been awake about 14 hours and the first officer had been awake for over 18 hours (see Figures 4 and 5). Although the duty day was not unusually long, the first officer, particularly, had been awake for an extended period of time. In addition, the accident occurred about 0447, and the flight crew was awake in opposition of their normal circadian rhythm. Neither flight crew member had a known sleep disorder or reported difficulty sleeping to their family during their off-duty periods.

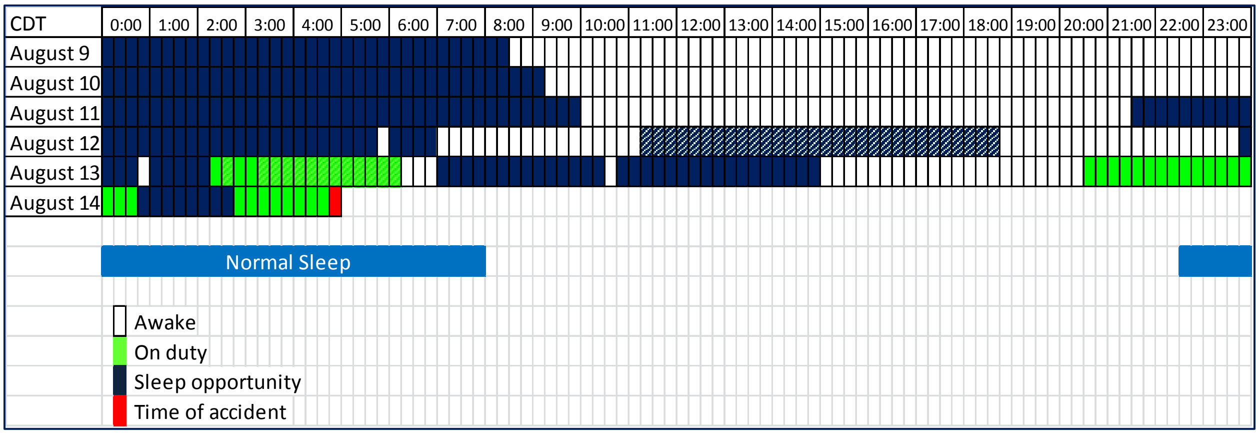

Figure 4. UPS 1354 captain's sleep/wake history.

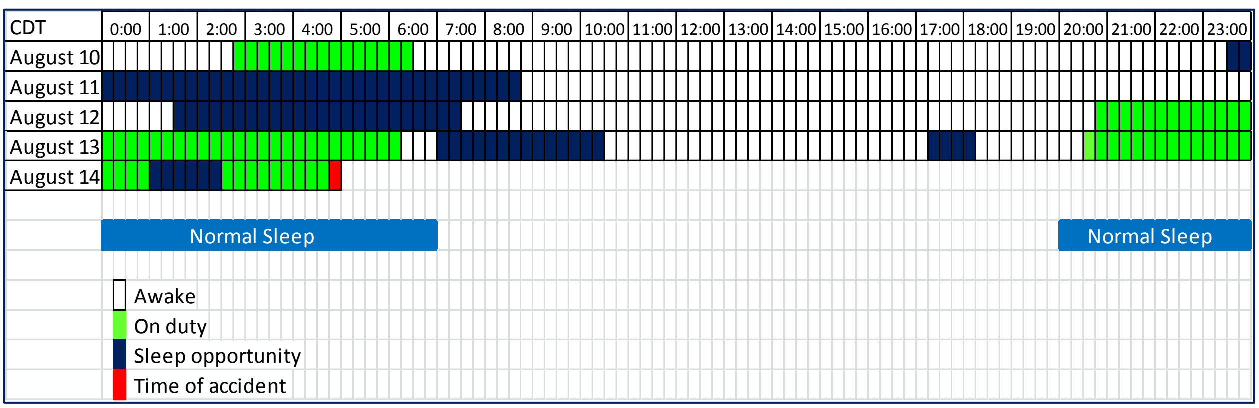

Figure 5. UPS 1354 first officer's sleep/wake history.

The investigation determined that the errors made by the flight crew during the approach (e.g., failing to clean up the FMC, missing callouts, continuation of an unstabilized approach) were consistent with the known effects of fatigue. Therefore, the NTSB cited the crewmembers' fatigue due to operating during the window of circadian low [*circadian factors*], and the first officer's ineffective off-duty time management and acute sleep loss [*quantity of sleep* and *time since awakening*], as contributing to the continuation of an unstabilized approach. As a result of this investigation, the NTSB made one safety recommendation to the FAA and two companion recommendations to UPS and the Independent Pilots Association related to fatigue. [See the full report at http://www.ntsb.gov/investigations/AccidentReports/Reports/AAR1402.pdf]

Sundance Helicopters sightseeing trip

On December 7, 2011, a Sundance Helicopters sightseeing tour Eurocopter AS350-B2 helicopter crashed near Las Vegas, Nevada, about 1630 Pacific standard time, fatally injuring all aboard (see Figure 6). The helicopter was operating as a “Twilight tour” sightseeing trip. Dusk light and visual meteorological conditions prevailed at the time of the accident. The helicopter had departed from Las Vegas McCarran International Airport (LAS), Las Vegas, Nevada, about 9 minutes before the crash.


