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ASSESSMENT OF FATIGUE IN AIRLINE PILOTS DURING FLIGHT DUTY PERIOD – AN EXPLORATORY ESSAY

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ABSTRACT

At a time when new aviation concepts such as Extended Minimum Crew Operations and Single Pilot Operations arise, assuming that technological advancements and automation can compensate for human loss of performance and resilience, studying the main tasks and outcomes in crucial areas is essential. Cognitive fatigue was monitored in participants using four methods recommended by the International Civil Aviation Organization (ICAO), two of which are subjective: the sleep diary (SD) and the Samn-Perelli 7-Point Fatigue Scale (SPS); the objective measures used were: the Psychomotor Vigilance Task (PVT) and actigraphy. Pilots' performance was also assessed with a fatigue management software (FAID®) during the flight duty periods (FDPs) and results were compared. Eleven flight sectors were analysed, for total of seven FDPs: at the beginning and the end of each FDP, some changes were observed concerning the assessment on the SPS scale, the reaction time (RT) and the fatigue score generated by the biomathematical models associated to the technique of the actigraphy and the software FAID®. This paper presents the results of a preliminary investigation that aims to use possible techniques for evaluating fatigue in a real work context.

Keywords: Cognitive Fatigue, Airline Pilots Performance, Flight Safety.

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1. INTRODUCTION

Companies are operating in a highly competitive environment in a context of increased cost of labour, fuel and airport fees, and fatigue risk management systems contribute to flexibly, optimizing crew "utilization" through deviations and derogations from prescriptive limits on duty times and rest durations (Bourgeois-Bougrine, 2020).

Fatigue is undoubtedly a phenomenon that affects alertness of airline pilots, increasing the risk of an incident, or even an accident, since it impairs their ability to operate the aircraft safely (Reis, Meste and Canhão, 2013), and Extended Minimum Crew Operations and Single Pilot Operations are currently under investigation, and their implementation will rely on comprehensive safety assessments and compliance with regulatory frameworks. The introduction of these operations raises numerous safety concerns that require careful consideration.

2. FATIGUE

Fatigue is "the inability to function at the desired level due to incomplete recovery from the demands of prior work and other working activities" (Kandera, Škultéty and Mesárošová, 2019). To effectively restore cognitive function, a restorative sleep is required, both in quantity and quality" (Kandera, Škultéty and Mesárošová, 2019).

2.1. Fatigue Consequences

Tn both group of pilots (L-H e SM-H), fatigue can manifest itself, for example, in the following situations (SKYbrary, 2012; FAA, 2012): radio calls being missed, equipment malfunctions not being detected, routine tasks being performed inaccurately (or even forgotten), lining up with the wrong runway, landing without clearance and, in extreme cases, falling asleep in a FDP.

According to data from the European Cockpit Association (ECA), obtained through questionnaires applied to more than 6,000 European airline pilots, it is known not only that about 80% of them have to deal with fatigue in the cockpit, but also that a significant part of the pilots has already fallen asleep unexpectedly (i.e. without notifying the other pilot beforehand) during the course of a flight (ECA, 2012).

3. MATERIALS AND METHODS

Airline pilots' cognitive fatigue was continuously monitored by two subjective measures (the sleep diary, SD, and the Samn-Perelli 7-Point Fatigue Scale, SPS) and two objective measures (the Psychomotor Vigilance Task, PVT, and the actigraphy) – all these methods were retired from IATA, ICAO and IFALPA, 2015 and Millar, 2012. A fatigue management software was also used to evaluate the pilot's fatigue throughout their flight duty periods (FDPs), the FAID®, the one being used by a Portuguese airline in the process of managing the fatigue of its crew members.

Subjective tools are based on self-report of the sleep (e.g., "extremely sleep, fighting sleep") and tiredness (e.g., "I am tired"). On the other hand, objective tools are mainly built based on the physiological features of the person or their physical manifestations (e.g. wrist inactivity), (Göker, 2018). Each tool has its own strengths and limitations, and they are often used together to provide a more comprehensive assessment of sleep and fatigue.

3.1. Sleep Diary (SD)

The SD is a useful tool when studying the quantity and quality of a person's sleep, especially if it is used in conjunction with other techniques, such as actigraphy, since, in this case, it becomes possible to make a comparison between the objective data of sleep and that perceived by the individual under study (IATA, ICAO and IFALPA, 2015; Millar, 2012).

