FRMS Report

(Part II)

A Scientific Approach for the Fatigue Risk Management in the Brazilian Civil Aviation

Revision # 1

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Content:

1. Abstract

This report presents a broad scientific approach for human fatigue risk management in the Brazilian civil aviation aiming at the development of the scientific bases for operational safety recommendations for the air transport system.

The study proposes a new methodology based on the bio-mathematical SAFTE-FAST human fatigue model that evaluates the risk exposure in 61 realistic initial conditions suitable to the particular rostering practices commonly used in Brazil and in line with the duty time limits currently adopted by Australia's CAO-48 and United States' FAR-117 Regulations. The validation of this methodology is pursued through the analyses involving real accidents that have been vastly discussed in operational safety literature.

The results so obtained do demonstrate, for instance, that the area of the FAST effectiveness curve below 80% (risk exposure area) for the second night shift starting at 02h00 is roughly ten times higher than for the first one.

Another important issue investigated in this study was the effect of successive early-starts, where we found a progressive decrease in the effectiveness parameter as the crewmember experiences consecutive work days under these scenarios. In fact, a recent experiment carried out with Brazilian civil aviation pilots (Licati *et al.,* 2015) suggested a chronic fatigue scenario, which, in turn, was attributed to the accumulated sleep deficit that builds up in successive early starts rostering patterns.

Lastly, this report presents a detailed and thorough calculation that provides flight time and flight duty time limits for minimum

and augmented crew based on the Australian model, but also taking into account the risk mitigations previously mentioned.

We would like to stress, however, that this work can be improved by the inclusion of further studies that could, in the future, determine and describe quantitatively the influence of workload, such as the number of sectors flown in a duty period, and the effects of de-synchronization of the biological clock resulted from crossing of time zones, which have been neglected in this work. However, even with these shortcomings, we believe that this report may provide a clear and scientifically based consolidation of parameters which may be used for constructing prescriptive duty-time limitations that are suitable for the Brazilian framework. In this way, we propose some prescriptive limits and constraints that could help in the construction of crew rosters that minimize human fatigue risks and maximizes the performance of aviation professionals so they could safely execute their tasks within satisfactory levels of alertness. This will ensure a higher operational safety margin in the Brazilian civil aviation system. The recommendations and criteria included in this report summarize the technical and scientific propositions of the following Brazilian civil aviation institutions: (1) SNA - Crew member national union, (2) ABRAPAC - Brazilian civil aviation pilot association, (3) ASAGOL - GOL Airlines crew member association, and (4) ATT - TAM Airlines crew member association.

These propositions seek to contribute with the Brazilian Civil Aviation Authority (ANAC) in the important task to remodel the regulations (RBAC).

2. Introduction

Human fatigue, according to the international community's definition, is a physiological state of reduced physical and mental capacity resulted by sleep deprivation, long awake hours, circadian rhythms and/or workloads due to physical and/or mental activity that may impair the level of alertness of an individual and his ability to adequately complete tasks related to operational safety (IATA, ICAO and IFALPA, 2011).

Therefore we verify that human fatigue and its consequences represent a great challenge in modern aviation. Although aircraft dispose of ever safer systems (especially after the development of EGPWS[1]), nonetheless, professionals involved continue to be subject to the oscillations of the level of alertness along the hours of work in the day as well as other circumstances involving prolonged wakefulness and sleep deficit.

Fatigue represents a risk factor that is inherit to aerial operations and can be adequately managed with state policies (Federal Laws and Regulations from Civil Aviation Authorities) and operational policies that should include in a clear and objective way the responsibilities that operators and crew share through the Fatigue Risk Management System (FRMS).

[1] The EGPWS (Enhanced Ground Proximity Warning Systems) alert pilots of the risk of ground collision and have been very effective in reducing Controlled Flight into Terrain (CFIT) accidents.

3. Methodology

For the quantitative analysis presented in Section 4, we adopted the three-process bio-mathematical model SAFTE-FAST (Hursh *et al.*, 2004). This tool was validated (Roma *et al.*, 2012) through objective measurements with PVT (Psychomotor Vigilance Test) and has been largely used for the implementation of FRMS by airline companies.

Figure 1 shows some of the most relevant aspects taken into account in the bio-mathematical model, such as: (1) the homeostatic process, (2) the circadian cycle, and (3) the sleep inertia. These features contribute for the calculation of the individual effectiveness (E) along the hours of the day.

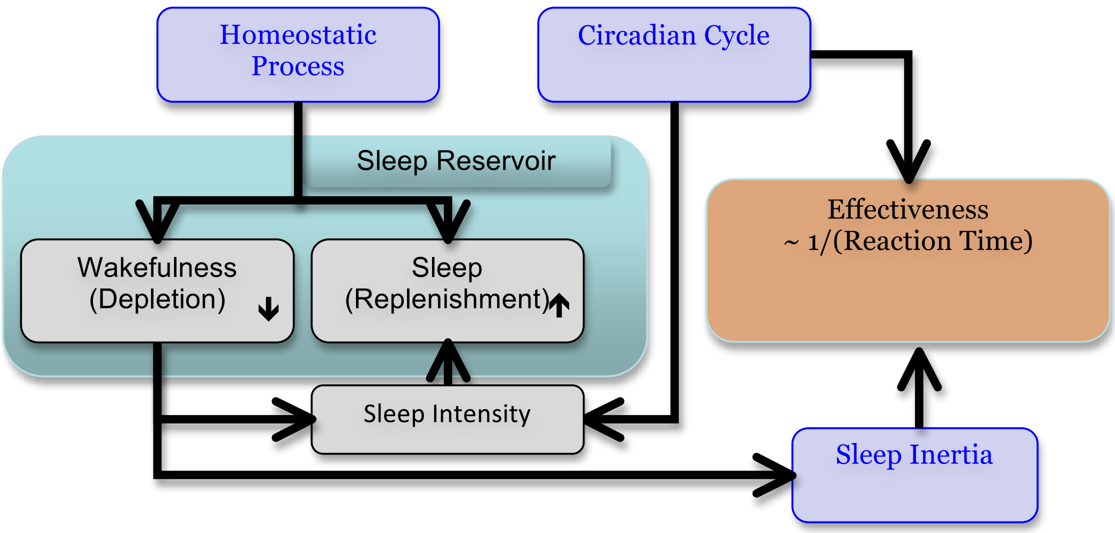

Figure 1: The SAFTE-FAST bio-mathematical model, adapted from Hursh *et al.* (2004).

The effectiveness obtained using the SAFTE-FAST model is assumed to be inversely proportional to the reaction time measured by the PVT device which, in turn, varies linearly with the lapses likelihood. This linear relationship is the basic assumption of the model and is presented in Figure 2 (Licati *et al.,* 2015).

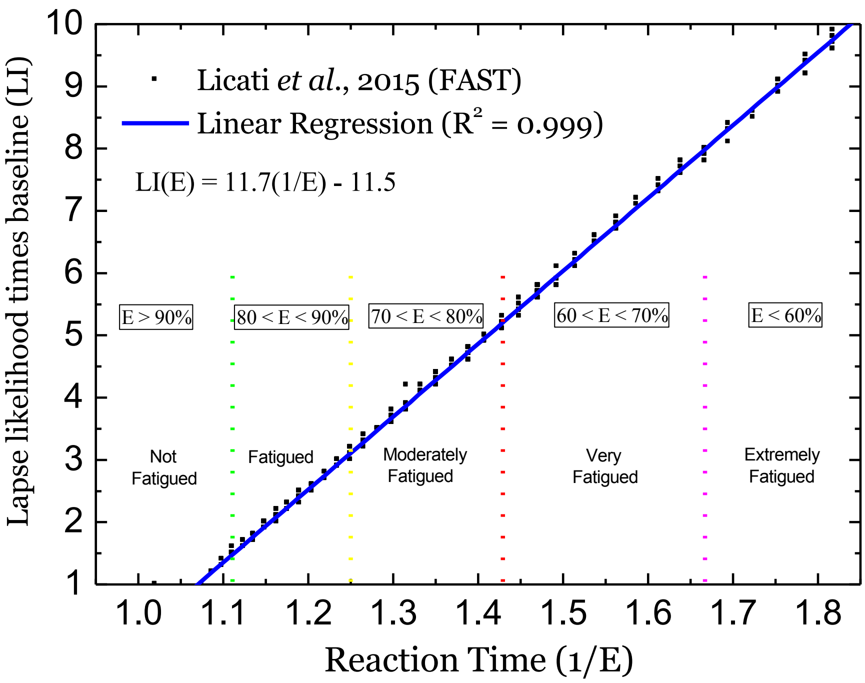

Figure 2: Lapse likelihood times baseline (Lapse Index) as a function of the reaction time in PVT.

At first approximation, we assume that the relative risk in operations (R) is directly proportional to the probability of lapses, i.e., proportional to 1/E such that R(E) = a + b/E, with a and b representing free parameters to be determined.

A recent experiment dedicated to the validation of the SAFTE-FAST model (Hursh *et al.,* 2006) analyzed 400 accidents caused by human failure in rail train transport in the United States. The workers were monitored during the 30 days prior to the accident in order to estimate (with the help of FAST software) the level of effectiveness at the moment of the occurrence.

The results are presented in Figure 3, together with the fitted function[2] R(E) = a + b/E, with a= 0.27 ± 0.20, b = 0.58 ± 0.16 (χ^2 = 3.02 and *n.d.f.* = 3).

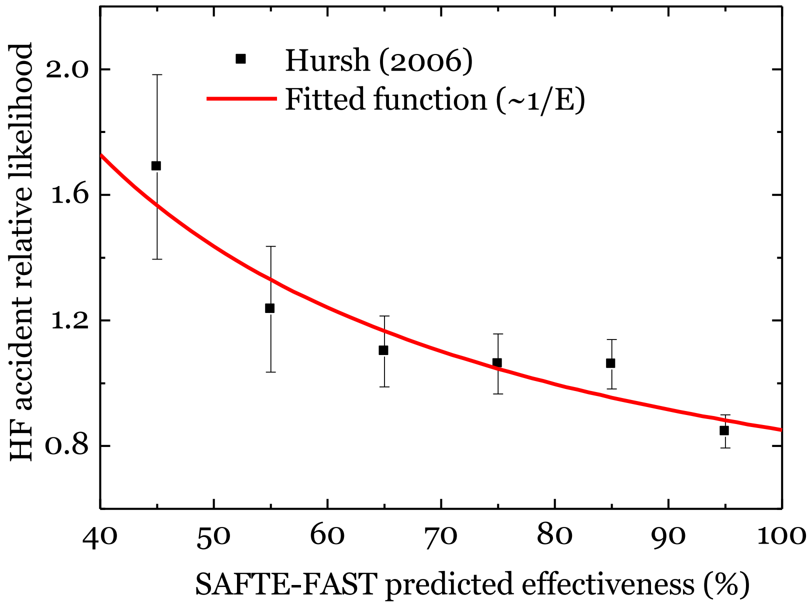

Figure 3: Human-Factor (HF) accident relative likelihood as a function of SAFTE-FAST predicted effectiveness. Details in the text.

The data of Figure 3 (Hursh *et al.*, 2006) represent the relative probability of accidents caused by human errors normalized by the amount of work hours (exposure). The error bars were estimated to be $N^{1/2}$, where N is the number of total accidents for a given effectiveness interval.

The risk exposure was calculated as a function of the area of the effectiveness curve along the duty period below a threshold value,

[2] For the statistical analyzes we have adopted the Least Squares Method described elsewhere (Helene, 2013).

herein fixed at 80%. This limit is close to the level of 77%, which corresponds to a blood alcohol concentration (BAC) of 0.05% (the equivalent ingestion of 1200 ml of regular beer) and should be interpreted as an adequate parameter to classify a potential risk exposure according to the context and purpose of this report. Therefore, duty periods that show effectiveness levels slightly below the threshold parameter of 80% but for a long period would be considered to have a significant exposure to risk. On the other hand, other scenarios with huge variations of effectiveness significantly below 80% even during short periods may also represent excessive (and maybe unacceptable) exposure to risk.