Figure 6. Main helicopter wreckage.

Maintenance was performed and completed on the accident helicopter the day before the accident, including a 100-hour inspection. The 100 hour inspection was to be completed every 100 flight hours and included a combination of visual, condition, and measurement checks throughout the helicopter. These checks were specified in the 100-hour checklist contained in the Eurocopter Aircraft Maintenance Manual. In addition, maintenance performed included the replacement of the tail rotor servo, the engine, and the main rotor fore/aft servo with a new (zero hour) unit. Following the maintenance, a quality control (QC) inspector inspected the work and completed a ground run and checks. On the morning of the accident, a check pilot performed a

Before First Flight (BFF) check (an external inspection of the helicopter), where he found the hydraulic belt loose, conducted a post-maintenance flight check. and then flew a tour flight in the accident helicopter. The accident pilot flew the accident helicopter on one tour flight before the accident flight.

Examination of the wreckage found that the flight control input rod was not connected to one of the three hydraulic servos that provides input to the main rotor. Missing from the wreckage were the bolt, washer, self-locking nut and split/cotter pin that normally secures the input rod to the main rotor/aft servo. Post-crash examination of likely scenarios for why the helicopter experienced a loss of control in flight determined that the disengagement of the fore/aft servo bolt was most likely. Further testing of the most likely explanation for how the bolt disengaged during flight determined that the hardware was improperly secured during the previous day's maintenance. Specifically, the split/cotter pin was not installed or not installed correctly, allowing the self-locking nut to separate from the bolt, and then the bolt to work its way out of the joint due to normal in-flight vibratory forces. At this time, the input rod would have separated from the linkage and the helicopter became uncontrollable.

The investigation focused on the mechanic and inspector who replaced then inspected, respectively, the fore/aft servo the day before the accident. It was the mechanic's responsibility to connect the input rod to the servocontrol distributor by 1) installing the pin, washer and nut, 2) torqueing the nut, and 3) securing the nut with the split/cotter pin (see Figure 7). If the nut meets the torqueing requirements per Eurocopter, it can be reused, otherwise it must be replaced with a new nut. During post-accident interviews, the mechanic indicated that the nut was airworthy and could be reused. After reassembly, he said he torqued and safetied everything, including securing the input rod connection with a split pin.

The inspector reported that he inspected the fore/aft servo input rod, hardware, and split pin and marked them with a torque pen and that he inspected the hydraulic lines that connect to the manifold; he did not find any problems during the inspections. The inspector also performed ground run and checks with the mechanic's assistance. The checks took about 40-45 minutes to complete and were completed about 1800 the day before the accident.

