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Seasonal variation in fatigue indicators in Brazilian civil aviation crew rosters

Sazonalidade de indicadores de fadiga nas escalas de trabalho dos aeronautas da aviação regular brasileira

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ABSTRACT | Background: Analyzing, understanding and managing fatigue risk in aviation is relevant for flight safety and to reduce human error. **Objective:** To analyze probable levels of fatigue among a convenience sample of Brazilian civil aviation pilots and flight attendants and to develop appropriate methods and indicators to quantify potential fatigue risk in critical phases of flight (landings and takeoffs). **Methods:** Data were obtained from flight rosters voluntarily and anonymously fed to a digital platform. Rosters were analyzed with software SAFTE-FAST, which considers homeostatic process and circadian cycles related to attention and wakefulness and sleep inertia. **Results:** The rosters for January (n=248), May (n=259) and July (n=261) 2018 were associated with incidence of 77, 54 and 77% respectively of least one event of minimal effectiveness (<77%) during critical phases of flight. The distribution of minimal effectiveness and hazard area during critical phases of flight exhibited significant seasonal oscillation upon comparing the results for January and July relative to May 2018 ($p<0.001$). **Conclusion:** Relative likelihood of fatigue was high in the crew rosters, with significant seasonal oscillation of minimal effectiveness and hazard area in critical phases of flight. These results point to the need for improved roster management since prescriptive rules were insufficient to mitigate risk.

Keywords | fatigue; aviation; biological models; risk assessment.

RESUMO | Introdução: Métodos de análise, compreensão e gerenciamento do risco da fadiga na aviação representam tópicos de interesse para a segurança de voo e mitigação de falhas humanas. **Objetivo:** Avaliar o provável nível de fadiga em uma amostra de conveniência de pilotos e comissários de voo da aviação regular brasileira, propondo metodologia e indicadores apropriados para a quantificação da potencial exposição ao risco da fadiga durante as fases críticas de voo (pousos e decolagens). **Métodos:** Os dados foram obtidos por envio espontâneo e anônimo das escalas de voo para uma plataforma, sendo estas analisadas com o *software* Sleep, Activity, Fatigue, and Task Effectiveness / Fatigue Avoidance Scheduling Tool (SAFTE-FAST), que leva em conta o processo homeostático, os ritmos circadianos associados à atenção e vigília e a inércia do sono. **Resultados:** As escalas dos meses de janeiro (n=248), maio (n=259) e julho (n=261) de 2018 tiveram incidência de 77, 54 e 77% de ao menos um evento com efetividade mínima nas fases críticas abaixo de 77%, respectivamente. As distribuições de efetividades mínimas e áreas de risco nas fases críticas apresentaram oscilação sazonal significativa, comparando os meses de janeiro ou julho com maio de 2018 ($p<0,001$). **Conclusões:** O estudo apontou probabilidade relativa elevada de fadiga nas escalas dos aeronautas, assim como oscilações sazonais significativas nas distribuições de efetividade mínima e aérea de risco nas fases críticas. Esses resultados indicam a necessidade de um melhor gerenciamento das escalas, visto que os limites prescritivos vigentes à época não foram suficientes para a mitigação dos riscos.

Palavras-chave | fadiga; aviação; modelos biológicos; análise de risco.

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INTRODUCTION

According to the International Civil Aviation Organization (ICAO), fatigue is a physiological state of reduced mental or physical performance capability resulting from sleep loss or extended wakefulness, circadian phase, or workload (mental and/or physical activity) that can impair a crew member's alertness and ability to safely operate an aircraft or perform safety related duties[1]. ICAO's "Fatigue Risk Management Systems" Annex 6 Part I states that "The State of the Operator shall establish regulations for the purpose of managing fatigue. These regulations shall be based upon scientific principles and knowledge, with the aim of ensuring that flight and cabin crew members are performing at an adequate level of alertness[1]." This is to say, fatigue should be adequately managed to avoid accidents or serious incidents in aviation due to human factors.

In Brazil, the Law no. 13,475/17[2], from August 2017, replaced the older Aircrew Law from 1984. With this, the National Civil Aviation Agency was charged of establishing a fatigue risk management system based on international civil aviation standards and recommendations. The recently published Brazilian Civil Aviation Regulation (RBAC 117)[3] brings additional requirements, but also some flexibilization by comparison to the aforementioned law.

