# Pilot Sleep in Long-Range and Ultra-Long-Range Commercial Flights

Amanda Lamp; David McCullough; Jane M. C. Chen; Rachelle E. Brown; Gregory Belenky

**INTRODUCTION:** Despite the clear need for understanding how pilot sleep affects performance during long-range (LR; 12-16h) and ultra-long-range (ULR; 16+h) flights, the scientific literature on the effects of sleep loss and circadian desynchronization on pilots' sleep in commercial aviation is sparse.

**METHODS:** We assessed pilots' sleep timing, duration, and post-trip recovery on two LR and two ULR nonstop California to Australasia routes. Pilot's sleep/wake history was measured with actigraphy and verified by logbook across 8–9 d.

**RESULTS:** Pilots averaged 8.210 ± 1.687 SD hours of sleep per 24 h across the study period. A logistic model of the circadian timing of sleep indicated that time of day and phase of trip are significant predictors of pilots being asleep. Significant two- and three-way interactions were found between time of day, phase of trip, and route. A significant difference in average sleep time was observed between baseline and recovery day 1 for one route. All other recovery days and routes were not significantly different from baseline.

**DISCUSSION:** For the four routes, the average amount of sleep per 24-h period during the study period was within the normal range with the circadian rhythm aligned to home-base time pre- and post-trip. Flight segments and layover conditions were associated with a misalignment of sleep relative to circadian rhythm, with layover sleep appearing to shift toward the local night. Full post-trip sleep duration recovery appears to occur for all routes within 1–2 d.

**KEYWORDS:** aviation, circadian rhythm, actigraphy, in-flight sleep, jet lag.

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A minimum of 7 h of sleep per 24 h is necessary for optimum health and performance, with a range of 7 to 9 h of sleep for adults (26–64 yr) and 7 to 8 h of sleep for older adults (65 yr and older) considered appropriate.[13] This sleep can be consolidated into one long night sleep or split between a night sleep and one or more naps to still yield full recuperative value[18,19] with the caveat that the recuperative value of naps is dependent on multiple factors such as circadian timing, sleep inertia, and implementation.[8] The critical factor for performance is total sleep time per 24 h[16,28] modulated by time awake, time of day, and time on task.[4,5]

In a recent study, commercial pilots flew long-range (LR; 12–16 h) four-segment international patterns. These patterns included Australia-Asia, Asia-Europe, Europe-Asia, and Asia-Australia with layovers in between each segment.[23] The measures taken included actigraphy, sleep/work logbooks, Samn-Perelli self-report fatigue scale, and the 5-min psychomotor vigilance task (PVT). Findings were that fatigue ratings were highest and PVT mean response speed lowest at the end of each flight and the highest fatigue rating occurred at the end of the last flight segment. Additionally, the high fatigue and low performance were predicted by the sleep in the 24 h prior to postflight. There were 19 pilots who participated in the study. These results suggest that in-flight fatigue countermeasures, including in-flight sleep, can be critical for maintaining alertness and performance during the flight, especially toward the end of each flight and during subsequent flight segments. Sleep history, more than duty history, was determined to predict fatigue and performance.[24] Another study with completely

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different flight types found similar results in that fatigue increased with the progression of flights.[25] The authors stated this result was not unexpected by reason of the combined effect of duration of time since last sleep and the length of time on task. Regarding how layover sleep impacts fatigue and sleepiness at the beginning of the inbound flight, from a study of eight LR and five ULR flights, it appears the total sleep time in the 24 h prior is the determinant factor.[7]

Circadian rhythm is a 24-h, sinusoidal rhythm in sleep, performance, and core body temperature.[6] When the core body temperature peaks around 20:00–22:00, there is a strong drive for wakefulness[17] and performance is sustained at a high level. This period is called the window of circadian high. Conversely, when core body temperature reaches its nadir between 02:00–06:00, the drive for sleep is strongest and performance is substantially degraded.[6] This period of time is called the window of circadian low (WOCL). Due to the nature of LR and ultra-long range (ULR; 16+ h) flights using a four-pilot crew, it is not possible for all pilots to sleep during the WOCL. It is common for the pilots flying the critical phases of flight such as top of climb and top of descent to pick the WOCL for their in-flight sleep. Thus, the amount and quality of sleep obtained is dependent on its temporal placement relative to the circadian phase.[16] Adverse effects of sleep loss ($<$7 h/24 h) are exacerbated at times when the circadian rhythm's drive for wakefulness is low.[13,28]