The threshold of 80% is slightly above 77% and is not supposed to be a go no go parameter. The limitations in the Brazilian infrastructure (as described in Section 4.2) as well as the complexities of manual flight operations do support that the caution zone starts at higher average effectiveness (typically below 90%). Consequently, operators shall establish more accurate measurements and/or mitigations in order to achieve satisfactory levels of safety against human fatigue for rosters with sustained operations (integrated over time) below this threshold of potential risk.

4. Results

4.1 An overview of human fatigue in the Brazilian civil aviation

Specifically for the Brazilian case, recent studies (Mello *et al.* 2008) demonstrated that pilots make 46% more errors per hour between 0:00 and 5:59 than during the interval between 6:00 and 11:59. These errors (named Class 3 errors) occur when the operational limits are exceeded and/or the operational procedures are not followed, which cause an aircraft to develop an undesirable flight situation from an operational safety stand point. According to Mello *et al.* (2008), 1065 errors were registered in 155,327 hours of flight, *i.e.* 6.86 errors for each 1000 hours of flight, or one error per 146 flight hours. These errors were distributed along the hours of the day according to Table 1.

Table 1: Normalized errors as a function of the time of the day, extracted from (Mello *et al.*, 2008).

Time of day	Clock-hour	Hours of flight (%)	Errors (N)	Errors/100 h flight time	Normalized data
Morning	6:00-11:59	54,364 (35%)	352	6.47	1.00
Afternoon	12:00-17:59	49,705 (32%)	335	6.74	1.04
Night	18:00-23:59	40,385 (26%)	275	6.81	1.05
Early morning	0:00-5:59	10,873 (7%)	103	9.47	1.46
Total		155,327	1065	6.86	1.06

Assuming that the statistical fluctuation of the data is approximately described by $N^{1/2}$ (N being the number of events for a given time interval), one can easily found 352 ± 19 errors in 54,364 hours flown between 6:00 and 11:59 (35% of the all the flights of the airline that was studied). The proportion of errors in this time interval is of 6.5 ± 0.4 errors per each 1000 flight hours. Following the same criterion, it can be calculated that 6.7 ± 0.4 errors occur from 12:00 to 17:59 (32% of all the airline's flights), 6.8 ± 0.4 errors from 18:00 to 23:59 (26% of all the airline's flights) and 9.5 ± 0.9 errors from 00:00 to 5:59 (7% of all the airline's flights) for each 1000 flight hours. It can be verified, thus, that there is no significant variation of occurrences of errors between 6:00 and 23:59, but a significant increase of occurrence (almost 50%) from 0:00 to 5:59. The difference obtained between this time interval and the reference value (from 6:00 to 11:59) is 3.0 ± 1.0 errors every 1000 flight hours, demonstrating that fatigue does contribute to at least 30% of all errors occurred from midnight to 6:00.

Another very interesting study in one o the largest airlines in Brazil (Quito, 2012) considered the effects of fatigue in FOQA events (Flight Operations Quality Assurance). The study analyzed crew rosters through the SAFTE-FAST model (Hursh *et al.*, 2004) and found that fatigue contributed in 79% of the events. This apparent discrepancy with the previous estimate of 30% strengthens the need for a standard methodology so that the data obtained by different operators could be compared through the same scientific basis. These bases could be defined in forthcoming new regulations in order to establish a uniform methodology that identifies latent and severe dangers and risks in regular operations. This standardization in the Brazilian civil aviation would be especially valuable to new and starting companies, which could guide their operations using these benchmarks and operational experiences developed under the Brazilian infrastructure and its reality.

Another quite interesting experiment carried out with Brazilian pilots proposed the correlation between subjective fatigue reports with quantitative predictions obtained with the SAFTE-FAST model (Licati *et al.*, 2015). The survey was conducted in 2012 with the data collection of 301 reports based on the model adopted by EasyJet (Stewart, 2009). The reports were answered spontaneously and anonymously by the pilots and included questions about physiological/cognitive aspects, contributing factors, countermeasures, as well as the information about the sleep/duty cycles within the last 72 hours before the fatigue sensation. In the last step, the reports were validated through the SAFTE-FAST model (Hursh *et al.*, 2004).

The distribution of pilot effectiveness by the time of the fatigue sensation is presented in Figure 4, where we found a surprisingly Gaussian shape with an average value of 73.8 ± 0.8%.

Another quite interesting result so obtained was related with the distribution of fatigue events along the time of the day (clock hours). As can be seen in Figure 5, the fatigue reports were concentrated in the window of circadian low (WOCL), but with a significant amount of events in a "shoulder-like" structure concentrated around 10:00, when one should expect that the individuals are performing at the optimum level of alertness. This puzzling result motivated the researchers to investigate the distribution of wakefulness before the fatigue sensation, another challenging and surprising result as shown in Figure 6.

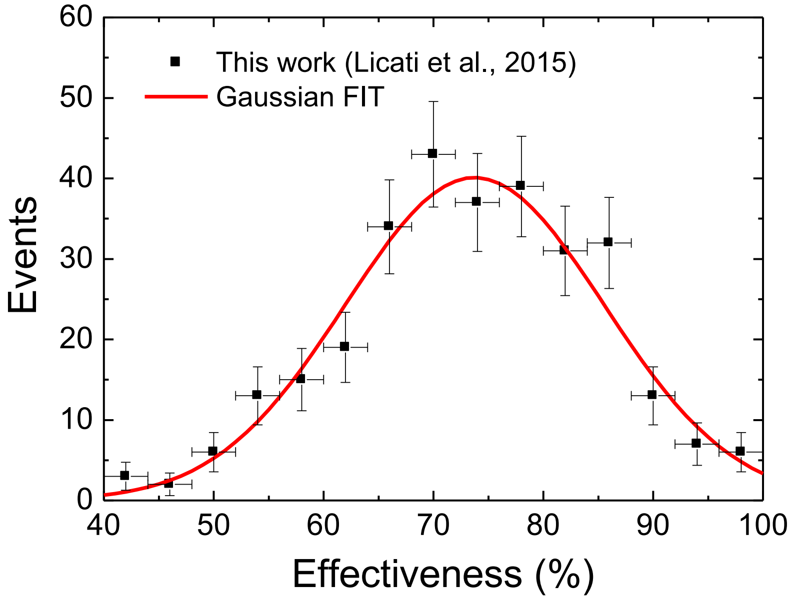

Figure 4: Distribution of pilot effectiveness at the time of fatigue sensation according with the SAFTE-FAST predictions (Licati *et al.*, 2015).

Combining the information presented in figures 4, 5 and 6 one can easily verify that the sample of pilots that was studied presented low levels of effectiveness with almost 50% of the reports concentrated at 10:00 in the morning and with a very small average wakefulness of 7 hours. In order to provide a suitable explanation for this apparent contradiction, the researchers decided to investigate the correlation between the time of the fatigue sensation (clock time) and the wake-up time (start of wakefulness).

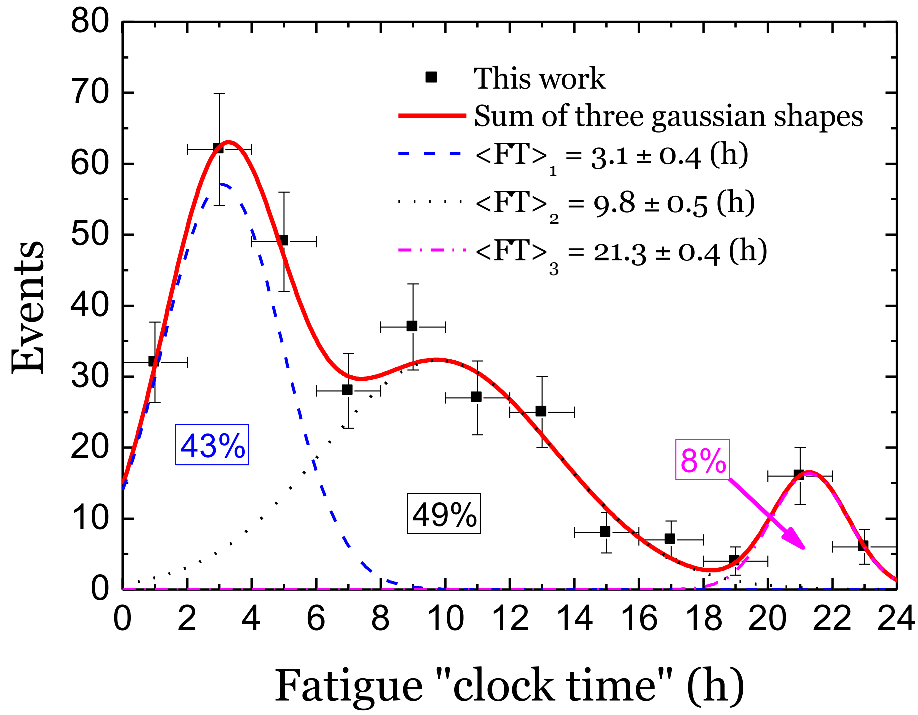

Figure 5: Distribution of fatigue reports as a function of the time of the day.

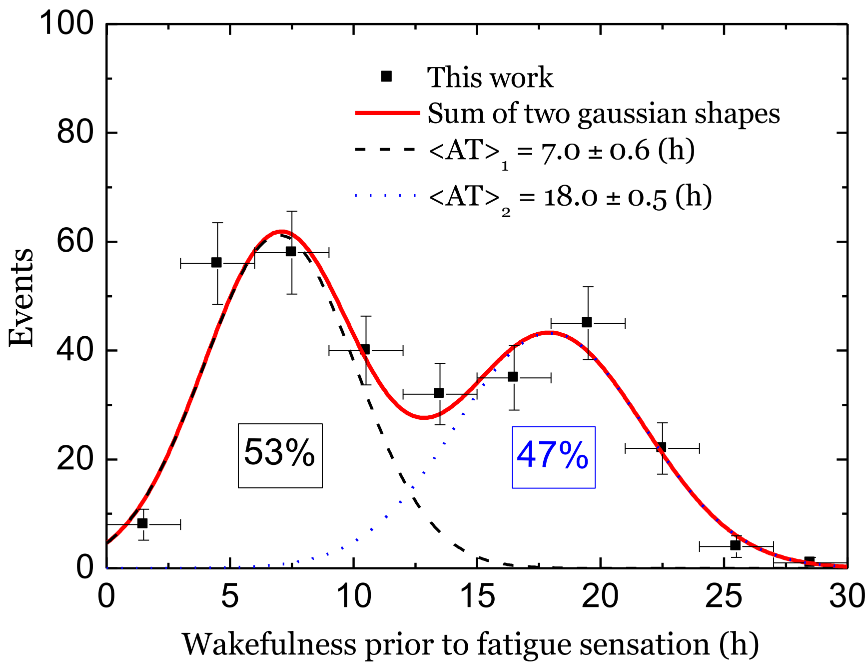

Figure 6: Distribution of wakefulness prior to fatigue sensation.

Figure 7 shows the fatigue clock time as a function of the wake-up time for all the data, where it is clear two quite distinct behaviors. The left side plot shows the fatigue events that took place one day after the start of wakefulness, while the right hand plot presents the events that occurred during the same day of the awakening. In the first case it is clear that the fatigue was felt essentially around 04:00 and almost independent of the start of wakefulness. In the second case, there is a strong variation in the fatigue time with the wake-up time. Figure 8 presents an exponential fitting (solid red line) with its respective limits (dashed blue lines) obtained via the propagation of uncertainties of the fitted parameters (Licati *et al.*, 2015).