Another relevant aspect is the investigation of aviation incidents caused by human factors in which fatigue might play a significant role[4]. The Brazilian National Commission of Human Fatigue has recently published a revised method to help the Aeronautic Accident Investigation and Prevention Center assess the role of fatigue in aviation accidents and serious incidents[5]. In addition, a recent study found that speech analysis might be useful to detect fatigue and sleepiness among pilots involved in human-error related accidents in aviation[6]. Further studies are necessary to enhance the knowledge on this subject and formulate safety recommendations to contribute to fatigue risk management.

Monitoring fatigue is also necessary due to the irregular working hours of crews[7]. A study performed with a large Brazilian carrier[8] found that the odds of pilot errors were 46% times higher in the early hours (0:00 to 6:00) compared to other shifts (6:00 to 12:00, 12:00 to 18:00 and 18:00 to 24:00). Another study, conducted in 2012, pointed to a situation of chronic fatigue among Brazilian civil aviation pilots[9] following analysis of 301 fatigue reports with the Sleep, Activity, Fatigue, and Task Effectiveness/Fatigue Avoidance Scheduling Tool (SAFTE-FAST)[10].

Biomathematical modelling of fatigue in aviation has called the attention of both scientists[10-12] and regulatory agencies[13-15]. For instance, the European Aviation Safety Agency recently performed a large-scale study to analyze the efficacy of flight time limitations to prevent fatigue[15]. Marquez et al.[16] found prevalence of in-flight unintentional sleeping of 57.8% among Brazilian pilots, which indicates sleep deprivation and/or fatigue.

Our aim in the present study was to develop an innovative approach to the analysis of fatigue risk in aviation by relating effectiveness calculated by means of SAFTE-FAST to the relative likelihood of accidents due to human factors. We analyzed alertness indirectly among a convenience sample of Brazilian crewmembers and used this data to calculate indicators of relative likelihood of fatigue and to investigate seasonal variations.

METHODS

SAMPLE

We recruited 323 crewmembers by convenience sampling including pilots and flight attendants of either sex, with no limits of age or years in the job. Rosters were obtained from the database developed for *Fadigômetro* Project ("Fatigue-meter"; for detail see www.fadigometro.com.br). We analyzed rosters for minimum crews (two pilots and minimum required number of flight attendants) in narrow-body aircrafts and excluded augmented crews (three pilots and 25% extra attendants or four pilots and 50% extra attendants).

ETHICAL ISSUES

The present study is part of project "Analysis of Fatigue in Brazilian Civil Aviation" approved by the research ethics committee of Institute of Biosciences, University of São Paulo (Certificate of Presentation for Ethical Appraisal no. 89058318.7.0000.5464). Confidentiality was ensured to eligible subjects who voluntarily agreed to participate by signing a digital informed consent form. We declare we have no commercial or labor duality or conflict of interest with any representative institution involved in the experiment, airline or government agency. It was ensured confidentiality for the airlines whose rosters were analyzed.

DATA COLLECTION

After eligible subjects filled a registration form validated through an SMS code theirs rosters since December 2017 were automatically fed to a system involving internal indexing encoding without human intervention. The participants were also requested to respond a biopsychosocial questionnaire with items on sociodemographic, behavioral and health aspects — this data is not described in the present article.

ROSTER DATA ANALYSIS

Rosters were digitized and analyzed by means of an online internal algorithm. We set some filters to extract CSV files according to specific categories, including aircraft type, crew rank and tasks, beginning and end of duty and flight times, ICAO airport codes and contractual basis. Routine tasks were divided into two groups, considering the flight events themselves (crewing - C) and non-flight work events (working - W). The latter include ground activities (reserves, training, etc.) or eventual tasks on board while flying as a passenger for airline purposes. In the present study we only considered crewing events.

The data were analyzed with software Statistical Product and Service Solutions (SPSS), version 20.0.0. We tested normality with the Kolmogorov-Smirnov test before inferential and nonparametric analysis (Kruskal-Wallis and Mann-Whitney tests).

SOFTWARE SAFTE-FAST

SAFTE-FAST is based on a biomathematical model that estimates an individual's effectiveness along the day (E_{SF}). Effectiveness is understood as a magnitude proportional to the velocity in which tasks are performed correctly. This model considers three aspects:

- homeostatic balance;
- sleep/wake circadian rhythm;
- sleep inertia.