The time zone shifts associated with LR and ULR flights affect the circadian rhythm. Circadian rhythms are entrained to a 24-h cycle by environmental factors (e.g., the light/dark cycle), are slow to adjust to a new time zone,[12,23] and adjust through external social cues such as meal timing. This circadian desynchronization is known as jet lag and has been associated with sleep disruption, degraded performance, an increased number of health complaints, and a decrease in feeling of well-being.[12,22,23] Sleep onset can be affected by not only circadian rhythms, but also psychosocial factors such as work scheduling and the availability of meals. In a recent study, investigators found that a recommendation to maintain a home base time sleep schedule while on layover during a ULR flight was unrealistic due to environmental and social time cues.[14] This study and another study on LR flights also demonstrated that pilots, while on layover, tend to sleep during the local night, but have a supplemental nap during their home base time night.[10,14] Studies are needed to ascertain what compensatory physiological effects occur over time due to sleep loss and circadian desynchrony, allowing for an understanding of the natural influence of this lost sleep time in regard to health and safety.[28] The current study was meant to contribute to the growing literature in this area and begin to fill in the gaps in our understanding of these phenomena.

LR and ULR flights involve extended flight times and crossing multiple time zones with the attendant potential for sleep loss compounded by circadian rhythm desynchronization. Recovery entails making up for lost sleep and resynchronizing with home base time circadian periodicity. There is limited scientific literature on pilot sleep before, during, and after LR and ULR flights, but there is a clear need for such research in light of the safety implications for the public. With the number of LR and ULR flights increasing, as well as the duration of the flights, understanding how these flights affect pilot sleep across time is important. We need to better understand what sleep looks like before these trips, how much sleep is obtained in flight, how the outbound flight affects layover sleep, and how inbound and prior trip sleep affects the post sleep days. This study was undertaken to answer these questions along with a better understanding of how these trips affect the circadian rhythm. Therefore, our objectives included: 1) determining total sleep time per 24 h throughout the data collection period for each route; 2) determining the timing of the sleep relative to the circadian phase to see if the circadian rhythm appears to shift on layover or post-trip; and 3) determining if sleep loss is fully recovered by 3 d post-trip.

## METHODS

### Subjects

There were 92 U.S.-based United Airlines pilots, including $N = 20$ Captains and $N = 72$ First Officers, who supplied sleep data for the study. The average age of the Captains was 59.78 ± 3.15 SD yr and the average age of the First Officers was 48.33 ± 8.06 SD yr, with $N = 77$ men and $N = 15$ women. All pilots were west coast, based in either San Francisco, CA (SFO), or Los Angeles, CA (LAX).

The study was approved by the Washington State University (WSU) Institutional Review Board. All United Airlines pilots flying Boeing-777 or Boeing-787 aircraft types on the studied routes were eligible to participate. Recruitment messages were sent out to all eligible pilots by the United Airlines Fatigue Risk Management team and/or the Airline Pilots Association, International. Pilots interested in participating contacted the WSU Sleep and Performance Research Center directly and were provided with an Institutional Review Board approved written consent form, which all of the pilots signed and returned to the WSU team before initiating the study. All individual data remained confidential and de-identified.

### Procedure

The sleep data for this project were taken from two larger United Airlines internal report studies that both included the PVT to measure cognitive performance, self-reported Samn-Perelli fatigue ratings, and self-reported Karolinska Sleepiness Scale ratings. The studied flights included SFO to Sydney, Australia (SYD), and Taipei, Taiwan (TPE), on the Boeing-777, and from LAX to Melbourne, Australia (MEL), and Shanghai, China (PVG), on the Boeing-787. Pilots either flew both SYD and TPE or MEL and PVG, so each pilot flew one LR and one ULR flight. All routes were westbound for the outbound segment and eastbound for the inbound segment. All flights were double augmented, which includes four pilots, with two flying crewmembers and two relief crewmembers. Double augmented flights allow each pilot to sleep about half of the flight time, excluding the half-hour before and after the critical phases and time needed to fully wake before returning to the flight deck. Therefore, in-flight sleep timing and maximum duration is dictated by the scheduled break plan strategy of the crew. Layover length ranged from 22–47 h. SFO-SYD and LAX-MEL are classified as ULR flights with longer flight durations and both involve a time difference of 5–7 h on the body clock (17–19 h on the calendar) depending on daylight saving differences throughout the year. SFO-TPE and LAX-PVG are classified as LR flights with shorter flight durations, and both involve a time difference of 8–9 h on the body clock (15–16 h on calendar), depending on daylight saving differences throughout the year (**Table I**). All data were collected in UTC and converted to home base time as per FAA FAR Part 117.3; the pilots do not acclimate on layover since the theater (geographical area) between departure and arrival points does not differ more than 60° longitude.