The diary used in this study is based on the one made by the National Sleep Foundation (2020) and it contains two extra sections: the first one is dedicated to the assessment on the SPS scale, whereas the second one is dedicated to the results obtained on the PVT tests.

3.2. Samn-Perelli 7-Point Fatigue Scale (SPS)

Initially, the SPS was developed as a tool to subjectively assess pilots' fatigue, but nowadays it is widely used in several research related to the issue of fatigue. The individual classifies his current state on a 7-point Likert scale (Greenberg, Aislinn and Kirsten, 2016), as can be seen in Table 1 (each one of the points is associated to a certain risk (IGOP and IPIECA, 2020).

Table 1. SPS checklist and risk level associated to each score (IATA, ICAO and IFALPA, 2015; IOGP and IPIECA, 2020).

Score	Description	Risk
1	Fully alert, wide awake.	Low
2	Very lively, responsive, not at peak.	Low
3	Okay, somewhat fresh.	Low
4	A little tired.	Moderate
5	Moderately tired, let down.	Moderate
6	Moderately tired, very difficult to concentrate.	High
7	Completely exhausted, unable to function effectively.	Very high

It is important to highlight that it has been demonstrated in a laboratory, under controlled experimental conditions, that the SPS is sensitive to the effects of sleep loss and the circadian body clock cycle (Kandera, Škultéty and Mesárošová, 2019).

3.3. Psychomotor Vigilance Task (PVT)

The PVT is a task of permanent attention that aims to measure the time with which the individual responds to a visual stimulus (Millar, 2012). Developed in the 1980s, it is the most popular validated reaction time (RT) test (Brunet et al., 2016).

The PVT-192 is the original device designed to measure a person’s RT. However, besides its high cost, it is too big for some research protocols that require a pocket device, such as a smartphone (Brunet et al., 2016). Recently, considering this need, efforts have been made to create more accessible and portable tools, such as the application used in this study, the sleep-2-Peak (s2P), available both for iOS (App Store) and Android (Google Play).

When opening the application, the individual has the possibility to introduce the time he went to sleep the previous night, the time he woke up, and if, at the time he intends to perform the test, he is under the effect of some substance, such as sleeping pills, alcohol or caffeine. To start the test, which lasts three minutes, the person press "Do test" and then "Start test". The task involves tapping on the smartphone screen (with the dominant index finger) as quickly as possible when the visual stimulus, a representation of the Sun, appears (Brunet et al., 2016). When finished, the individual has immediate access to all his reaction times (RTs), as well as their average value.

The application presented is validated by a study conducted by Brunet et al. (2016), which “showed that a 3-min version of s2P, a PVT-type test designed for smartphones, is a valid tool for differentiating alert from sleepy states in the same individual and is as sensitive as the gold-standard PVT for tracking fatigue-related changes during an extended wakefulness and sleep loss condition”.

3.4. Actigraphy

Since polysomnography (PSG) is an impractical tool for daily fatigue management (Fatigue Science, 2017), actigraphy appears as an alternative and less invasive option. The device used in this technique (actigraphy) contains an accelerometer that tracks the frequency of wrist movements. These are then processed by algorithms that provide information regarding the sleep/wake cycle (Russel et al., 2016).

The device used in this study was a wearable ReadibandTM 5. This device was validated by Russel et al. (2016), who concluded that "The Fatigue Science actigraph was 93% accurate in determining sleep scoring when contrasted to results derived from sleep scoring using gold-standard polysomnography."

Information is essential for the subsequent application of the SAFTETM (Sleep, Activity, Fatigue and Task Effectiveness) fatigue model. This biomathematical model is one of the most used in researches carried out in the area of fatigue and human performance, having been tested and validated by several entities, such as the US Army, the US Department of Transportation and the Federal Aviation Administration (FAA), (Fatigue Science, 2017).

The SAFTETM model, after the person has used ReadibandTM 5 for three consecutive nights, analyzes all the information collected and then provides a score (from 0 to 100%), known as SAFTETM Alertness Score (Fatigue Science, 2017), e. g. for a score of 70% (cognitive performance reduced by 30%), fatigue affects performance in the same way as a blood alcohol concentration of 0.08%. Table 2 shows the risk of accident or serious error associated with each score (from the SAFTE™ Alertness Score) and the increase in RT.