Figure 1 represents a summary description of SAFTE-FAST[10]. Homeostatic balance is described as a "sleep reservoir" that becomes progressively depleted along the waking hours and is replenished by sleep. Replenishment (sleep accumulation) is determined by the intensity, duration and quality of sleep. Intensity is a function of the sleep debt and the sleep/wake circadian rhythm, therefore the more the sleep deprivation and sleepiness, the higher the "reservoir" replenishment rate and vice versa. The third component seeks to reproduce impairments in cognitive performance due to sleep inertia, i.e. transient post-sleep decay of performance associated with the time needed to reach normal alertness[10].

SAFTE-FAST PARAMETERS, CRITERIA AND SUGGESTED FITTING

We set the following values and criteria for the SAFTE-FAST parameters:

1. Sleep onset time: 23:00;
2. Minimum sleep duration: 60 minutes;
3. Maximum sleep duration on workdays/off days: 8/9 hours;
4. Naps included automatically before the duties that start at night and go thru the dawn;
5. Maximum nap duration: 210 minutes;
6. Anticipation of sleep onset time when waking up too early in the morning;
7. Excellent quality of sleep at home/hotel.

These parameters correspond to the standard SAFTE-FAST (version 2.0.5.148) configuration with the addition of #4 and #6 to obtain results reflecting ideal work circumstances. All these parameters and criteria might be improved in future analysis of the biopsychosocial questionnaire, for which purpose also objective actigraphy measurements might be added.

SAFTE-FAST also considers the time needed to prepare for work (at home/hotel) which was set as 60 minutes in the present study, as well as commuting times (home-airport, airport-home, hotel-airport, airport-hotel) which were also set as 60 minutes.

Shortly, we modelled ideal work circumstances for crewmembers, therefore results should expectably fall within the upper limits of cognitive performance calculated from a combination of wake time along the workday, sleep opportunities according to the work schedule and SAFTE-FAST standardized hypotheses. Our intention was to describe the relative likelihood of accidents caused by human factors (P_{HF}) as inverse function of E_{SF}, i.e. $P_{HF}(E_{SF})=b/E_{SF}$, where b is a constant which value must be determined.

CATEGORIZATION OF RELATIVE LIKELIHOOD AS A FUNCTION OF E_{SF}

Fadigômetro Project set three E_{SF} ranges to categorize relative likelihood of fatigue in aviation operations:

- low: $E_{SF}>90\%$;
- medium: $77\%<E_{SF}\leq 90\%$;
- high: $E_{SF}\leq 77\%$.

These cut-off points were selected based on a SAFTE-FAST validation study that analyzed the relationship between E_{SF} and economic impacts of rail accidents[17]. The results indicated that the total cost of accidents caused by human factors was about 4.5 times higher for $E_{SF}\leq 77\%$ versus $E_{SF}>90\%$. In addition, the total cost varied by 7% upon comparing $E_{SF}>90\%$ versus $77\%<E_{SF}\leq 90\%$, whence the latter was characterized as a transitional range. Regulatory agencies and airlines may adopt other parameters to analyze the relationship between effectiveness ranges and relative likelihood of accidents.

CRITICAL PHASES OF FLIGHT, EFFECTIVENESS AND HAZARD AREA

SAFTE-FAST considers as critical the first and last 30 minutes of each phase of flight, which generally includes takeoff, climb, descent and landing. These phases are characterized by greater mental workload, consequently greater cognitive demands, which are particularly susceptible to the influence of external (meteorological conditions, air traffic, communication with air trafic controllers, etc.) and internal (operational procedures, aircraft limitations, flight deck communications, etc.) factors.

To achieve a global assessment of fatigue we devised an extensive variable that involves the length of risk exposure at critical phases of flight. Named by us as hazard area, it is a two-dimensional quantity that takes into account the length of time (in minutes) and level of effectiveness below 77% during critical phases of flight. First formulated by Rangan and Van Dongen in 2013[18], it was applied in the present study by setting the E_{SF} 77% threshold to critical phases of flight only.