Pilots' sleep/wake history was measured objectively by actigraphy supplemented by self-report using a sleep/work logbook. For each route, data collection was from 3 d prior to the outbound flight continuously through 3 d following the inbound flight, with a total of 8–9 d studied. Both the use of the actigraph verified by logbook and study period duration are in keeping with the standard aviation best practices and recommendations by the International Civil Aviation Organization.[7,15] Pilots received and were trained to use an actigraph (Philips-Respironics, Bend, OR) and the sleep/work logbook approximately 1 wk before the studied trip(s) to record all sleep throughout the data collection period. Actigraphy is an accepted technique for measuring total sleep time with high reliability and validity. It is used in the Fatigue Risk Management System field and for sleep studies generally across many fields.[1,26,27] An actigraph is a watch-like device that measures and records wrist movements using an accelerometer. Movement is recorded in 1-min bins, then an algorithm scores the movement as either sleep or wake in each 1-min bin. Actigraphs were configured to record and display Zulu time (UTC). Pilots were also required to record the date and time (in Zulu) of any episode of sleep longer than 10 min using the sleep/work logbook.

### Statistical Analysis

Actigraph data were imported using proprietary software (Philips Actiware 6), then cleaned by comparing the actigraph algorithm for sleep to the self-reported sleep/wake history in each individual pilot's logbook and their event markers to ensure the algorithm correctly captured the sleep period. The data were then imported, processed, and analyzed using the open source statistical programming language R.

To visualize the sleep patterns and distribution, the data were plotted into 1-h wide columns with the height of each column indicating the number of pilots with any amount of scorable sleep during each consecutive 1-h bin. A line representing the percentage of pilots asleep in any given hour was plotted on a second axis. Due to the nature of pilot's schedules, some datasets are incomplete during the pre-trip and post-trip (recovery) days.

Circadian timing of sleep was analyzed with 1-h bins using logistic regression. This analysis was conducted to predict the probability of pilots being asleep across time using phase of trip, clock time, and route flown as predictor variables. Phase of trip divided the study period by pre-trip days, outbound flight, layover, inbound flight, and post-trip days. In keeping with previous aviation research, circadian phase was approximated using clock time, relative to home base time, in the city where each trip began and ended.[9] Clock time was given in discrete 1-h intervals. To account for the periodic nature of clock time, the clock time predictor was included in the model with a trigonometric transformation.[3] Independent variables were added to the model and tested sequentially, beginning with lower order main effects and ending with higher order three-way interactions. Likelihood ratio tests were performed with each added variable to determine if the model fit was significantly improved.

Sleep duration was analyzed with 24-h bins from noon-to-noon in home base time (HBT) using a linear mixed-effects model (LMEM) approach. The LMEMs are an extension of the linear regression model that are particularly suited for nested designs and designs with unbalanced samples or missing data. In addition to the fixed-effects used in linear regressions, LMEMs allow for the inclusion of random effects, those variables whose values are assumed to be drawn from a larger population of values. In a repeated measure design, subject ID is included as a random effect (referred to as a random factor) when responses are anticipated to be correlated within subjects. The decision to include a random intercept, slope, or both depends on if subjects differ from each other by some baseline amount (random intercept), and if they are expected to differ over time (random slope). Random factors are often not the variable of interest in these designs, but rather included to account for individual differences in subjects. For in depth information on linear mixed-effects models and associated methodological considerations, see Linear Mixed Effects Models.[21]