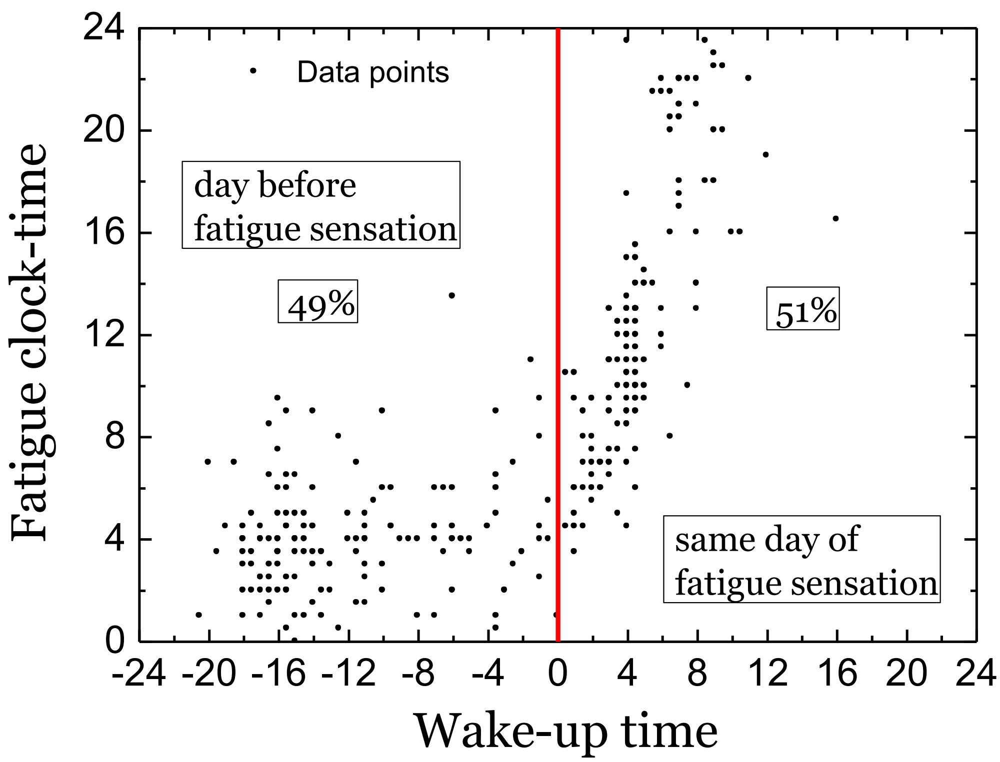

Figure 7: Fatigue reported clock-time versus wake-up time.

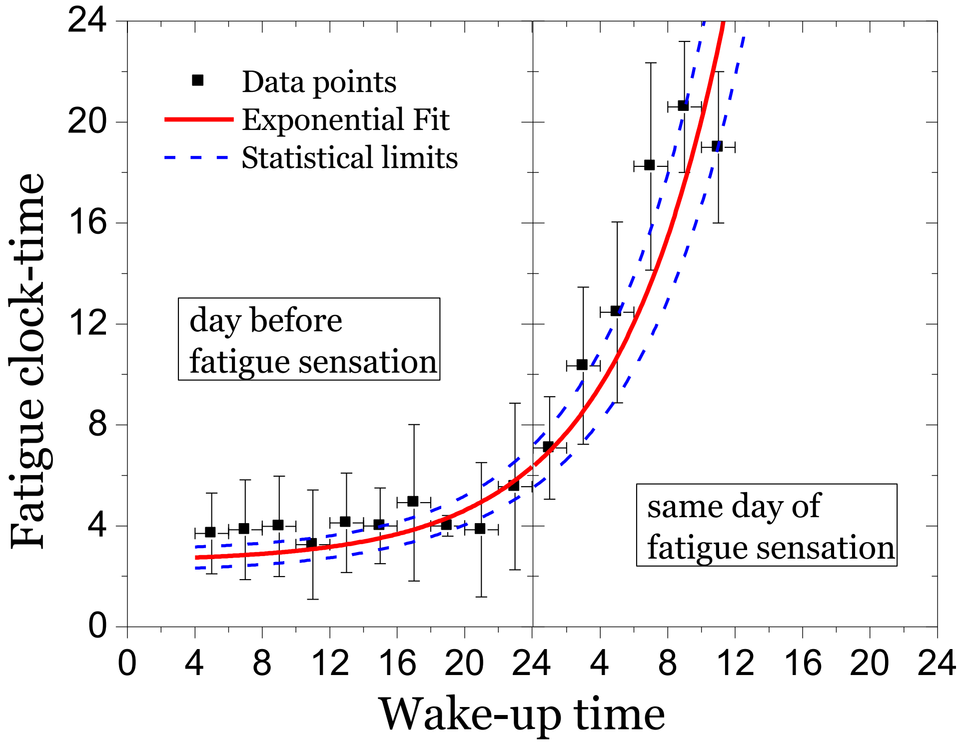

Figure 8: Relationship between the wake-up time and the fatigue clock-time (solid squares). The solid red line represents the exponential fitting with its respective statistical limits shown by the dashed blue lines.

This result demonstrates the contribution of two distinct effects. The first one is related with the higher probability of fatigue reports during the WOCL and is almost independent of the wake-up time. The second effect is probably related with the rostering structure that generates a progressive sleep debt in consecutive early starts duties without adequate sleep opportunity. The latter can be further verified by the inspection of the amount of sleep reported by the pilots within the last 24 hours prior to the fatigue sensation (Figure 9), as well as with the analysis of the chronic sleep debt accumulated in the last 72 hours (Figure 10).

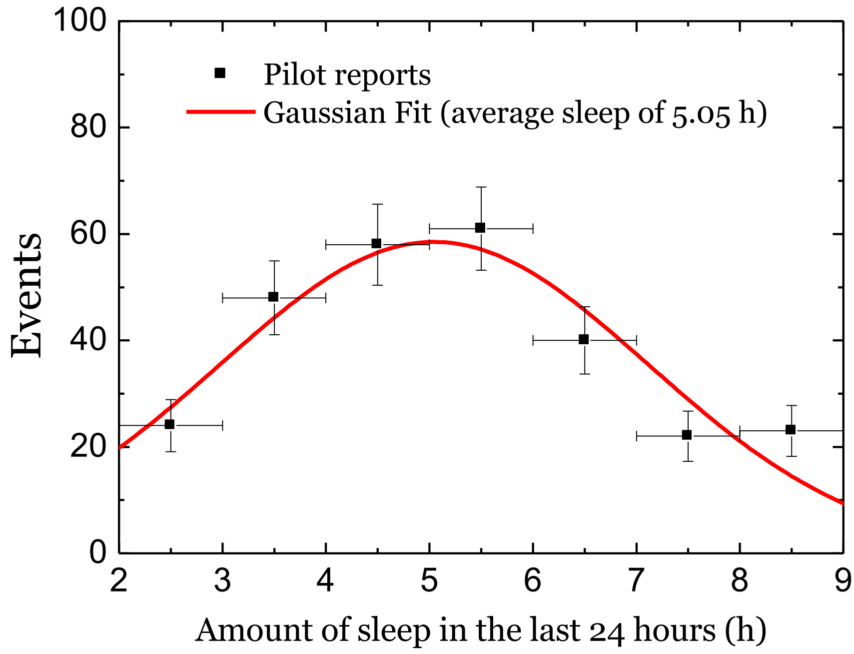

Figure 9: Distribution of the amount of sleep reported by the pilots within the last 24 hours prior to the fatigue sensation.

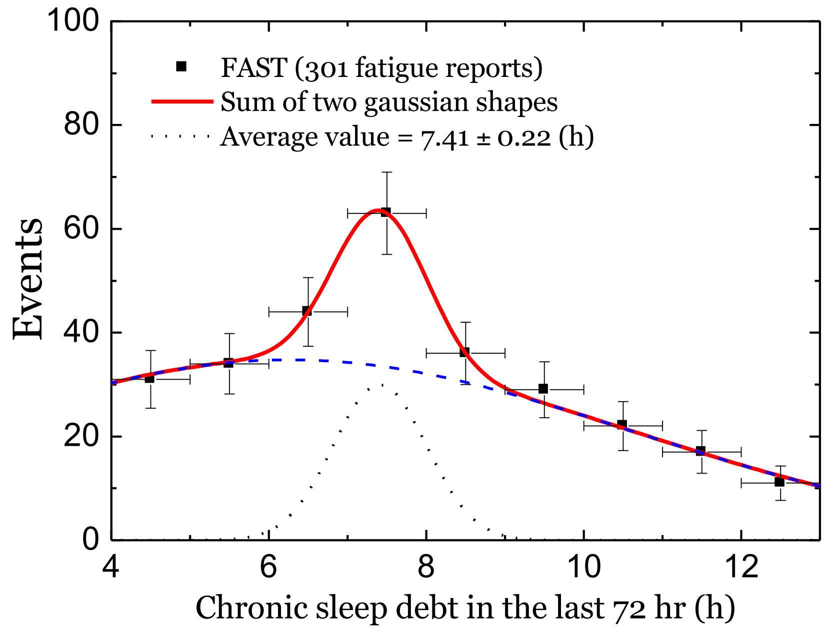

Figure 10: Distribution of chronic sleep debt within the last 72 hours prior to the fatigue sensation.

In order to estimate the relative risk in flight operations due to fatigue one can compare the previous data from Licati *et al.* (2015) with another recent cabin-crew experiment performed in the USA (Roma *et al.*, 2012).

Figure 11 shows the histograms of the crewmembers effectiveness predicted by FAST (upper panel) as well as in objective measurement done with PVT (lower panel). The plots were extracted from Roma *et al.* (2012).

The average FAST predicted effectiveness is 87.87%, in comparison with our previous result obtained in Brazil of 73.8%. So, at first approximation, one can estimate the relative risks between the two datasets as the ratio between the corresponding average risks obtained via the relationship presented in Figure 3, such that:

$$\frac{\langle R \rangle_{BRA}}{\langle R \rangle_{USA}} \cong 1.136$$

Consequently, the average risk obtained with the Brazilian sample of pilots is roughly 14% higher than the risk obtained in the analysis of the data presented by Roma *et al.* (2012).

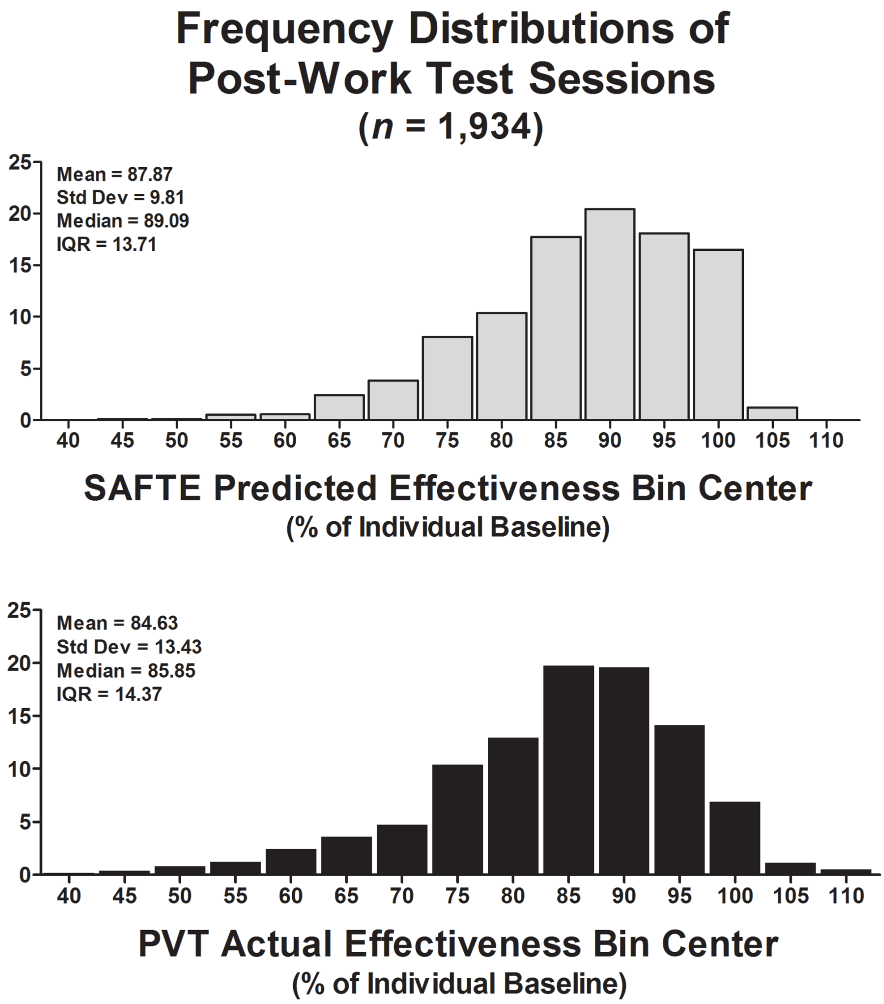

Figure 11: Histograms of cabin-crew effectiveness in USA predicted by the SAFTE-FAST model (upper panel) and through objective measurements on PVT (lower panel). The plots were extracted from Roma *et al*. (2012).