RESULTS

RELATIONSHIP BETWEEN E_{SF} AND RELATIVE LIKELIHOOD OF ACCIDENTS CAUSED BY HUMAN FACTORS ACCORDING TO THE ADOPTED FITTING

To investigate the relationship between effectiveness and relative likelihood of accidents caused by human factors we fitted a model that combined objective data

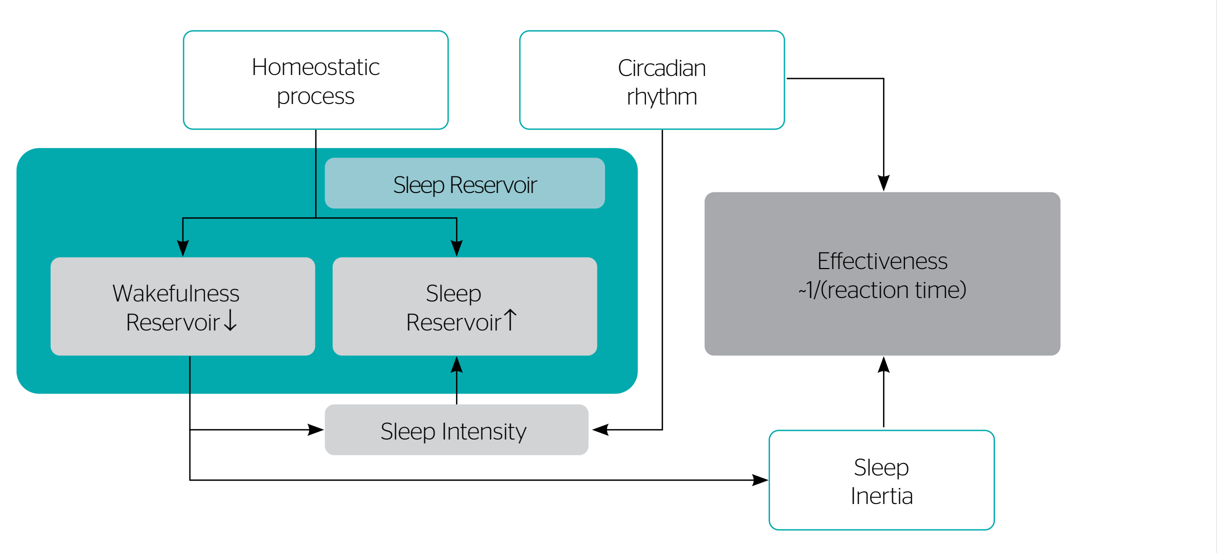

Figure 1. Diagram representing the Sleep, Activity, Fatigue, and Task Effectiveness/Fatigue Avoidance Scheduling Tool (SAFTE-FAST), adapted from Hursh et al.[10].

for accidents[19] and effectiveness outcomes on SAFTE-FAST. We began by assuming that the relative likelihood of accidents is inversely proportional to the SAFTE-FAST-estimated effectiveness, i.e. $P_{HF}(E_{SF})=b/E_{SF}$. Our intention was to select one single parameter (b) to analyze the relationship between P_{HF} and E_{SF}. The data fitted in the model were obtained from a validation study of SAFTE-FAST[19] based on 400 rail accidents caused by human factors in the United States. Locomotive crews were monitored 30 days prior to accidents, which enabled the authors to use this model to estimate the value of E_{SF} at the time of accidents. The results are described in Figure 2 together with the fitted function $P_{HF}(E_{SF})=b/E_{SF}$ [with $b=0.796\pm0.030$, $\chi^2=4.89$, df=5 and $P(\chi^2>4.89)=43\%$] obtained by means of the least square method[20] with E_{SF} expressed as decimal units. The relative likelihood of accidents increased by 30% upon comparing effectiveness 100% [$P_{HF}(1)=0.796$] versus 77% [$P_{HF}(0.77)=1.034$]. The error bars in Figure 2 were estimated as proportional to $\sqrt{N}/N$, where N is the total number of accidents per effectiveness range (Hursh, 2015, personal communication).

The purpose of estimating the relationship between P_{HF} and E_{SF} is to analyze the relative variation in the likelihood of accidents for pairs of different values of E_{SF}; instead of representing an absolute parameter for the analysis. As was mentioned, the studies on rail accidents[17,19] were performed to validate the SAFTE-FAST biomathematical model and showed that the incidence of accidents increases when E_{SF} decreases. The extrapolation of railroad accident data to the aviation modal should be done carefuly, but is justified given the latter have insufficient statistics[21] to develop similar analyses.