The LMEM used in this analysis was chosen in part for how it handles missing data. LMEMs compute parameter estimates using maximum likelihood, which has the advantage of being theoretically unbiased under missing completely at random and missing at random conditions.[20] Maximum likelihood, as with multiple imputation, has been shown to yield smaller error in parameter estimates than listwise deletion, pairwise deletion, and regression imputation.[20]

**Table I.** Flight Schedules Including Layover.

| ROUTE | OUTBOUND DEPARTURE | OUTBOUND DURATION (h) | LAYOVER DURATION (h) | INBOUND DEPARTURE | INBOUND DURATION (h) |
|---|---|---|---|---|---|
| SFO-SYD | 22:40 | 14.9 | 27.9 | 17:30 | 13.6 |
| SFO-TPE | 12:45 | 15.4 | 39.3 | 17:50 | 11.8 |
| LAX-MEL | 22:35 | 15.8 | 26 | 16:25 | 14.5 |
| LAX-PVG | 12:45 | 13.8 | 22.8 | 1:25 | 11.3 |

For each route, a LMEM was constructed in R using the lmer() function in the lme4 package. Day of study and Route being flown were analyzed as predictors of Sleep duration. As the independent variables of interest, Day was included as a fixed factor, while subject ID was included as a random factor to control for intraclass correlation (i.e., intraindividual variability). The main effect of Day was then tested using Wald *F*-tests with Satterthwaite approximations for degrees of freedom. For routes demonstrating a significant main effect of Day, *t*-tests with Satterthwaite approximations for degrees of freedom of model coefficients were reported. The Holm-Bonferroni procedure was performed to control for familywise error, mitigating the inflation of Type I error due to running a series of hypothesis tests. Of the three preflight days, preflight day 2 was considered to be the most adequate baseline (labeled "BL"), as it had less missing data than preflight day 1 and was not close enough to the scheduled flight day for preduty naps or other preflight activities that may affect sleep duration. Not including the 24 h prior to the flights is in keeping with standard aviation best practices.[29] The 3 recovery days were postflight day 1, postflight day 2, and postflight day 3 (labeled "R1", "R2", and "R3" respectively).

To test whether postflight sleep duration (recovery sleep) was similar to preflight sleep duration (normal sleep duration), a linear mixed model was constructed for each of the four studied routes using the LMER package in R. For each model, the categorical predictor variable, Day, consisted of BL, R1, R2, and R3. The outcome variable, Sleep Duration, was the estimated amount of sleep each subject received in the baseline and 3 recovery days in minutes. Subject ID was included as a random intercept variable to account for within-subject correlation of estimated sleep duration. Dummy coding was used to estimate model coefficients, where $\beta_0$ equals the mean of BL, $\beta_1$ equals the difference between BL and R1, and $\beta_2$ equals the difference between BL and R2, and $\beta_3$ equals the difference between BL and R3. Individual *t*-tests were used to test the null hypotheses that $\beta_1$, $\beta_2$, and $\beta_3$ are equal to zero, or in other words, the hypothesis that R1, R2, and R3 would not be significantly different from BL, respectively.

For circadian timing, we hypothesized that pilots' circadian timing of sleep would remain in phase with HBT during pre- and post-trip days, and sleep timing would likely shift toward local time due to psychosocial factors on layover. For sleep duration, we hypothesized that when compared to the baseline day, pilots would sleep significantly more during the first postflight day (R1). We also hypothesized that the final 2 postflight days (R2 and R3) would not be significantly different than the baseline day. Comparisons between days were made using Welch two sample *t*-tests. Our threshold for statistical significance was set at 0.05.

**Table II.** Average Sleep per 24-h Period.

| | DAY 1 | DAY 2 | DAY 3 | DAY 4 | DAY 5 | DAY 6 | DAY 7 | DAY 8 | DAY 9 | AVERAGE |
|---|---|---|---|---|---|---|---|---|---|---|
| SYD | 8.0 | 8.5 | 8.1 | 5.8$^{\dagger}$ | 11.2 | 4.7$^{\ddagger}$ | 9.5 | 8.5 | 7.8 | 8.0 |
| TPE | 7.8 | 8.2 | 7.1 | 9.5$^{\dagger}$ | 8.3 | 3.9$^{\ddagger}$ | 9.3 | 8.0 | 7.8 | 7.77 |
| MEL | 7.8 | 8.1 | 8.1 | 6.0$^{\dagger}$ | 8.8 | 5.4$^{\ddagger}$ | 8.8 | 7.6 | 8.2 | 7.6 |
| PVG | 8.0 | 7.8 | 7.1 | 9.4$^{\dagger}$ | 5.4$^{\ddagger}$ | 7.9 | 8.0 | 7.9 | | 7.7 |