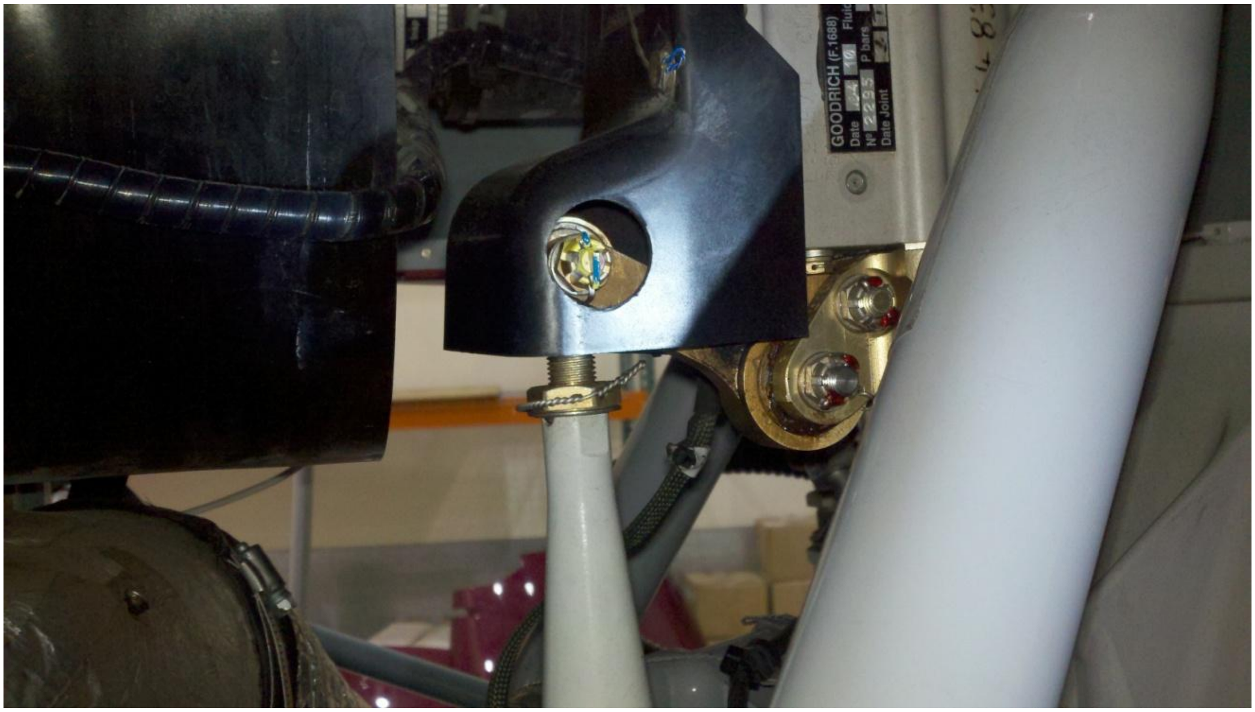

Figure 7. A properly installed nut and split/cotter pin of the fore/aft servo input rod connection.

Despite the statements made by the mechanic and inspector, as previously discussed, the evidence indicates that the split/cotter pin was not present or not installed improperly; however, neither the mechanic nor the inspector recognized this. There were no significant issues in either of their performance histories, time pressure, or environmental issues to explain the performance lapses. Although the investigation also focused on the maintenance work cards, the information presented in this example will focus on the role of fatigue on the performance of these individuals. Data sources included interviews and company records.

Both the mechanic and inspector were contacted on December 5 to report for work the next day (December 6) although they were both previously scheduled off duty. The mechanic reported that his normal bedtime was about 0200 and he would wake up between 1000 and 1200. On December 5, he went to bed about 2200, but had difficulty falling asleep until about 0000 and received about 5 hours of sleep. The QC inspector reported that his normal bedtime was about 2200 or 2300 and he would wake up about 0730 or 0800. On the night of December 5, he went to bed about 2100 and awoke at 0400. When he conducted the inspection on December 6, he had been awake over 14 hours.

Both the mechanic's and inspector's work shift normally began at 1200, but on December 6 they reported for duty about 6 hours earlier (see Table 1). Research shows that adjusting to an early morning shift (phase advance) can be more difficult than adjusting from a day shift to a night shift (phase delay).(5) In addition, the mechanic began his duty day with a 3 hour sleep debt. The investigation also found that maintenance personnel did not receive human factors training which should have included causes of fatigue, its effects and effective countermeasures.

Table 1. The mechanic's and inspector's shift information

Personnel	Normal Shift	Shift Originally Scheduled for December 6	Actual December 6 Shift
Mechanic	1200 to 2300	Off duty	0550 to 1846
Inspector	1200 to 2300	Off duty	0531 to 1855

Although the investigation could not determine the specific sequence of events that led to the maintenance errors on the part of the mechanic and inspector, the fundamental errors of omission made are consistent with the known adverse effects of fatigue. Therefore, the NTSB cited the mechanic's fatigue [*circadian factors* and *quantity of sleep*] as contributing to the improper or lack of installation of the split/cotter pin and the inspector's fatigue [*circadian factors*] as contributing to inadequate post-maintenance inspection. As a result of this investigation, the NTSB made two safety recommendations to the FAA related to fatigue. [See the full report at http://www.ntsb.gov/investigations/AccidentReports/Reports/AAR1301.pdf]

Conclusion

Continuous operations in aviation means that fatigue will always be a concern, especially when there is an accident. As investigators, we must thoroughly gather and examine the data to determine what role, if any, fatigue played in an accident by considering the 5 factors that can lead to a fatigued state (circadian factors, time since awakening, quantity of sleep, quality of sleep, and sleep disorders). This paper highlighted two NTSB investigations in which fatigue was determined to be a contributing factor in the accident, and resulted in five safety recommendations to improve flight crew and maintenance operations as well as training for fatigue. However, these accidents had vastly different circumstances and the conclusions were made using different sources of data. The UPS investigation harvested considerable amounts of time-stamped data such as cellular telephone, hotel and company records to determine the flight crew's sleep opportunities, which was supplemented by family and colleague interviews. The Sundance investigation, on the other hand, relied primarily on interviews with the involved individuals and some company records. There is no right or wrong way to gather and analyze fatigue related data. Technology is becoming more commonplace and thus, the use of electronically-based data to make these determinations will only continue. If organized and analyzed correctly, this data can provide additional detail and confidence to investigators about whether fatigue was a factor in an investigation. But in the end, the key to any robust investigation is to ask the right questions and gather as much data as possible to ensure important fatigue-related factors are not being missed.

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