SAMPLE DEMOGRAPHIC DATA

The sample comprised 323 Brazilian civil aviation crewmembers, 309 of whom responded the biopsychosocial questionnaire. A total of 219 (71%) were male and 90 (29%) female, 166 (54%) were pilots and 143 (46%) flight attendants, with average age 39±9.5, 34.4±6.4, 40.5±9.5 and 34.5±6.9 respectively.

ROSTER ANALYSIS

We selected rosters for months in 2018, one corresponding to the low season (May, n=248) and two to the high season (January, n=259, and July n=261). Our intention was to analyze three periods of work under the same collective labor agreement (in vigor from 1 December 2017 through 30 November 2018). The low-season month was defined as the reference to investigate the eventual influence of high season on some fatigue indicators. Due to the additive nature of the hazard area, we selected three 31-day months and flights with minimal crews, whose members who entered the study until 28 September 2018.

Minimal effectiveness in critical phases

Minimal effectiveness in critical phases (E_{MC}) — i.e. the minimum value of E_{SF} during the first and last 30 minutes of each phase of flight — is highly relevant to identify key causes of in-flight fatigue (i.e. rosters most likely to interfere with the sleep/wake cycle). Figure 3 depicts the relative frequency of E_{SF} and corresponding mean, median and interquartile range (IQR) for the January, May and July 2018 rosters. We found that 77% of rosters for January and July exhibited at least one event of $E_{MC}<77\%$; the corresponding rate for May was 54%.

Hazard area in critical phases of flight

The distribution of the hazard area in critical phases of flight (HA_C) for the analyzed months and corresponding mean, median and IQR is depicted in Figure 4.

Statistical analysis of E_{MC} and HA_C distribution

We subjected the E_{MC} and HA_C distribution to the Kolmogorov-Smirnov test, which evidenced that none

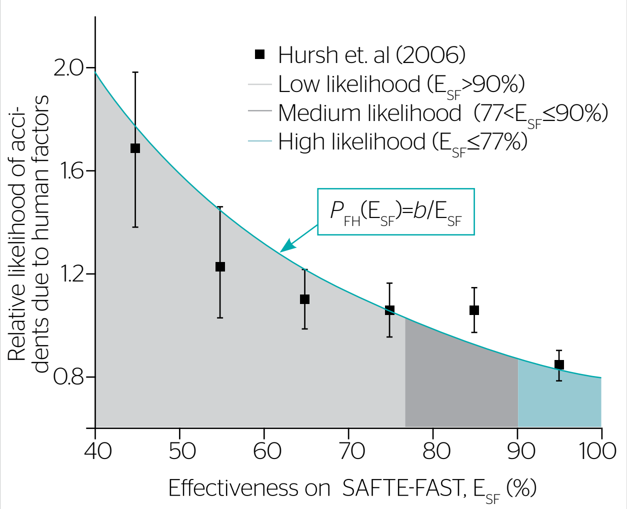

Figure 2. Relative likelihood of accidents caused by human factors according to effectiveness on Sleep, Activity, Fatigue, and Task Effectiveness/Fatigue Avoidance Scheduling Tool (SAFTE-FAST) (n=400).

was normal, $p<0.001$. For this reason we had resource to nonparametric tests to verify the hypothesis of seasonal variability. The results are described in Table 1, which shows statistically different distribution of both E_{MC} and HA_C (Kruskal-Wallis test) between the analyzed months ($p<0.001$). On pairwise comparison (Mann-Whitney test) we detected significant effect of seasonality between the high-season and the low-season months for both variables ($p<0.001$). In turn, we did not find significant difference between the two high-season months for either E_{MC} ($p=0.773$) or HA_C ($p=0.815$). All these analyses were performed with software SPSS version 20.0.0.

DISCUSSION

The results described here are part of the dataset established for *Fadigômetro* Project grounded on three aspects:

- Operational approach;
- Automated roster collection;
- Scientific methods.

The operational approach is achieved because rosters are evaluated as a whole, and thus allow calculating relevant fatigue indicators under the real circumstances of operations. Automated roster collection is an innovative technique that enables large-scale storage of data and to generate random convenience samples. The third aspect concerns the scientific methods chosen, which are based on the SAFTE-FAST biomathematical model, the relationship between E_{SF} and the relative likelihood of accidents (Figure 2) and the notion of hazard area. We chose SAFTE-FAST over other models with similar characteristics and limitations[10-12,14] based on technical criteria, since this tool exhibited satisfactory predictive ability relative to objective data collected with the psychomotor vigilance test (PVT)[22].