*Each day is a 24-h period calculated from noon-to-noon in home base time (HBT; 19:00–19:00 UTC), beginning 3 d before the Outbound Flight (Day 1, 2, and 3), including the Outbound flight (Day 4), layover days (which varied for each trip but were in between the boxes marked by $^{\dagger}$ and $^{\ddagger}$), Inbound flight (boxes marked by $^{\ddagger}$), and the 3 postflight days (3 d of boxes after the boxes marked by $^{\ddagger}$). Average sleep was assessed for each day for each trip and then across all days for each trip.

## RESULTS

Pilots averaged 8.210 ± 1.687 SD of sleep per 24 h across the study period with mean baseline sleep of 8.174 ± 1.687 SD for the 24-h BL day. Average sleep per 24-h period across the 8- to 9-d study period demonstrated that although the sleep during the outbound and inbound flights was restricted, pilots increased their subsequent sleep periods to maintain an average over all studied days between 7 and 8 h. This allows for a normal, healthy amount of sleep[13] that is sufficient to maintain safe alertness and performance levels (**Table II**).

Our dataset used to assess circadian timing of sleep across the flights included 24,792 observations. **Fig. 1** is a visualization of the sleep patterns and distribution with the data plotted into 1-h wide columns with the height of each column indicating the number of pilots with any amount of scorable sleep during each consecutive 1-h bin.

Likelihood ratio tests (Time.S and Time.C are Sine and Cosine transformations of clock time, respectively; Route represents the city being flown to and from, and Phase corresponds to the baseline, outbound, layover, inbound, and recovery portions of the study period) indicated that Time.S, Time.C, and Phase significantly improved the fit of the model (df = 1, deviance = 6336, $P < 0.000$, df = 1, deviance = 1356, $P < 0.000$, and df = 8, deviance = 168, $P < 0.000$, respectively, **Table III**), while Route did not (df = 3, deviance = 4.6, $P = 0.205$). The two-way interactions of Time.S:Phase, Time.C:Phase, Time.S:Route, Time.C:Route, and Phase:Route all significantly improved the fit of the model (df = 8, deviance = 1172, $P < 0.000$, df = 8, deviance = 2519, $P < 0.000$, df = 3, deviance = 183, $P < 0.000$, df = 3, deviance = 28, $P < 0.000$, and df = 24, deviance = 42, $P = 0.013$, respectively). Finally, the three-way interactions of Time.S:Phase:Route and Time.C:Phase:Route both improved the fit of the model (df = 24, deviance = 268, $P < 0.000$ and df = 24, deviance = 459, $P < 0.000$).

In an ordinary linear model, these interactions would be interpreted as changes in the slope of a line across phase, route, or both, but given that clock time is transformed in the present model, these interactions are interpreted as changes in the shape and location of the distribution of sleep across levels of phase and route.

To characterize the change in circadian timing across the 8–9-d study period, estimates for when pilots were most likely to be asleep were extracted from the model (**Table IV**). For the baseline period, the model predicts peak sleep times fall between 02:27 and 04:21 HBT, and during the recovery period peak sleep times are predicted between 03:28 and 04:26 HBT, with exception of R1 PVG, which occurred at 04:59 HBT. For layover, peak sleep times are predicted to be between 07:08 and