4.2 Relevant Parameters: Brazil, Australia and USA

This section is dedicated for the comparison of few relevant parameters (shown in Table 2) found in Brazil, Australia and USA that could play a significant role in the aviation industry.

Considering the country dimensions one can easily verify that USA holds the fourth position of the world, followed by Brazil (5^{th}) and Australia (6^{th}).

On the other hand, the gross domestic product (GDP) and more specifically, the per capita income are quite different among these three nations. Brazil has a GDP of US$ 2.224 trillions, while Australia and USA have US$ 1.482 and US$ 17.416 trillions, respectively. The per capita income shows that Brazil is still very far away (61^{st}) from the positions hold by Australia (5^{th}) and USA (9^{th}). All these data are from 2014.

Considering the industrial data, Australia has 862 aircrafts operated by 30 airlines, Brazil has 563 aircrafts operated by 12 airlines and the USA has 3,774 aircrafts with 128 airlines. In this regard, the Brazilian and Australian fleets are quite similar to each other, but significantly lower than the huge size of US commercial fleet (approximately a factor 7 for the case of Brazil).

Regarding the number of passengers per year once again Brazil and Australia have similar results (Australia roughly 30% higher), while in USA this value jumps to 848 millions. In this regard, the ratio of the fleet size and passengers per year between USA, Australia and Brazil are 6.7:1.5:1 and 7.6:1.3:1, respectively.

Data	BRAZIL [(a)]	USA [(b)]	AUS [(c)]
HDI	79	5	2
Terrestrial dimension (km^2)	8,515,767	9,371,175	7,692,014
Average commuting time	49%: less than 1h 45%: 1 to 3 h 7%: more than 3h (Giustina *et al.*, 2013)	Less than 1 hour	Less than 1 hour
Percentage of precision approach airdromes	~18%	~100%	~100%
Average days off per month	8/9	12	10 to 12
More than one airdrome as contractual basis	Yes	No	No
Fleet	563	3,774	862
Number of pilots	~ 7 k	~ 70 k	11,345
Passengers per year	111 Mi	848 Mi	147 Mi
Average JACDEC index [(d)]	0.679 (54º)	0.090 (35º)	0.022 (16º)
Number of airlines	12	128	30

Table 2: Relevant indicators: Brazil, USA and Australia.
(a) http://www.anac.gov.br/Noticia.aspx?ttCD_CHAVE=1297
(b) http://www.rita.dot.gov/bts/press_releases/bts015_15
(c) https://www.casa.gov.au/standard-page/appendix-operating-statistics
(d) http://www.jacdec.de/airline-safety-ranking-2015/

Regarding the distribution of the flights around the countries Brazil presents a clear concentration in the South and South-East regions, while in Australia most of the flights are generally in the seashore and concentrated in the larger cities such as Canberra, Sydney and Melbourne. In the U.S. the flights are more uniformly distributed within the country.

Considering the geographic location, Brazil and Australia have quite similar latitudes, which is a relevant characteristic for the evaluation of the incidence angles of the solar light at different clock times.

Other important parameter to be considered is the huge commuting that we have in Brazil. Approximately 49% of the crewmembers have a commuting of less than one hour, while 45% can spend up to three hours to go from his residence to the airport or vice-versa (Giustina *et al.*, 2013). A huge pressure for this very high commuting is originated by flight schedules planned in the contractual basis with more than one airport, like São Paulo, Rio de Janeiro and Belo Horizonte. In these bases the crewmembers are scheduled to begin their duties either in Congonhas or Guarulhos in São Paulo, Santos Dumont or Galeão in Rio de Janeiro and Pampulha or Confins in Belo Horizonte. In fact, the average time spent between Congonhas and Guarulhos in São Paulo is approximately 01:10h [3]. In Australia and USA crewmembers are generally scheduled for a specific airport, which propitiates a much lower commuting.

Other peculiarity in Brazil is the absence of effective subway systems connecting the airports, which restricts the ground displacements of the crewmembers and, consequently, increases the commuting due to the huge traffic jams in the big cities.

The contractual bases in USA are usually well distributed around the country, while in Australia the major airlines operate in five different bases. In Brazil, the four major airlines concentrate their

[3] http://www.airportbusservice.com.br/br/linhas

flight operations in the South and South-East regions, generating an undesirable commuting of crewmembers that live in the North, North-East and Middle-West regions.

Another important parameter relevant for risk analyses is the proportion of airports equipped with high precision approach systems. As presented in Table 2, only 18% of the airports in Brazil are equipped with precision approach procedures, in huge contrast with the situation found in USA and Australia, where almost all airports are equipped with these systems. Consequently, the level of alertness required by the pilots for a safe operation in a non-precision approach should be significantly higher than the level required for approach procedures with higher degrees of automation (see section 3). This characteristic should be taken into account by the risk analyses and in the definition of threshold parameters.

Operational safety indicators can be also measured by the JACDEC ranking, which includes several information, such as: RPK, cumulative data on the number of passengers, fatalities, accidents and incidents, transparency of the country with respect to the data, IOSA certification, among others.

The averaged JACDEC index of all the Brazilian's, Australian's and American's airlines up to the 60th position of the 2015 ranking shows that Australia holds the 16th place, followed by the USA (35th) and Brazil (54th). Such finding clearly demonstrates the opportunities for improvement in the Brazilian civil aviation.

4.3 Flight and Duty Time limitations: FAR-117, CAO-48 and the "Brazilian proposal"

4.3.1 Scenarios, average risk and hazard area:

This section describes the evaluation of risks due to human fatigue within the prescriptive limits (minimum crew only) adopted in USA (FAR-117) and Australia (CAO-48).

The analysis uses the primary reference of the crewmember effectiveness during the duty period in scenarios likely found in Brazil. The calculation of the effectiveness as a function of time is performed by the SAFTE-FAST model through the partnership with the Institutes for Behavior Resources, herein denoted IBR.

The controls for the Auto Sleep Settings are:

- Auto Sleep Control: ON;
- Auto Sleep Preconditioning: ON;
- Auto Sleep Default: ON;
- Auto Sleep Work: ON;
- Auto Sleep early-start: OFF;
- Auto nap: ON;
- Auto-augmentation: OFF.

The parameters for the Auto Sleep Settings are:

- Maximum sleep in the off days: 9 hours
- Maximum sleep in the work days: 8 hours
- Start of the "awake zone": 1300
- End of the "awake zone": 1900
- Bed time: 2300

- Intrinsic software commute [4]: zero
- Minimum sleep: 60 minutes

The following tables present all the scenarios and initial conditions studied in this work.

Scenario 1: Crew member checks in fully recovered				
Check-in (h)	Δ = 2h	Δ = 3h	Duty time (h)	# results
02:00	M1	M3	10	2
04:30	M5	M7	10	2
05:30	M9	M11	12	2
12:30	M13	M15	13	2
14:30	M17	M19	12	2
15:00	M21	M23	12	2
15:30	M25	M27	11	2
19:30	M29	M31	12	2
22:30	M33	M35	11	2
23:30	M37	M39	10	2

Table 3: Initial conditions adopted in the present analysis for a crew member commencing the duty period fully recovered. A portion of the flight can elapse between 0000 and 0600 in this scenario.

According with table 3, two different wakefulness prior to check-in were considered, one with 2 hours (Δ = 2h) and another one with three hours (Δ = 3 h). The labels M1, M3, M5, etc..., refer to the respective initial condition and are used for notation purposes only.

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[4] The commute in the FAST software was set to zero since the simulations already assume pre-defined and realistic wakefulness hypotheses by the check-in time.

Scenario 2: Crew member starts the second work day after completing the scenario 1 in the first day				
Check-in (h)	Δ = 2h	Δ = 3h	Duty period (h)	# results
02:00	M2	M4	10	2
04:30	M6	M8	10	2
05:30	M10	M12	12	2
12:30	M14	M16	13	2
14:30	M18	M20	12	2
15:00	M22	M24	12	2
15:30	M26	M28	11	2
19:30	M30	M32	12	2
22:30	M34	M36	11	2
23:30	M38	M40	10	2

Table 4: Initial conditions for the crew member that starts the second day after completing the first day in the scenario 1. A portion of the flight can elapse between 0000 and 0600.

Scenario 3: Crew member checks-in fully recovered					
Check-in (h)	Δ = 2h	Δ = 3h	Δ = 4h	Duty period (h)	# results
06:30	M41	M43	--	13	2
07:30	M45	M47	--	14	2
09:30	M49	M51	M53	14	3

Table 5: Initial conditions for a crew member commencing the duty period fully recovered. No portion of the flight elapses between 0000 and 0600. These are typical early-starts conditions.

Scenario 4: Crew member in the third consecutive day after the completion of two successive early-starts					
Check-in (h)	Δ = 2h	Δ = 3h	Δ = 4h	Duty time (h)	# results
06:30	M42A	M44A	--	13	2
07:30	M46A	M48A	--	14	2
09:30	M50A	M52A	M54A	14	3

Table 6: Initial conditions for a crew member in the third consecutive day after the completion of two successive early-starts.

Scenario 5: Crew member in the sixth consecutive day after the completion of five successive early-starts					
Check-in (h)	Δ = 2h	Δ = 3h	Δ = 4h	Duty time (h)	# results
06:30	M42	M44	--	13	2
07:30	M46	M48	--	10	2
09:30	M50	M52	M54	12	3

Table 7: Initial conditions for a crew member in the sixth consecutive day after five successive early-starts.

The simulations were carried out entirely by the IBR team for all the initial conditions depicted in Tables 3 to 7. The plots and the results were gently provided by Lauren Waggoner, PhD (IBR) and are presented below in Figures 12 to 17.

Figure 12: SAFTE-FAST predicted effectiveness for the first night shift with check-in at 02:00 and Δ = 2 h (M1). The duty period is expressed by the solid black.

Figure 13: SAFTE-FAST predicted effectiveness for the second consecutive night shift with check-in at 02:00 and Δ = 2 h (M2).

Figure 14: SAFTE-FAST predicted effectiveness for the first night shift with check-in at 04:30 and Δ = 2 h (M5).

Figure 15: SAFTE-FAST predicted effectiveness for the first night shift with check-in at 04:30 and Δ = 3 h (M7).