Table 2. Risk of accident or serious error associated with the SAFTE™ Alertness Score and the increase of RT (Fatigue Science, 2017, 2020).

SAFTE™ Alertness Score [%]	Increased RT [%]	Risk
[90;100]	[0;11]	Very low
[80;90[	]11;25]	Low
[70;80[	]25;43]	Elevated
[60;70[	]43;67]	High
[0;60[	]67;100]	Very high

3.5. FAID®

FAID® (Fatigue Assessment Tool by InterDynamics) is an analytical tool which can support the management of hours of work within an organization's fatigue risk management guidelines (InterDynamics, 2014a). Based on formulas tested and validated at the Centre for Sleep Research, in University of South Australia, this program was created with the objective of assessing the level of fatigue to which a worker is exposed during a shift. The algorithm takes into consideration, fundamentally, factors such as the time and duration of shifts, break times, previous periods of service and the opportunity to sleep between different working hours (InterDynamics, 2014a; McCulloh et al., 2007).

In the aviation industry, flight crews, especially those operating L-H flights, have to deal with multiple time zones, resulting in a higher level of fatigue. In this sense, a specialized version of FAID® has been developed, based on the FAID® Time Zone model (InterDynamics, 2014b). It is a biomathematical model that, besides the factors mentioned in the previous paragraph, considers the number of time zones crossed and the direction of flight (East – West or West – East), (InterDynamics, 2014c).

The software provides a score (FAID® Score) that should be interpreted as an indication of the likelihood of performance impairment associated with fatigue (InterDynamics, 2014a). These scores range from 0 to 150, and the higher the value, the greater the risk associated with fatigue (euroAtlantic Airways, 2020). As previously shown in Table 2, the SAFTETM Alertness Score's values range from 0 to 100%, but a higher value corresponds to a lower risk of accident or serious error. Thus, and to make the comparison between these two scales more intuitive, it was decided to compress and invert the FAID® scale, as can be seen in the second and third columns of Table 3, respectively (all the values regarding FAID® Score presented in section 4. are in accordance with the third column of this table). The risk scale presented in Table 3 is the one used by the airline of the pilots under study.

Table 3. Risk of accident or serious error associated with the FAID® Score (euroAtlantic Airways, 2020).

FAID® Score	New scale [%]	Inverted new scale [%]	Risk

[120;150]	[80;100]	[0;20]	Extreme
[90;120[	[60;80[	]20;40]	High
[70;90[	[46,67;60[	]40;53,33]	Moderate
[0;70[	[0;46,67[	]53,33;100]	Low

3.6. Daily Procedure Followed by the Pilots

The collection of data from the four pilots was carried out in July and August 2020. All flights reviewed were conducted under the "EASA temporary exemptions under Article 71(1) of Regulation (EU) 2018/1139" (EASA, 2020) and with the respective endorsement of the National Civil Aviation Authority (ANAC).

During the entire data collection period, the day started with the filling of the SD, in the section "Fill in the morning, after waking up". To complete this task, pilots were required to rate their status when waking up, according to the SPS scale, and to do a PVT test on the s2P application.

On flight days, pilots were asked to complete a document providing relevant information about the FDP, namely: the date, so that performance during the flight(s) could be related to the sleep periods considered relevant; the time zone difference between the place of departure and the final destination; the take-off hours, in Universal Coordinated Time (UTC); the flight time of each sector. Before the first sector, pilots classified their status (SPS) and performed a PVT test (s2P). This information was updated after each sector. Finally, and again during the whole data collection period, the day ended with the filling of the SD, in the section "Fill at night, before going to bed". As was the case in the morning, pilots rated their status at bedtime (SPS) and did a new PVT test (s2P).

The pilots kept the wearable ReadibandTM 5 on their wrist throughout the whole study period, removing it only for activities that could put it in direct contact with water (they all started using the device at least three days before their first FDP). FAID® Score values were directly provided by the airline, through fatigue reports from the pilots involved.

4. RESULTS

Table 4 presents the location and the codes IATA (International Air Transport Association) and ICAO) of the airports involved in the analyzed flight sectors.

Table 4. Airports' location and codes (Great Circle Mapper, 2020).