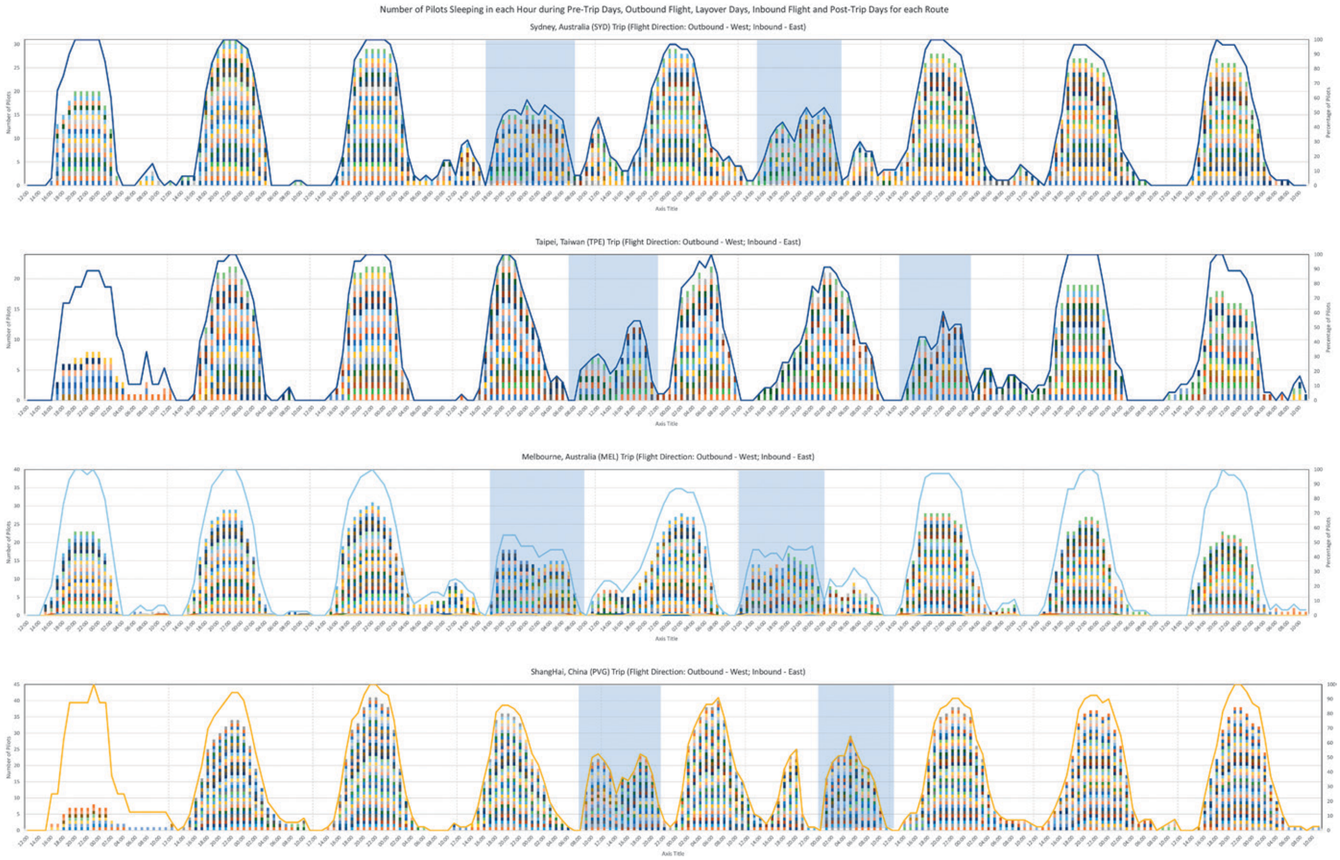

**Fig. 1.** Number of pilots sleeping in each hour during the 3 d prior to the trip, the outbound flight, a 22- to 47-h layover, the inbound flight, and the 3 d after the trip for the San Francisco–Sydney, San Francisco–Taipei, Los Angeles–Melbourne, and Los Angeles–Shanghai trips. Days are divided into 24-h blocks, noon-to-noon home base time (HBT).

12:07 HBT. However, when converted to local time, peak sleep times are predicted to occur between 01:21 and 04:07 HBT, indicating that pilots are adjusting their sleep timing to local time rather than HBT (**Fig. 2**).