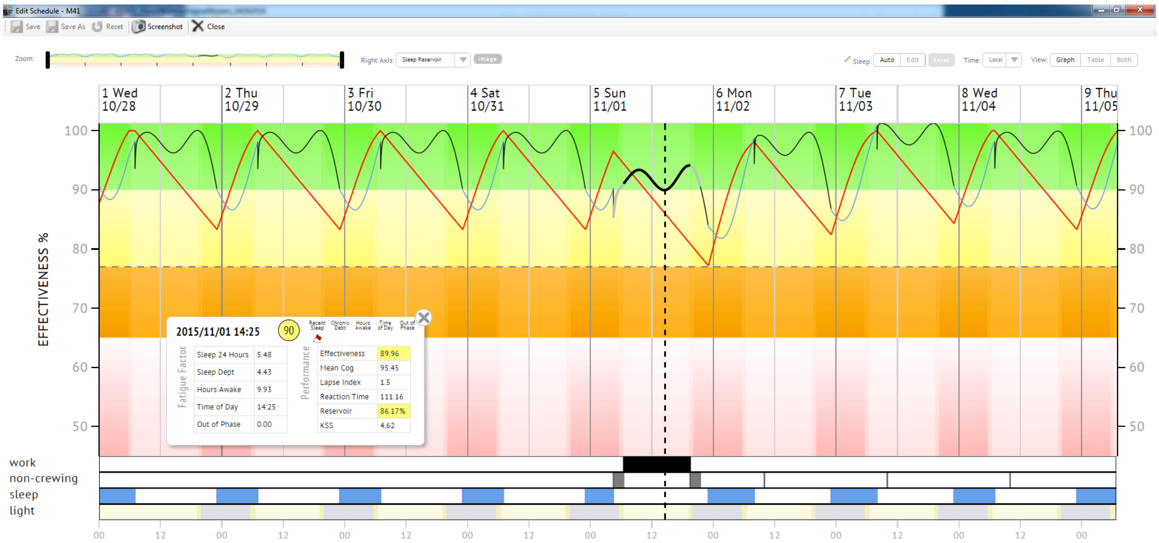

Figure 16: SAFTE-FAST predicted effectiveness for the first shift with check-in at 06:30 and Δ = 2 h (M41).

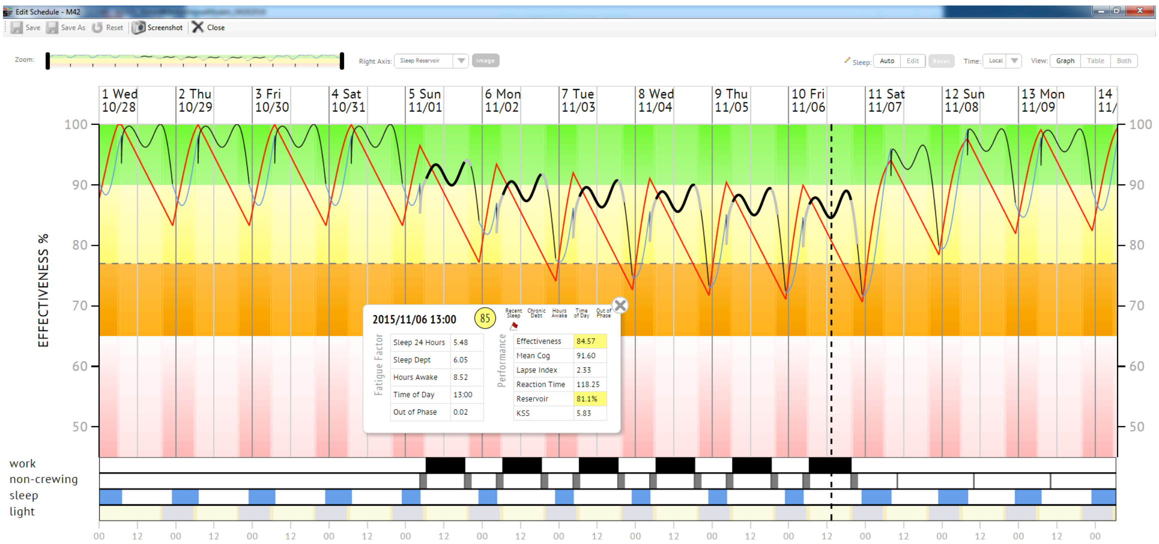

Figure 17: SAFTE-FAST predicted effectiveness for six consecutive work days starting at 06:30 with Δ = 2 h. The sixth day is labeled as M42.

In order to achieve a continuous function for the effectiveness along the duty period an interpolation was carried out using the effectiveness data provided by the IBR in 30 minutes interval. The result for M1 is presented by the red line of Figure 18, together with the original histogram from the IBR team. The average effectiveness for this initial condition was 78.92%.

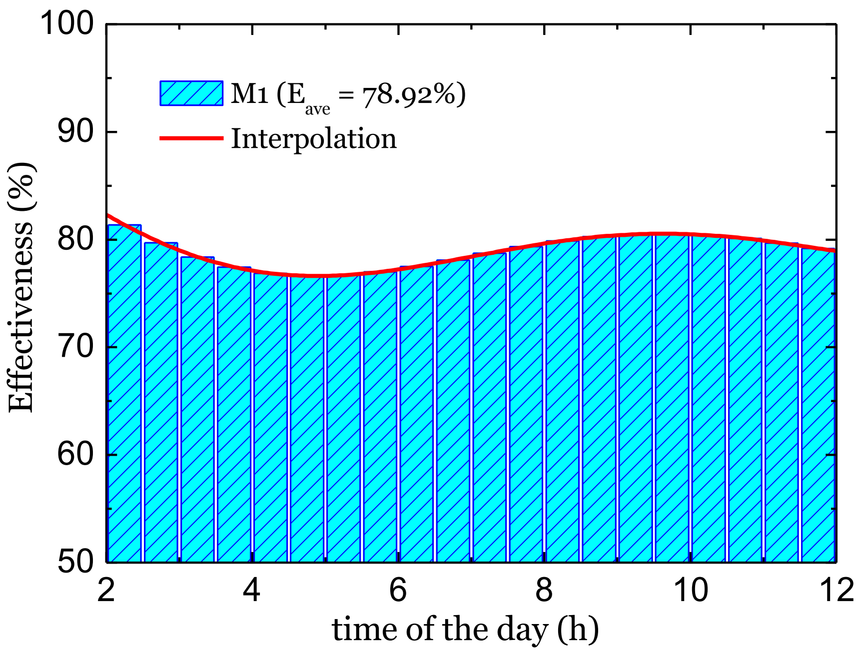

Figure 18: Interpolation of SAFTE-FAST predicted effectiveness during the first night shift with check-in at 02:00 and Δ = 2 h (M1). The average effectiveness E_{ave} = 78.92% was calculated by the integral of E(t) from the check-in until the check-out.

Using the relationship presented in Figure 3 one can estimate the risk due to fatigue along the duty period. The result for M1 is shown in Figure 19.

In the next step we evaluate the hazard area (HA) below our threshold value of effectiveness E_{Th}=80%. As seen by the inspection of Figure 20, the total costs for human-factor accidents vary quite significantly when the effectiveness drops below 77%, supporting our strategy to map the area below 80%.

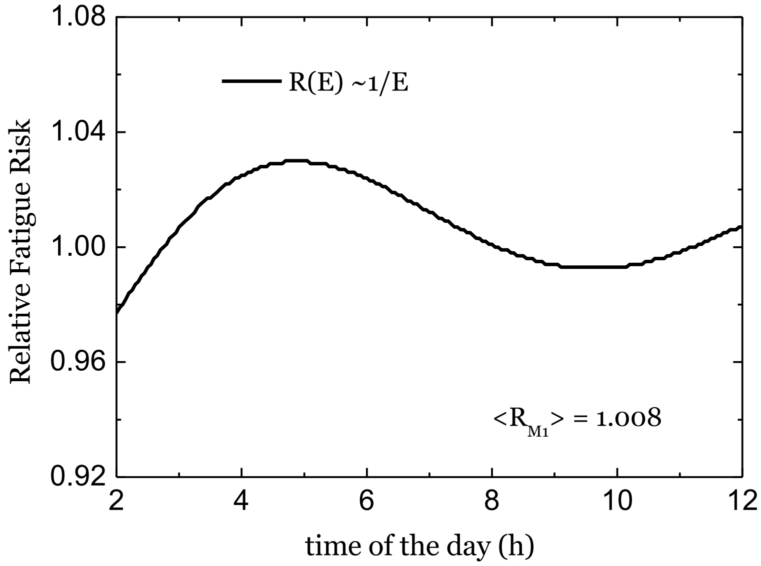

Figure 19: Relative fatigue risk during the first night shift with check-in at 0200 and Δ = 2 h (M1). The average relative risk of 1.008 was calculated by the integral of R(t).

Figure 21 shows a comparison between the first and the second night shifts with Δ = 2 h (M1 and M2) with its respective hazard areas, where one clearly verifies an increase of almost a factor of ten in the risk exposure comparing the first and the second night shift (M2/M1 ~ 10). Table 8 summarizes all the results obtained for the six scenarios and more than 60 different initial conditions.

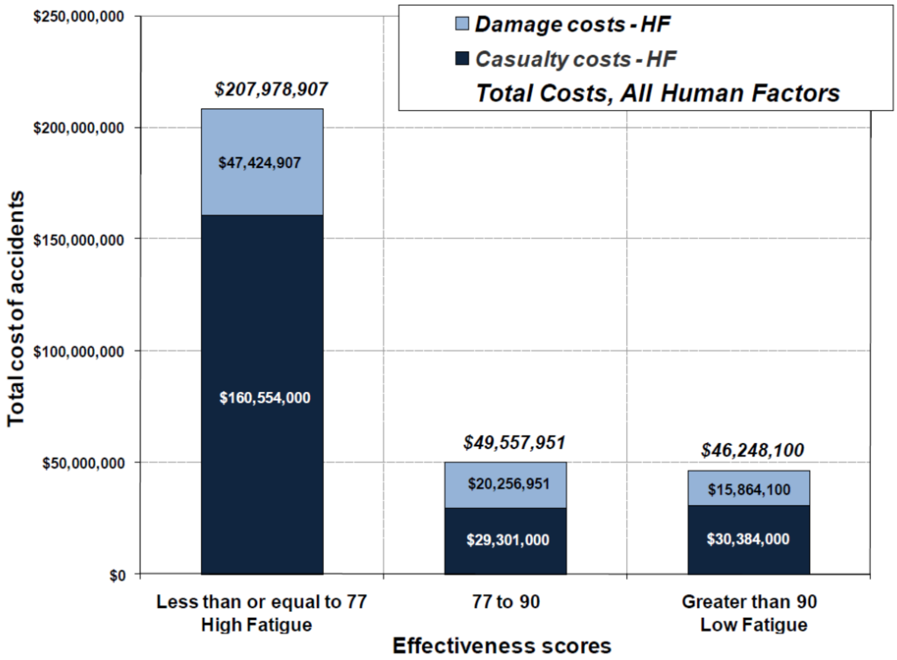

Figure 20: Total cost of human-factor accidents as a function of SAFTE-FAST predicted effectiveness. The plot was extracted from Hursh *et al.* (2011).

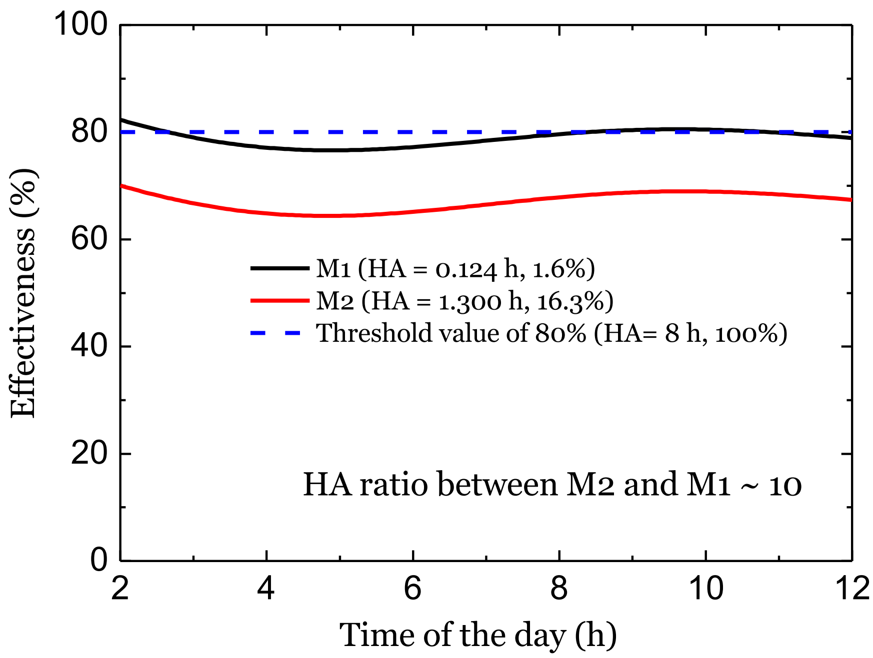

Figure 21: Comparison between the hazard areas (HA) obtained in the first (M1) and in the second (M2) night shifts with check-in at 02:00 and Δ = 2 h. Details in the text.