Country (City)	IATA Code	ICAO Code
Portugal (Lisbon)	LIS	LPPT
Nigeria (Lagos)	LOS	DNMM
São Tomé e Príncipe (São Tomé)	TMS	FPST
United Arab Emirates (Dubai)	DWC	OMDW
Afghanistan (Kabul)	KBL	OAKB

4.1. Airline Pilot 1

Overview:

43-year-old male with 7,000 flight hours.
Used ReadibandTM 5 for 16 days, averaging 7.2 hours of sleep per night with 0.62 awakenings per hour.
SAFTETM Alertness Score: 92.90% (very low risk of accident).
SPS scale: 3.81 after waking up, 5.00 before bed.
Reaction Times (RTs): 487.60 ms after waking up, 514.25 ms before bed.
Best RT: 413 ms.

Flight Duty Period 1.1 (Day 4):

Two sectors: LIS – LOS and LOS – LIS.
Night before: 5.8 hours of sleep, 0.52 awakenings per hour (below recommended values).
SPS scale: Level 4 after waking up, Level 5 before first sector, Level 6 after first sector.

RTs: 520 ms after waking up, 533 ms before first sector, 541 ms after first sector, 522 ms after second sector.
SAFTETM Alertness Score: 92.7% before first sector, 89.7% after first sector, 88.4% after second sector.
FAID® Score: 94.17% after first sector, 83.35% after second sector.

Flight Duty Period 1.2 (Day 16):

One sector: TMS – LIS.
Night before: 7.6 hours of sleep, 1.05 awakenings per hour (quality below recommended values).
SPS scale: Level 6 after waking up.
Pilot 1 experienced increased fatigue and reaction times during flight duty periods, indicating elevated risk of accidents or errors, especially when sleep quality and quantity were below recommended values.

Table 5. Pilot 1 performance: sectors LIS – LOS and LOS – LIS.

	LIS – LOS		LOS – LIS
Hour (UTC)	09:10 h		17:50 h
Flight Time	05:10 h		04:55 h
SPS Scale	Before: 5	After: 6	After: 6
PVT Test [ms]	Before: 533	After: 541	After: 522
SAFTE™ [%]	Before: 92.7	After: 89.7	After: 88.4
FAID® [%]		After: 94.17	After: 83.35

Table 6. Pilot 1 performance: sector TMS – LIS.

	TMS – LIS	
Hour (UTC)	13:00 h	
Flight Time	05:25 h	
SPS Scale	Before: 2	After: 4
PVT Test [ms]	Before: 493	After: 514
SAFTE™ [%]	Before: 93.9	After: 94.7
FAID® [%]		After: 93.78

4.2. Airline Pilot 2

Overview:

45-year-old male with 450 flight hours.
Used ReadibandTM 5 for 18 days, averaging 5.2 hours of sleep per night with 1.19 awakenings per hour.
SAFTETM Alertness Score: 76.56% (elevated risk of accident).
SPS scale: 3.11 after waking up, 3.33 before bed.
Reaction Times (RTs): 191.22 ms after waking up, 179.56 ms before bed.
Best RT: 157 ms.

Flight Duty Period 2.1 (Day 4):

Two sectors: LIS – LOS and LOS – LIS.
SPS scale: Level 3 after waking up, Level 2 before first sector, Level 3 after first sector, Level 5 after second sector.
RTs: 167 ms after waking up, 187 ms before first sector, 174 ms after first sector, 193 ms after second sector.
SAFTETM Alertness Score: 91.3% before first sector, 88.2% after first sector, 79.0% after second sector.
FAID® Score: 94.33% after first sector, 83.35% after second sector.

Flight Duty Period 2.2 (Days 6-7):

Four sectors: LIS – DWC, DWC – KBL, KBL – DWC, DWC – LIS (Pilot 2 operated only in DWC – KBL and KBL – DWC).
Night before: 3.1 hours of sleep, 1.94 awakenings per hour (below recommended values).

Pilot 2 experienced elevated fatigue and reaction times during flight duty periods, indicating an increased risk of accidents or errors, especially when sleep quality and quantity were below recommended values. Table 7 and 8 shows the results obtained by pilot 2 during the two flight sectors.

Table 7. Pilot 2 performance: sectors LIS – LOS and LOS – LIS.