A significant main effect was found across levels of Day for the SFO-SYD route [$F(3,71.992) = 6.360$, $P = 0.001$]. A main effect was not observed across levels of Day for the LAX-MEL route [$F(3, 34.046) = 2.002$, $P = 0.133$], the LAX-PVG route [$F(3, 65.991) = 0.529$, $P = 0.664$], or the SFO-TPE route [$F(3, 29.999) = 0.469$, $P = 0.706$]. For the SFO-SYD route, a significant difference was observed between BL and R1 [$\beta_1 = 77.737$, $t(72.010) = 2.997$, $P = 0.004$], with pilots sleeping an average of 77.737 min longer on R1 than BL. Neither R2 nor R3 were significantly different than BL [$\beta_2 = 4.421$, $t(72.010) = 0.170$, $P = 0.865$ and $\beta_3 = -31.579$, $t(72.010) = -1.217$, $P = 0.227$, respectively].

**Table III.** Probability of Sleep.

| | DF | DEVIANCE | RESID. DF | RESID. DEV | *P*-VALUE |
|---|---|---|---|---|---|
| NULL | | | 24,743 | 32,731 | |
| Time.S | 1 | 6,336 | 24,742 | 26,395 | <0.000 |
| Time.C | 1 | 1,356 | 24,741 | 25,039 | <0.000 |
| Phase | 8 | 168 | 24,733 | 24,871 | <0.000 |
| Route | 3 | 4.6 | 24,730 | 24,866 | 0.205 |
| Time.S:Phase | 8 | 1,172 | 24,722 | 23,694 | <0.000 |
| Time.C:Phase | 8 | 2,519 | 24,714 | 21,175 | <0.000 |
| Time.S:Route | 3 | 183 | 24,711 | 20,992 | <0.000 |
| Time.C:Route | 3 | 28 | 24,708 | 20,963 | <0.000 |
| Phase:Route | 24 | 42 | 24,684 | 20,921 | 0.013 |
| Time.S:Phase:Route | 24 | 268 | 24,660 | 20,653 | <0.000 |
| Time.C:Phase:Route | 24 | 459 | 24,636 | 20,194 | <0.000 |

Probability of sleep as predicted by clock time phase of trip and route flown, where Time.S and Time.C represent Sine and Cosine transformations of clock time, respectively. Route represents the city being flown to and from, and Phase corresponds to the baseline, outbound, layover, inbound, and recovery portions of the study period.

## DISCUSSION

We found that pilots averaged 8.210 ± 1.687 h of sleep per 24 h across the study period with mean baseline sleep of 8.174 ± 1.687 for the 24-h BL day. This baseline sleep was higher than seen in a recent study that included 332 pilots' data from LR and ULR flights where mean baseline sleep was found to be 6.8 h per 24 h.[29] This sleep on average is enough to sustain

**Table IV.** Peak Sleep Time.

| | PRE3 | PRE2 | PRE1 | LOV | POST1 | POST2 | POST3 |
|---|---|---|---|---|---|---|---|
| **PEAK SLEEP TIME, HOME BASE TIME** | | | | | | | |
| LAX-MEL | 03:35 | 03:41 | 03:46 | 07:08 | 04:08 | 04:04 | 03:59 |
| LAX-PVG | 03:48 | 03:33 | 02:47 | 12:07 | 04:59 | 03:54 | 04:04 |
| SFO-SYD | 03:31 | 04:21 | 04:33 | 07:17 | 04:06 | 04:26 | 04:04 |
| SFO-TPE | 04:05 | 04:09 | 03:43 | 09:21 | 03:28 | 03:51 | 03:46 |
| **PEAK SLEEP TIME, LOCAL TIME** | | | | | | | |
| LAX-MEL | 03:35 | 03:41 | 03:46 | 02:08 | 04:08 | 04:04 | 03:59 |
| LAX-PVG | 03:48 | 03:33 | 02:47 | 04:07 | 04:59 | 03:54 | 04:04 |
| SFO-SYD | 03:31 | 04:21 | 04:33 | 02:17 | 04:06 | 04:26 | 04:04 |
| SFO-TPE | 04:05 | 04:09 | 03:43 | 01:21 | 03:28 | 03:51 | 03:46 |

Peak sleep times in home base time (HBT) and local time across the study period for each route.

performance over multiple days. Focusing on the average sleep within each 24-h period, acute sleep restriction appeared to occur during the 24 h associated with the outbound and inbound flights, with pilots preparing for the loss of sleep by taking pre- and/or post-trip naps when there was a late departure or early arrival relative to HBT and making up the sleep loss within 24 h or less of each flight segment. This making up of the sleep loss included layover sleep, which was over 8 h for all three flights that had a layover length longer than 24 h. After the inbound flight, when pilots returned to their domicile, they either increased their first night's sleep duration (as with SFO-SYD) or immediately went back to their normal domicile sleep duration, averaging around 7–9 h per night. These results are consistent with the current literature, which demonstrates full trip recovery is expected within 3 d postflight.[2,11,29]