The E_{MC} histograms (Figure 3) evidence a peak in the 70%–75% range distribution for the high-season months, when 77% of the participants exhibited $E_{MC} \leq 77\%$. Differently, in the low-season only 54% of the participants exhibited $E_{MC} \leq 77\%$. These results indicate that roster management should be improved and that the prescribed rules then in force were insufficient to reduce the risk of fatigue. Corroborating this finding, the Working Time Society recently published a consensus on the inefficacy of prescriptive rules for certain conditions[23].

E_{MC} is highly relevant to identify key aspects of flights liable to cause fatigue, although it does not enable to analyze global exposure to relative risk of fatigue in monthly flight rosters, since the software only considers minimal effectiveness for a given individual and period. To illustrate, let us consider two monthly rosters, one associated with tens of events of $70\% \leq E_{MC} \leq 75\%$ and the other with just one event of $65\% \leq E_{MC} \leq 70\%$. Based on E_{MC}, one would expect for the latter to cause more fatigue than the former. However, since the former comprises tens of flights liable to cause fatigue, one may safely assume that the probability of human error would be higher, particularly as a function of the higher number of takeoff and landing maneuvers under conditions of poorer cognitive performance. Therefore, E_{MC} is not efficacious to quantify relative risk

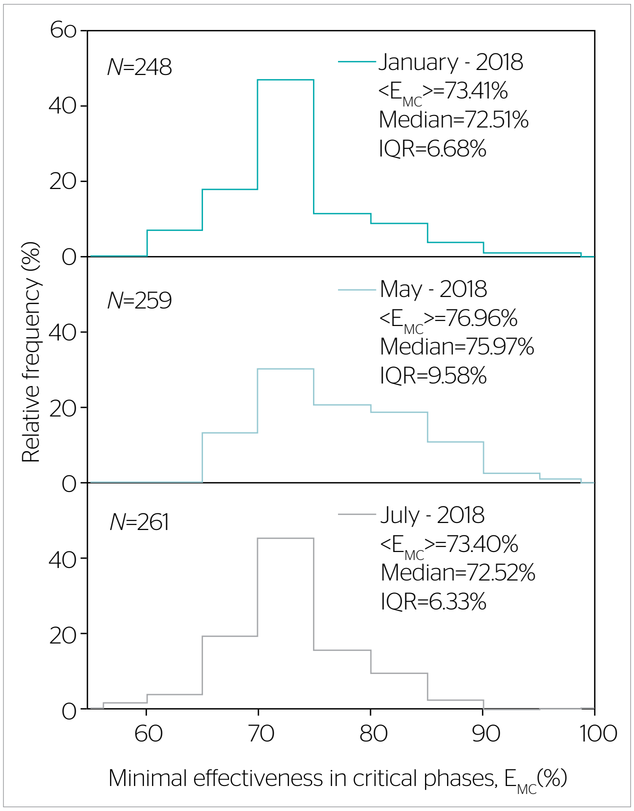

Figure 3. Relative frequency of minimal effectiveness in critical phases of flight for January (above), May (center) and July (below) 2018.