	LIS – LOS		LOS – LIS
Hour (UTC)	09:10 h		17:50 h
Flight Time	05:10 h		04:55 h
SPS Scale	Before: 2	After: 3	After: 5
PVT Test [ms]	Before: 187	After: 174	After: 193
SAFTE™ [%]	Before: 91.3	After: 88.2	After: 79.0
FAID® [%]		After: 94.33	After: 83.35

Table 8. Pilot 2 performance: sectors DWC – KBL and KBL – DWC.

	DWC – KBL		KBL – DWC
Hour (UTC)	16:50 h		00:00 h
Flight Time	03:15 h		03:15 h
SPS Scale	Before: 3	After: 3	After: 5
PVT Test [ms]	Before: 178	After: 207	After: 197
SAFTE™ [%]	Before: 81.4	After: 81.7	After: 50.8
FAID® [%]	Before: 78.11	After: 72.65	After: 50.85

4.3. Airline Pilot 3

Overview

53-year-old male with 1,050 flight hours.
Used ReadibandTM 5 for 15 days, averaging 7.3 hours of sleep per night with 0.35 awakenings per hour.
SAFTETM Alertness Score: 91.15% (very low risk of accident).
SPS scale: 2.33 after waking up, 3.80 before bed.
Reaction Times (RTs): 187.80 ms after waking up, 190.15 ms before bed.
Best RT: 160 ms.

Flight Duty Period 3.1 (Day 4):

One sector: LIS – DWC.
Night before: 7.1 hours of sleep, 0.28 awakenings per hour (good quality sleep).
SPS scale: Level 3 after waking up, Level 1 before flight, Level 4 after flight.
RTs: 175 ms after waking up and before flight.
SAFTETM Alertness Score: 94.2% before flight, 97.8% after flight.
FAID® Score: 90.38% after flight.

Flight Duty Period 3.2 (Day 15):

Two sectors: LIS – TMS and TMS – LIS.
Night before: 7.9 hours of sleep, 0.38 awakenings per hour (close to good quality).
SPS scale: Level 2 after waking up, Level 2 before first sector, Level 3 after first sector, Level 4 after second sector.
RTs: 226 ms after waking up and before first sector.
Pilot 3 generally maintained a very low risk of accidents or errors, with good sleep quality and stable alertness scores, though fatigue increased slightly during flight duty periods. Table 9 and 10 shows the results obtained by pilot 3 during flight sectors.

Table 9. Pilot 3 performance: sector LIS – DWC.

	LIS – DWC	
Hour (UTC)	06:25 h	
Flight Time	08:35 h	
SPS Scale	Before: 1	After: 4
PVT Test [ms]	Before: 175	After: -----

SAFTE™ [%]	Before: 94.2	After: 97.8
FAID® [%]		After: 90.38

Table 10. Pilot 3 performance: sectors LIS – TMS and TMS – LIS.

	LIS – TMS		TMS – LIS
Hour (UTC)	04:55 h		13:55 h
Flight Time	05:50 h		05:55 h
SPS Scale	Before: 2	After: 3	After: 4
PVT Test [ms]	Before: 226	After: -----	After: 230
SAFTE™ [%]	Before: 82.7	After: 89.3	After: 88.9
FAID® [%]		After: 90.53	After: 81.41

4.4. Airline Pilot 4

Overview:

38-year-old male with 5,100 flight hours.
Used ReadibandTM 5 for 8 days, averaging 6.6 hours of sleep per night with 1.06 awakenings per hour.
SAFTETM Alertness Score: 87.33% (low risk of accident).
SPS scale: 4.88 after waking up, 5.00 before bed.
No average RT values presented.

Flight Duty Period 4.1 (Day 7):

One sector: DWC – LIS.
Night before: 3.9 hours of sleep, 1.54 awakenings per hour (below recommended values).
SPS scale: Level 4 after waking up, Level 2 before flight, Level 6 after flight.
RTs: 178 ms before flight, 197 ms after flight.
SAFTETM Alertness Score: 75.3% before flight, 82.0% after flight.
FAID® Score: 85.64% after flight.
Pilot 4 experienced increased fatigue and reaction times during the flight duty period, indicating a moderate to high risk of accidents or errors, especially when sleep quality and quantity were below recommended values. Table 11 shows the results obtained by pilot 4 during this flight sector.