Regarding the circadian rhythm, the significant two-way interactions indicate pilots' sleep changes by phase (e.g., layover vs. post trip) or route (e.g., MEL vs. SYD). Significant three-way interactions indicate pilots' sleep patterns are not shifting consistently between routes. This makes sense as the routes have different duty periods and layover lengths. Pilots anchored their sleep on the HBT (02:00–06:00) before the outbound flight segments (pre-trip days) for each route. During outbound and inbound flights, strict synchronization of sleep to home base time is lost and sleep is modulated by break schedule. During the layover, pilots appear to begin to shift their sleeping pattern to coincide with the local night. The circadian rhythm shift during layover may be due to beginning acclimation to the new light-dark cycle and/or psychosocial factors such as meal timing and arrival and departure times to and from the layover cities, as supported by the recent literature.[10,14] Once home after the inbound flight, pilots' circadian rhythms immediately resynchronized to HBT.

The aspects of the study that would limit generalizability include only studying four commercial airline long range and ultra-range routes. Future research should look more closely at how the trip schedules and interindividual variability affect layover sleep duration and timing. Future research could include sleep quality indicators such as sleep quality, efficiency, and latency with the possibility of measuring cardiopulmonary coupling to assess desynchronization of the cardiac rhythm and sleep stages. Another possible direction would be to model circadian time, such as with CPSS. This model uses light levels to estimate circadian phase. For the purpose of this paper, our results assume that all pilots lived in domicile and therefore were acclimated to HBT. This may not accurately reflect reality if some pilots commute. Additionally, circadian phase may vary up to 5 h in entrained individuals so we recognize anchoring all pilots on HBT may not be precise for circadian timing but this study still adds useful, informative results to the current literature. Future studies will be needed to further elucidate these additional factors. We think our findings are solid and deserve replication in a separate study.

For all studied routes, pilots appeared to maintain normal, healthy average levels of average sleep across each trip. The amount of sleep per 24-h period during the pre-trip baseline and post-trip recovery days are within the normal range with the circadian rhythm aligned to home base time. Sleep restriction occurred acutely in flight, but was made up within the first 24 h either on layover or on the first post-trip day. Taken in combination, pilots' sleep duration and circadian timing of sleep appeared to be enough to maintain acceptable performance during the flights. These data also demonstrated that the current recovery period after LR and ULR trips is sufficient to maintain safety and allow pilots to obtain adequate sleep and resume their home base time circadian timing of sleep with full post-trip recovery occurring within 1 to 2 d for all routes.

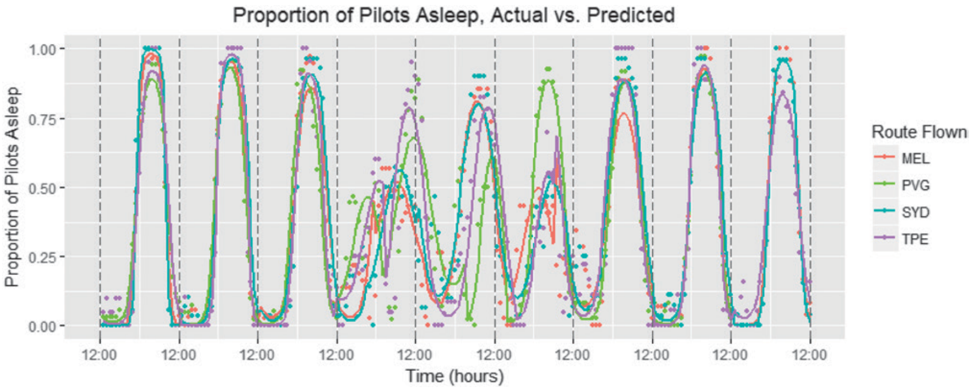

**Fig. 2.** Actual portion of pilots asleep in any given hour (represented as points) vs. predicted proportion of pilots asleep (represented as line).

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