Model ID	E_ave (%)	<R>	HA (h)	HA (duty-1)	HA (duty-2)	HA (duty-3)
1	78.92	1.008	0.124	0.119	0.119	0.119
2	67.00	1.140	1.300	1.179	1.066	0.955
3	77.69	1.019	0.232	0.215	0.205	0.198
4	56.90	1.295	2.310	2.091	1.880	1.671
5	84.73	0.957	0.000	0.000	0.000	0.000
6	76.45	1.032	0.355	0.307	0.264	0.232
7	80.97	0.989	0.018	0.014	0.014	0.014
8	69.10	1.113	1.090	0.970	0.855	0.750
9	88.34	0.929	0.000	0.000	0.000	0.000
10	83.76	0.965	0.000	0.000	0.000	0.000
11	84.78	0.956	0.000	0.000	0.000	0.000
12	76.63	1.030	0.405	0.382	0.344	0.297
13	94.72	0.887	0.000	0.000	0.000	0.000
14	96.18	0.876	0.000	0.000	0.000	0.000
15	94.72	0.887	0.000	0.000	0.000	0.000
16	92.55	0.900	0.000	0.000	0.000	0.000
17	92.77	0.902	0.054	0.007	0.000	0.000
18	94.16	0.891	0.018	0.000	0.000	0.000
19	92.77	0.902	0.000	0.000	0.000	0.000
20	90.21	0.919	0.074	0.013	0.000	0.000
21	91.78	0.910	0.092	0.026	0.000	0.000
22	93.23	0.899	0.043	0.003	0.000	0.000
23	91.78	0.910	0.092	0.026	0.000	0.000
24	89.23	0.928	0.123	0.039	0.001	0.000
25	92.45	0.905	0.054	0.007	0.000	0.000
26	93.94	0.893	0.018	0.000	0.000	0.000
27	92.45	0.905	0.054	0.007	0.000	0.000
28	92.03	0.906	0.041	0.002	0.000	0.000
29	85.13	0.965	0.281	0.234	0.175	0.110
30	73.71	1.079	1.094	0.930	0.753	0.568
31	84.38	0.971	0.326	0.272	0.205	0.132
32	70.12	1.123	1.399	1.198	0.984	0.762
33	80.12	1.001	0.282	0.262	0.236	0.197
34	66.33	1.156	1.521	1.367	1.204	1.027
35	80.33	0.999	0.265	0.249	0.224	0.187
36	66.66	1.152	1.488	1.337	1.177	1.003
37	78.76	1.011	0.273	0.256	0.230	0.192
38	67.90	1.132	1.214	1.090	0.958	0.811
39	78.66	1.012	0.281	0.262	0.236	0.197
40	59.20	1.261	2.080	1.872	1.653	1.420
41	92.01	0.902	0.000	0.000	0.000	0.000
42A	88.41	0.928	0.000	0.000	0.000	0.000
42	86.84	0.940	0.000	0.000	0.000	0.000
43	88.77	0.925	0.000	0.000	0.000	0.000
44A	82.44	0.976	0.000	0.000	0.000	0.000
44	79.08	1.006	0.153	0.150	0.150	0.150
45	94.95	0.882	0.000	0.000	0.000	0.000
46A	93.21	0.894	0.000	0.000	0.000	0.000
46	92.32	0.900	0.000	0.000	0.000	0.000
47	92.15	0.901	0.000	0.000	0.000	0.000
48A	88.55	0.927	0.000	0.000	0.000	0.000
48	86.45	0.943	0.000	0.000	0.000	0.000
49	97.35	0.868	0.000	0.000	0.000	0.000
50A	98.47	0.860	0.000	0.000	0.000	0.000
50	97.72	0.865	0.000	0.000	0.000	0.000
51	96.32	0.874	0.000	0.000	0.000	0.000
52A	93.01	0.895	0.000	0.000	0.000	0.000
52	90.08	0.916	0.000	0.000	0.000	0.000
53	93.99	0.889	0.000	0.000	0.000	0.000
54A	84.25	0.961	0.000	0.000	0.000	0.000
54	76.33	1.034	0.514	0.406	0.347	0.322

Table 8: Average effectiveness, average relative risks and hazard areas (HA) for all the 61 initial conditions of the simulations. The areas labeled duty-1, duty-2 and duty-3 refer to the hazard area reducing the duty time by 1, 2 and 3 hours, respectively.

Figure 22 shows the hazard areas as a function of the average risks for all the data, where one clearly identifies a transition region between R = 0.9 and R = 1. More precisely, one can define three bands considering the average effectiveness of the corresponding duty. A low risk region for $E_{ave} \geq 90\%$ (green), a medium risk region (caution zone) for $77 \leq E_{ave} < 90\%$ (amber), and a high risk region (danger zone) for $E_{ave} < 77\%$ (red).

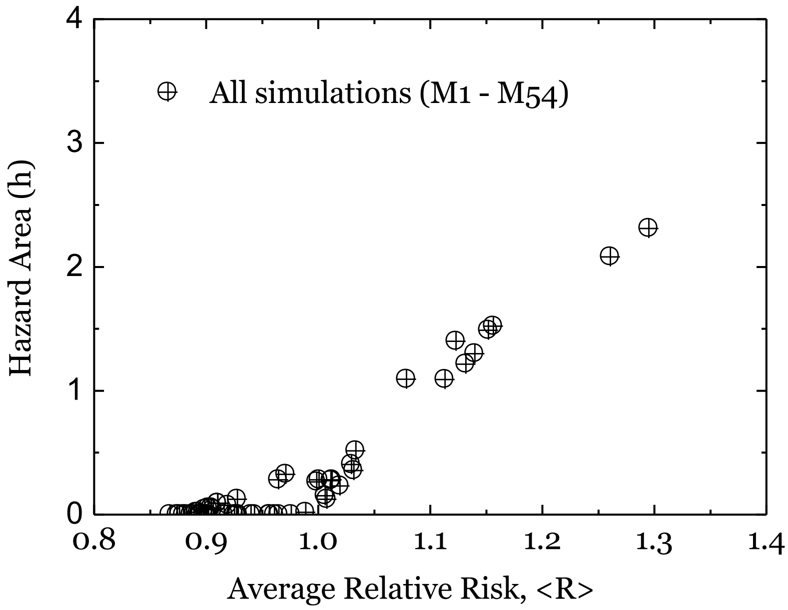

Figure 22: Average relative risk (<R>) and the corresponding hazard area (HA) below 80% for all the initial conditions investigated in the present work. Details in the text.

Figure 23 presents the relationship between the average relative risk and the hazard area for all the initial conditions studied in this work. The three regions are represented by the green circles (low risk), amber triangle (medium risk) and red squares (high risk). The amber triangle corresponds to the average HA of all the events within the transition region ($77 \leq E_{ave} < 90\%$).

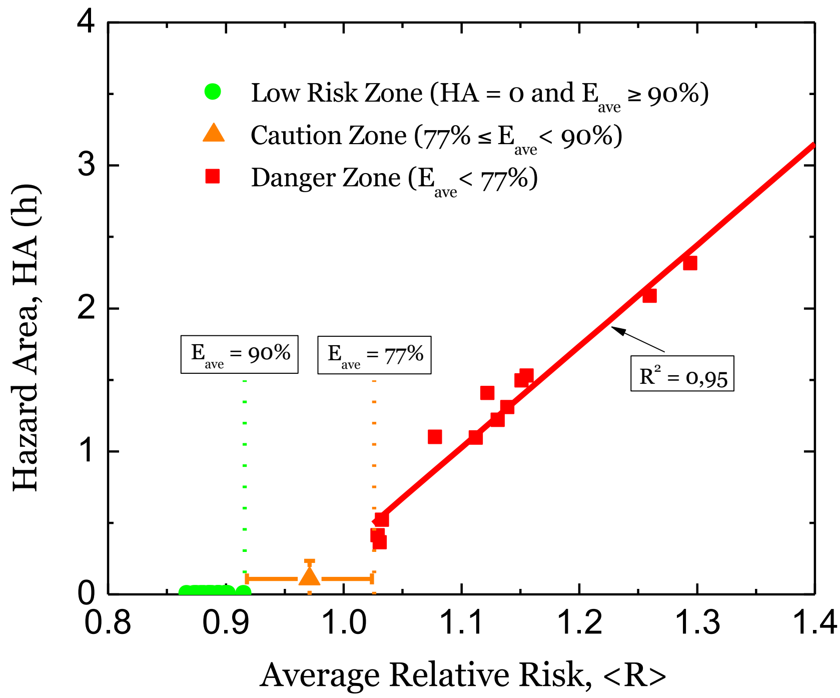

Figure 23: Relationship between the average relative risk and the hazard area (HA) for all the initial conditions considered in the simulations. Details in the text.

Obviously that the linear relationship between <R> and HA for the average effectiveness below 77% reflects our choice for the threshold value of 80% to calculate the areas. It is worth-mentioning, however, that this value is not supposed to provide a go no go decision, but to establish a reference limit where the risk exposure (HA) increases linearly.

So, in order to verify that the proposed method is in fact useful for risk mitigation, we have included in the present analysis two famous fatigue-related accidents that were largely studied with the help of the SAFTE-FAST model. The first one was the AIA 808 that crashed in Guantanamo Bay, Cuba in 1993 and the second one was the Comair 5191 (2006) in Lexington, USA.

For the Guantanamo Bay accident, the NTSB report concluded that the most likely cause for the accident was:

"The impaired judgment, decision-making, and flying abilities of the captain and flight crew due to the effects of fatigue [sleep deprivation]; the captain's failure to properly assess the conditions for landing and maintaining vigilant situational awareness of the airplane while maneuvering onto final approach; his failure to prevent the loss of airspeed and avoid a stall while in the steep bank turn; and his failure to execute immediate action to recover from a stall."

In order to estimate the AIA 808 crew effectiveness by the time of the accident, Wesensten and Belenky performed a SAFTE-FAST analysis (private communication). The results are presented in Figure 24 for the Captain (upper panel), First Officer (middle panel) and Flight Engineer (lower panel).

In the case of Comair 5191, recent studies showed that the Air Traffic Controller presented an SAFTE-FAST predicted effectiveness of about 71% by the time of the accident (Pruchnicki, Wu & Belenky, 2011).

So, by applying the same method we obtained the line shapes for the effectiveness of the crew members (or ATC) of the flights AIA 808 (Figure 25A) and Comair 5191 (Figure 25B), respectively. With these line-shapes, the corresponding average risks and hazard areas can be easily calculated as shown in Figure 26.