Table 11. Pilot 4 performance: sector DWC – LIS.

	DWC – LIS	
Hour (UTC)	06:45 h	
Flight Time	08:45 h	
SPS Scale	Before: 2	After: 6
PVT Test [ms]	Before: 178	After: 197
SAFTE™ [%]	Before: 75.3	After: 82.0
FAID® [%]		After: 85.64

5. DISCUSSION

The data collected by the actigraph showed that, on average, only pilots 1 and 3 reached the quantity of sleep recommended for most adults, recording values above 7 h. In terms of sleep quality, pilot 3 was the only one who recorded an average value of awakenings per hour of sleep that reflected the good quality of it. Pilots 1, 2 and 4 recorded values over 0.37 awakenings per hour of sleep, which indicates that their sleep was too fragmented. Pilot 2 mentioned that the temperatures recorded during the data collection period impaired the possibility of having a restorative sleep. In fact, the ideal bedroom temperature is between 18 and 20 °C (IATA, ICAO and IFALPA, 2015), so, taking into account that the study was conducted in the summer months, this factor may have influenced the sleep pattern of the pilot.

Throughout all the analyzed FDPs, the workload to which the pilots were subjected contributed to a progressive increase in the fatigue perceived by them, which resulted in an increase of the level chosen on the SPS scale. In general, it was also possible to observe an increase in the RT between the beginning of the FDP and the end of the last sector.

As can be verified by the results obtained by the four pilots, the risk of serious error associated with the results of the PVT tests (RTs) tends to be higher than the risk associated with the values provided by the SAFTETM biomathematical model. Thus, in several analyzed flight sectors, it was not possible to verify the correspondence between the SAFTETM Alertness Score and the increase of the RT, previously illustrated in Table 2. It is in this context that the differences between the laboratory data used in the development of the SAFTETM model and the methods used in this work may be more relevant, namely: the PVT tests in this study lasted three minutes, while the tests for the development of the model lasted ten minutes (Roma et al., 2012); the devices used to measure the pilots' RTs (smartphones) were not the same as those used in the development of the model, due to their high cost and big dimensions (Brunet et al, 2016).

At the end of the analyzed flight sectors, it was possible to obtain four of the five levels of serious error risk contemplated by the SAFTETM model, from the lowest to the highest (very low risk, low risk, elevated risk, very high risk). However, with the FAID® Time Zone model, only the two lowest risk levels (low risk, moderate risk) were obtained. The fact that FAID® does not consider the actual sleep time obtained by the pilots (InterDynamics, 2014c), unlike the SAFTETM model, may have contributed to underestimate their actual levels of fatigue. One of the assumptions of FAID® is that "recovery from work-related fatigue by sleeping can be obtained at any time an individual is not working" (InterDynamics, 2014c), but this assumption may not be verified.

The highest levels of error risk occurred, both in the SAFTETM model and in the FAID® Time Zone, after the flight KBL – DWC (pilot 2). In the case of the first model, the risk was very high, which would have been expected considering that, after the flight, almost 24 hours had passed since the pilot's last night of sleep. In the case of the second model, the risk was moderate and FAID® Score was the lowest of all those registered (50.85%). The FAID® considers the recent work history (InterDynamics, 2014c), so the fatigue accumulated in the flights LIS – LOS, LOS – LIS (performed two days before the FDP 2.2.), LIS – DWC and DWC - KBL contributed to an increase in the risk associated with the FAID® Score.

For future research we need long-term studies to assess the cumulative effects of SPO on pilot health, performance, and safety, mainly Investigating the interaction between pilots and advanced automation systems to optimize workload distribution and situational awareness.

6. CONCLUSIONS

Although this study has a very small sample, when trying to verify that the level of fatigue remains at least as acceptable, there is still a risk of neglecting the multifactorial nature of chronobiology and sleep. In fact, the results obtained showed that the four airline pilots felt the effects of cognitive fatigue during the flight sectors.

Considering the duration of some of the FDPs, it was possible to observe significant changes in the fatigue scores produced by SAFTETM and FAID® Time Zone models. However, a greater variation in risk was observed when the assessment was made by the first model. There was even a flight that started with a low risk of error but ended with a very high risk.

Despite regulations limiting flight time and enabling optimal rostering, fatigue is something that cannot be prevented completely.

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