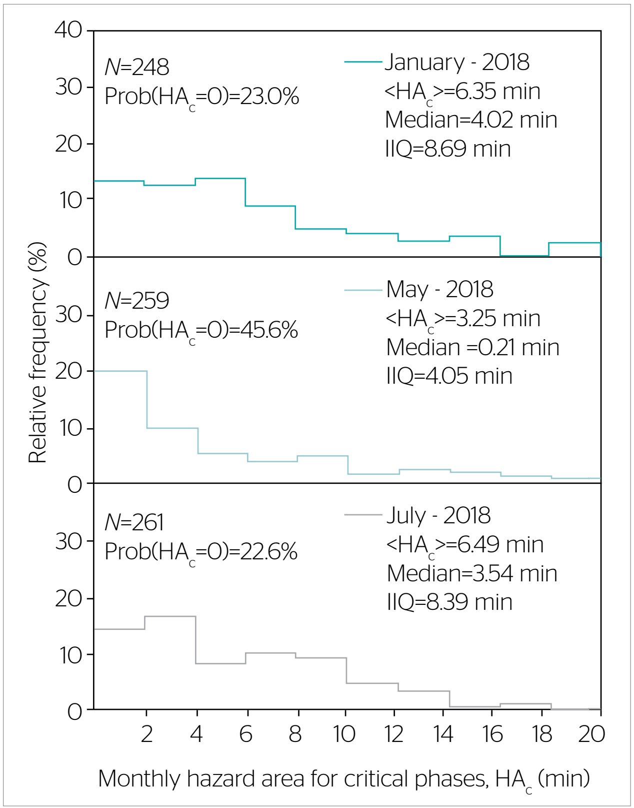

Figure 4. Relative frequency of monthly hazard areas (in minutes) for critical phases of flight relative to January (above), May (center) and July (below) 2018 rosters. Null hazard areas were considered in statistical analysis but not represented in histograms.

for global rosters; it enables consistent assessments of seasonal variations, as Table 1 shows.

In turn, the notion of hazard area does enable global assessments of rosters, because it represents the total sum of all hazard areas for a given crewmember along a definite period. It is also appropriate to investigate seasonal variations in the relative likelihood of fatigue and to measure relative effects of changes in regulations, among them the major ones the Brazilian National Civil Aviation Agency RBAC 117 introduced in prescriptive rules[3].

As Figures 3 and 4 show, there was significant variation in the median and IQR for the distributions of E_{MC} and HA_C upon comparing the low-season (median E_{MC}=75.97%, IQR=9.58%; median HA_C=0.21 min, IQR=4.05 min) and the combined results (N = 509) for the high-season months (median E_{MC}=72.52%, IQR=6.43%; median HA_C=3.70 min, IQR=8.46 min). The Mann-Whitney test evidenced significant seasonal variation of both E_{MC} and HA_C between January and May and July and May ($p<0.001$). Therefore, these indicators are highly relevant to consistently quantify seasonal variations in fatigue among aircrews. We observe that these conclusions are independent from any eventual imprecision in the relationship between P_{HF} and E_{SF} (Figure 2) resulting from the fact we had resource to a

Table 1. Statistical analyses of minimal effectiveness and hazard area in critical phases of flight in January (n=248), May (n=259) and July (n=261) 2018 rosters; Statistical Product and Service Solutions (SPSS) version 20.0.0.

Tests	Normality				Nonparametric for independent samples								
	Kolmogorov-Smirnov				Kruskal-Wallis					Mann-Whitney			
Variables	Groups	Statistic	DF	p	Groups	N	H	DF	p	Groups	N	Z	p
Minimal effectiveness in critical phases (E_{MC})	Jan 2018	0.146	248	<0.001	Jan 2018 May 2018 Jul 2018	768	46.248	2	<0.001	Jan and May 2018	507	-5.866	<0.001
	May 2018	0.095	259							May and Jul 2018	520	-5.886	
	Jul 2018	0.133	261							Jan and Jul 2018	509	-0.289	0.773
Hazard area in critical phases (HA_C)	Jan 2018	0.212	248	<0.001			49.829			Jan and May 2018	507	-6.146	<0.001
	May 2018	0.276	259							May and Jul 2018	520	-6.131	
	Jul 2018	0.245	261							Jan and Jul 2018	509	-0.234	0.815

DF: Degrees of freedom.

rail accident model due to the lack of statistics for the aviation accidents.

Our outcomes are partial inasmuch as we did not include non-crewing events in the analysis. The results obtained represent the lower limits of hazard areas and the upper limits of effectiveness since they overestimate the sleep opportunities in rosters. More robust analyses that include all the events of the rosters aiming to identify the root causes of fatigue are in the scope of the *Fadigômetro* Project and will be published later.

CONCLUSION

In the present study we evidenced the feasibility of assessing alertness among Brazilian civil aviation pilots and flights attendants by coupling a web-based platform to the SAFTE-FAST biomathematical model, i.e. *Fadigômetro* Project. The distribution found for minimal effectiveness in critical phases of flight point to a decay of alertness among crewmembers and thus to a need for better roster management. The prescriptive rules then in force were insufficient to reduce the risk of fatigue. The distribution of both minimal effectiveness and hazard area for critical phases of flight exhibited significant seasonal (high versus low) variation. Finally, the analyzed variables were adequate to quantify relative risk of fatigue and subsequent identification of hazards to thus ground safety recommendations in civil aviation.

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