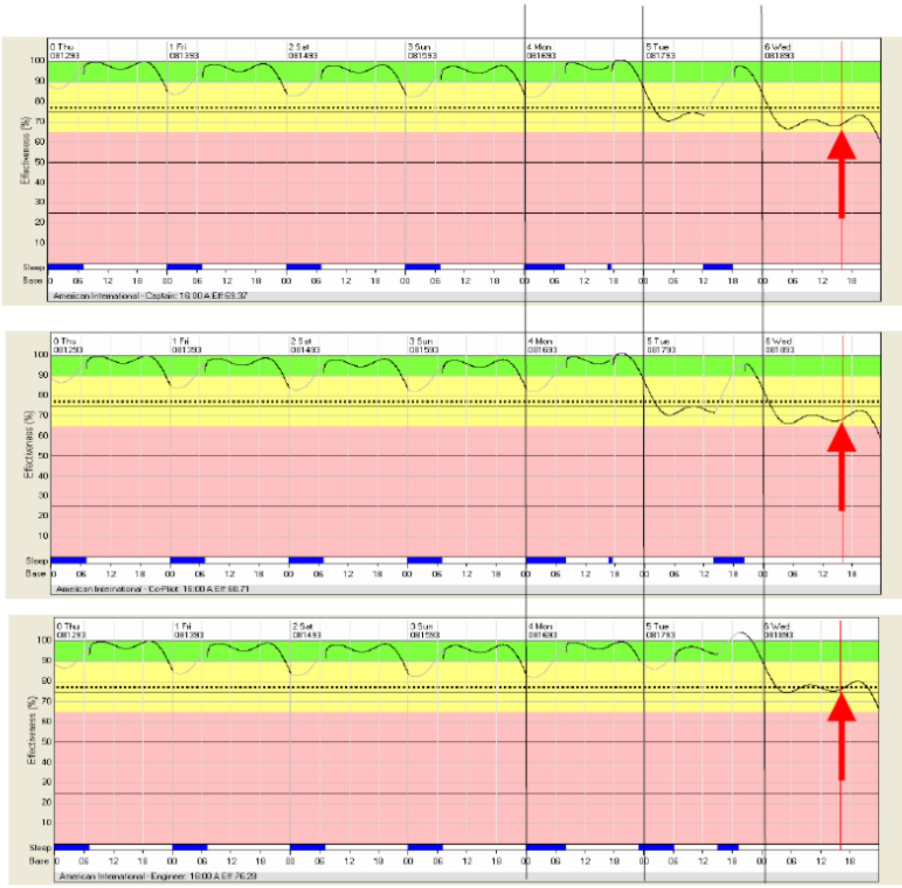

Figure 24: SAFTE-FAST analysis of flight AIA 808 (Guantanamo Bay) obtained by Wesensten & Belenky (private communication).

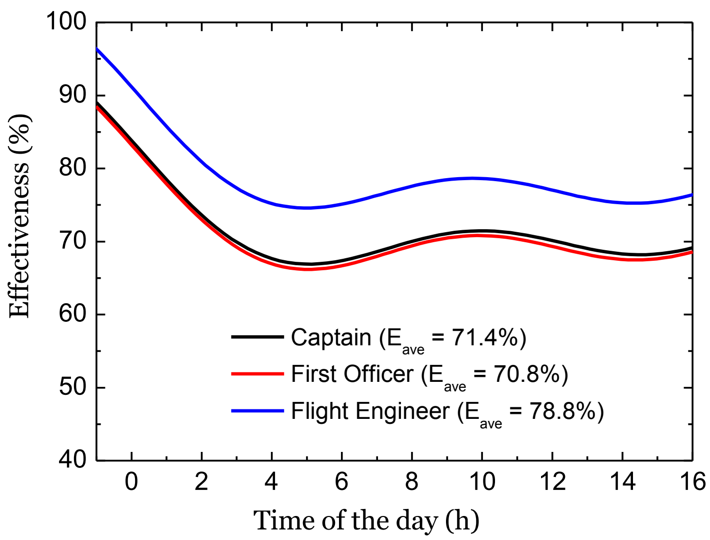

Figure 25A: Line shapes for the SAFTE-FAST predicted effectiveness for the crew members of flight AIA 808 (Guantanamo Bay). Details in the text.

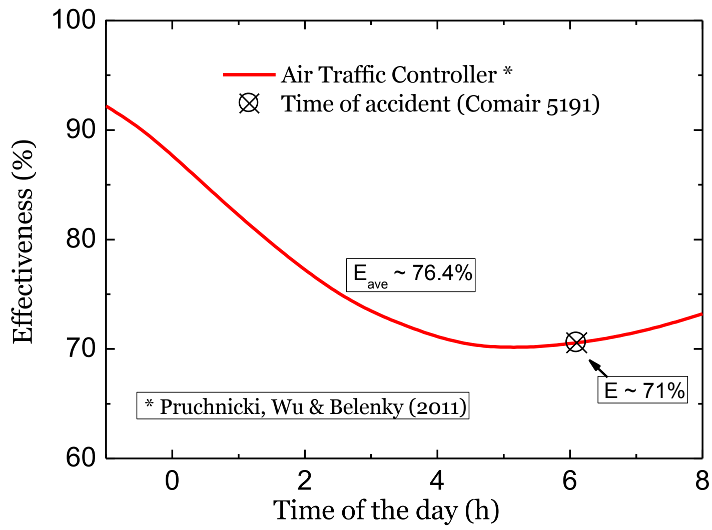

Figure 25B: SAFTE-FAST predicted effectiveness of the Air Traffic Controller in charge during Comair 5191 crash. The solid red line was extracted from Pruchnicki, Wu & Belenky (2011).

From the inspection of Figure 26 the hazard areas of the pilots of the flight AIA 808 have magnitude comparable with the results achieved for the second night shift or the third early-morning, making it salient the need for risk mitigation in rosters with these characteristics.

Specifically for the second consecutive night shift, it is strongly **recommended** that the flight schedules **do avoid take-off and/or landing operations during the WOCL** and always respecting clockwise check-in times for successive days of work within 0000 and 0600.

Other interesting results that were observed are the average risks and hazard areas for the flight engineer of the Guantanamo Bay and for the air traffic controller of the Comair 5191. In both cases, the average effectiveness was very close to 77%, showing undoubtedly that this parameter has to be taken into account very carefully during the risk analysis and mitigation.

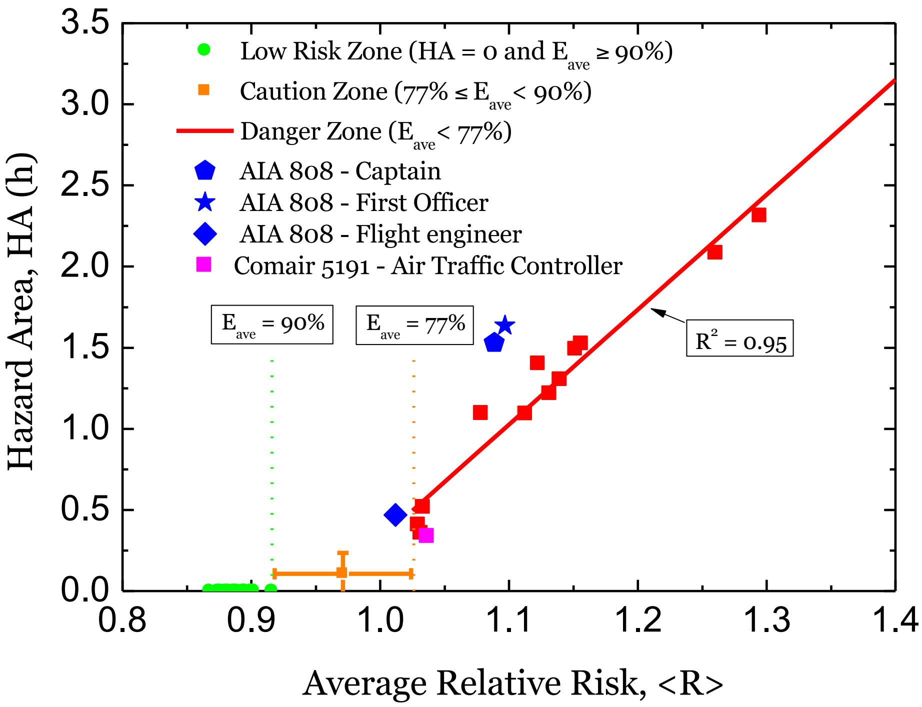

Figure 26: Relationship between the average relative risk and hazard area obtained for the 61 initial conditions of this work, together with the results obtained for the accidents in Guantanamo Bay (blue symbols) and Lexington (magenta square).

4.3.2. Risk analysis of FAR-117 duty time prescriptive limits (minimum crew - one and two sectors only)

Table 9 shows the prescriptive limits of FAR-117 for minimum acclimatized crew with its respective average risks and hazard areas.

FAR-117 duty time limits (1 or 2 sectors) in scenarios 1 and 3 with Δ = 2 hours					
Check-in (h)	Initial condition label	Maximum duty time (h)	Average Effectiveness (%)	Average risk	Hazard area (h)
0000-0359	M1	9	78.92	1.008	0.119
0400-0459	M5	10	84.73	0.957	0
0500-0559	M9	12	88.34	0.929	0
0600-0659	M41	13	92.01	0.902	0
0700-1159	M49	14	97.35	0.868	0
1200-1259	M13	13	94.72	0.887	0
1300-1659	M21	12	91.78	0.910	0
1700-2159	M29	12	85.13	0.965	0.281
2200-2259	M33	11	80.12	1.001	0.282
2300-2359	M37	10	78.76	1.011	0.273

Table 9: Average effectiveness (FAST), average risks and hazard areas for a fully recovered crewmember under FAR-117 limits. The average daily hazard area is 0.102 h. Details in the text.

The average "daily" hazard area was calculated by weighting the values obtained for each check-in interval (last column in the right) with its corresponding bin size in time.

FAR-117 duty time limits (1 or 2 sectors) in scenarios 2 and 4* with Δ = 2 hours				
Check-in (h)	Initial condition label	Maximum duty time (h)	Average risk	Hazard area (h)
0000-0359	M2	9	1.140	1.179
0400-0459	M6	10	1.032	0.355
0500-0559	M10	12	0.965	0
0600-0659	M42A(*)	13	0.928	0
0700-1159	M50A(*)	14	0.860	0
1200-1259	M14	13	0.876	0
1300-1659	M22	12	0.899	0.043
1700-2159	M30	12	1.079	1.094
2200-2259	M34	11	1.156	1.521
2300-2359	M38	10	1.132	1.214

Table 10: Average risk and hazard area for a crew member in the second successive night flight or during the third early-start (*) under the FAR-117 limits. Details in the text.

FAR-117 duty time limits (1 or 2 sectors) in scenarios 2 and 5* with Δ = 2 hours				
Check-in (h)	Initial condition label	Maximum duty time (h)	Average risk	Hazard area (h)
0000-0359	M2	9	1.140	1.179
0400-0459	M6	10	1.032	0.355
0500-0559	M10	12	0.965	0
0600-0659	M42(*)	13	0.940	0
0700-1159	M50(*)	14	0.865	0
1200-1259	M14	13	0.876	0
1300-1659	M22	12	0.899	0.043
1700-2159	M30	12	1.079	1.094
2200-2259	M34	11	1.156	1.521
2300-2359	M38	10	1.132	1.214

Table 11: The same notation adopted for table 10, but replacing the third consecutive early-start by the sixth. The daily hazard area is 0.56 h. Details in the text.

4.3.3 Risk analysis of CAO-48 duty time prescriptive limits (minimum crew, one and two sectors only)

CAO-48 duty time limits (1 or 2 sectors) in scenarios 1 and 3 with Δ = 2 hours				
Check-in (h)	Initial condition label	Maximum duty time (h)	Average risk	Hazard area (h)
0500-0559	M9	11	0.929	0
0600-0659	M41	12	0.902	0
0700-0759	M45	13	0.882	0
0800-1059	M49	14	0.868	0
1100-1359	M13	13	0.887	0
1400-1459	M17	12	0.902	0.054
1500-1559	M25	11	0.905	0.007
1600-2259	M29	10	0.965	0.175
2300-0459	M1	10	1.008	0.124

Table 12: Average risks and hazard areas for a fully recovered crew member under CAO-48 limits. The average daily hazard area is 0.085 h. Details in the text.

CAO-48 duty time limits (1 or 2 sectors) in scenarios 2 and 4* with Δ = 2 hours				
Check-in (h)	Initial condition label	Maximum duty time (h)	Average risk	Hazard area (h)
0500-0559	M10	11	0.965	0
0600-0659	M42A(*)	12	0.928	0
0700-0759	M46A(*)	13	0.894	0
0800-1059	M50A(*)	14	0.860	0
1100-1359	M14	13	0.876	0
1400-1459	M18	12	0.891	0.018
1500-1559	M26	11	0.893	0.018
1600-2259	M30	10	1.079	0.753
2300-0459	M2	10	1.140	1.300

Table 13: Average risks and hazard areas for a crewmember in the second successive night flight or during the third early-start (*) under CAO-48. Details in the text.

CAO-48 duty time limits (1 or 2 sectors) in scenarios 2 and 5* with Δ = 2 hours				
Check-in (h)	Initial condition label	Maximum duty time (h)	Average risk	Hazard area (h)
0500-0559	M10	11	0.965	0
0600-0659	M42A(*)	12	0.940	0
0700-0759	M46A(*)	13	0.900	0
0800-1059	M50A(*)	14	0.865	0
1100-1359	M14	13	0.876	0
1400-1459	M18	12	0.891	0.018
1500-1559	M26	11	0.893	0.018
1600-2259	M30	10	1.079	0.753
2300-0459	M2	10	1.140	1.300

Table 14: The same notation as for table 13, but replacing the third consecutive early-start by the sixth. The average daily hazard area is 0.546 h. Details in the text.

4.3.4 Flight duty time limitations for minimum crew: a proposal for the Brazilian scenario

Step 1: As a starting point we take CAO-48 limitations in scenarios 2 and 4 with Δ = 2 hours

This procedure was adopted considering that the duty and flight time limitations should account for crewmembers checking-in fully recovered as well as in duties that take place in the second night flight and during successive early-starts.

In these cases (fully recovered and during the second night flight/successive early-starts) the daily averaged hazard areas obtained for CAO-48 are significantly lower than FAR's, supporting our decision of taking CAO's as the initial reference.

Regarding the parameter Δ, it is likely that in several and frequent occasions in huge metropoles the crewmembers need to anticipate their displacement in order to reach the airport at the scheduled time, suggesting that 2 hours may not cover all conceivable situations. However, since the following tables are supposed to be applied all over the country, we fixed Δ = 2 hours for the calculations that are presented in this report. This decision assumes that FURTHER MITIGATIONS recommended in this report will be adopted, either for the risks found in the second night flight, as well as in successive early-starts.

Step 2: Limiting the maximum duty-time to 12 hours

As shown by Goode (2003), the relative proportion of human factor accidents over exposure (time on duty prior to accident) increases enormously for 13 hours or above (Table 15). In fact, the relative proportion of accidents normalized by the exposure (last column) stays roughly constant until 6 hours on duty, with an increase of 32% (from 0.84 to 1.11) as the duty hours increase from 5 to 8 h.

Taking the value within 7 to 9 hours as a reference (1.11) one finds that the accident proportion relative to exposure increases almost 50% from 8 to 11 hours **and more than 500% from 8 to 13 hours or more**. This result clearly demonstrates that duty times of 13 hours or more increase by a factor 5 the accident/exposure ratio compared with the results found within 7 to 9 hours on duty.

Captain duty hours and accidents by length of duty

Hour in duty period	Captain's hours	Exposure proportion	Accidents	Accident proportion	Accident proportion relative to exposure proportion
1–3	430,136	0.35	15	0.27	0.79
4–6	405,205	0.33	15	0.27	0.84
7–9	285,728	0.23	14	0.25	1.11
10–12	109,820	0.09	8	0.15	1.65
13 or more	12,072	0.01	3	0.05	5.62
Total	1,242,961	1.00	55	1.00	1.00
Calculated χ^2		14.89		10% χ^2	7.8
Degrees of freedom		4		5% χ^2	9.5

Table 15: Proportion of accidents relative to exposure as a function of the time on duty. Extracted from Goode (2003).

On the other hand, in the analysis done by Goode (2003) only three accidents occurred above 13 hours, while between 10 and 12 one finds 8. Despite to the fact that these results are statistically relevant, we decided to add together all the accidents (and exposure captain's hours) from 10 to 13 hours and above[5], taking into account the ratio found within 1 and 3 hours as the reference (t_{duty} = 2 hours). The result of this re-analysis is presented in figure 27, together with one exponential fitting of the form:

$$\frac{\left(\frac{\Delta A / A}{\Delta E / E}\right)_{t_{duty}}}{\left(\frac{\Delta A / A}{\Delta E / E}\right)_{t_{duty}=2}} = C_1 \exp^{\left(t_{duty}/\tau\right)} + C_2,$$

where $\Delta A/A$ and $\Delta E/E$ are the accident and the exposure proportions as a function of t_{duty}, respectively. The parameter τ was fixed at 3.542 h with $C_1 = 0.050 \pm 0.024$, $C_2 = 0.89 \pm 0.21$ and $\chi^2/\text{D.O.F.} = 0.031$. The error bars in Figure 27 were assumed to be proportional do the square root of the number of accidents, but normalized by the total accident/exposure ratio within 1 to 3 hours (0.79).

Surprisingly, another independent analysis carried out by Folkard & Tucker (2003) also showed this same exponential behavior, as presented by the blue histograms of Figure 27.

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[5] The interval above 13 hours on duty was not specified by Goode (2003), even though the author mentioned that the measurements covered the intervals between 13 and 15 hours and above 16 hours. Considering the lack of accidents above 16 hours (Table 15) and the plausible hypothesis that the density of captain hours is negligible above 16 hours, we adopted 15 hours as the upper limit for the analysis. In this regard, the data point between 10 to 15 hours in figure 27 is centered at 12.5.

Table 15A shows the relative increase in the ratio (ΔA/A)/(ΔE/E) for different time on duties taking as the reference t_{duty} = 8 hours. The results show, for instance, that increasing the duty period from 12 to 13 (14) hours increases the accident proportion relative to exposure about 20% (47%).

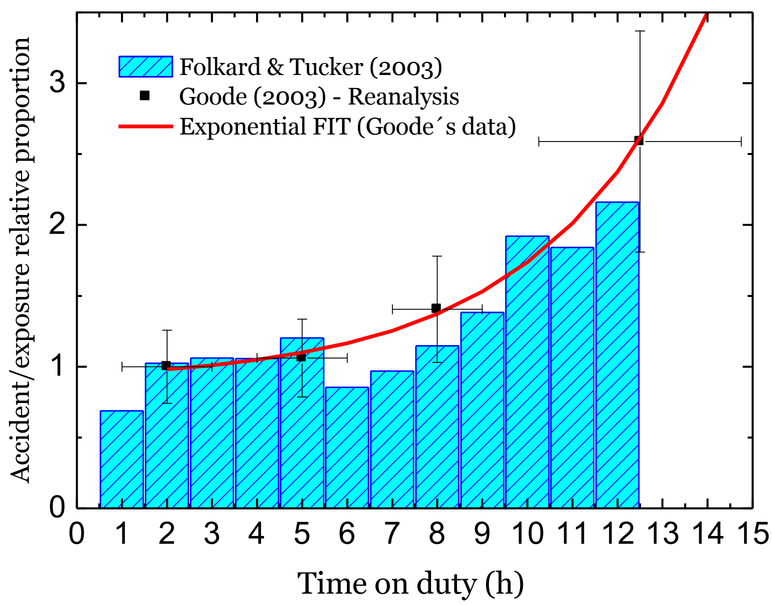

Figure 27: Reanalysis of Goode's data (solid squares) for the relative accident/exposure proportions as a function of the time on duty. The blue histogram is the prediction done by Folkard & Tucker and the solid red line the exponential fitting of Goode's data (reanalysis). Details in the text.

Time on duty (h)	Relative increase in the accident/exposure ratio (reference at t_{duty} = 8 hours)
10	+27%
11	+47%
12	+73%
13	+108%
14	+155%

Table 15A: Relative increase of (ΔA/A)/(ΔE/E) obtained with the exponential function of figure 27 and taking 8 hours as the reference value.

Another interesting point from Goode's measurements is the extremely small proportion of flight schedules with 13 hours or more with respect to the total exposure (less than 1%). This result makes it clear that the substantial increase in the accident/exposure ratio above 12 hours cannot be justified from cost perspectives due to its negligible industrial impact.

For this reason, **we recommend that the flight duty time for minimum crew be restricted to 12 hours**. From the industrial point of view, Brazil currently adopts the limit of 11 hours and one can certainly claim that this restriction has essentially NO IMPACT in the operational costs, but brings a significant benefit on safety as seen in Figure 27.

After steps 1 and 2 we obtain the following numbers:

Duty time limits (1 or 2 sectors) in scenarios 2 and 4* with Δ = 2 hours				
Check-in (h)	Initial condition label	Maximum duty time (h)	Average risk	Hazard area (h)
0500-0559	M10	11	0.965	0
0600-0659	M42A(*)	12	0.928	0
0700-0759	M46A(*)	**13 → 12**	0.894	0
0800-1059	M50A(*)	**14 → 12**	0.860	0
1100-1359	M14	**13 → 12**	0.876	0
1400-1459	M18	12	0.891	0.018
1500-1559	M26	11	0.893	0.018
1600-2259	M30	10	1.079	0.753
2300-0459	M2	10	1.140	1.300

Table X: Risk analysis for FDT limits restricted to 12 hours in scenarios 2 and 4 with Δ = 2 hours. Details in the text.

Step 3: Limit the night shifts to 9 hours of duty time (hazard areas in red)

In order to elucidate the step 3 we show in Figure 28A a comparison between Table X and the current Brazilian Regulations (Federal Law 7.183/84) with the corresponding numbers obtained for the hazard areas.

It is clearly verified that the highest hazard areas occur in the shifts that start (M2) of end (M30) during the dawn. In both cases, the magnitudes of the hazard areas are similar to the ones found in the Guantanamo Bay and Lexington accidents as shown in Figure 26. For this reason, we have taken the limit of nine (9) hours of Duty Time for these intervals. This value corresponds to the duty time limit adopted in the Project Law 8255/14 for Operators without an FRMS. Table Y presents these new limits, which reduce the hazard areas by 11 and 25% for M2 and M30, respectively.

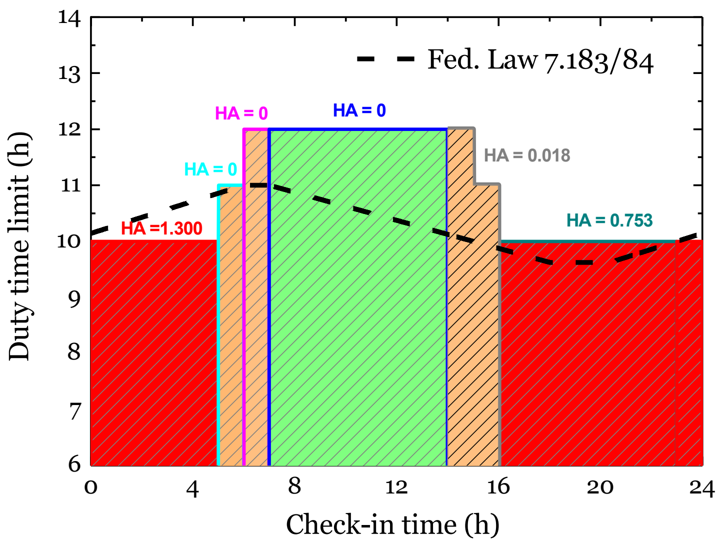

Figure 28A: Prescriptive limits of Table X (and its respective hazard areas) and in the Federal Law 7.183/84 (dashed line). The time intervals in red or amber indicate the need for risk mitigation.

Duty time limits (1 or 2 sectors) in scenarios 2 and 4* with Δ = 2 hours				
Check-in (h)	Initial condition label	Maximum duty time (h)	Average risk	Hazard area (h)
0500-0559	M10	11	0.965	0
0600-0659	M42A(*)	12	0.928	0
0700-0759	M46A(*)	12	0.894	0
0800-1059	M50A(*)	12	0.860	0
1100-1359	M14	12	0.876	0
1400-1459	M18	12	0.891	0.018
1500-1559	M26	11	0.893	0.018
1600-2259	M30	**10 → 9**	1.079	0.753 → 0.568
2300-0459	M2	**10 → 9**	1.140	1.300 → 1.179

Table Y: Steps 1, 2 and 3 are included. Details in the text.

Step 4: mitigation procedure for limits in amber (transition region)

The risk mitigation in the amber region was performed by taking the lowest value between the current Brazilian limits (Federal Law 7.183/84) and the proposed limits of Table Y. This combined approach assures that the fatigue risk for the future limits are maintained lower or equal than its current magnitude. This strategy was adopted due to the absence of experiments that include objective measurements under realistic operational circumstances found in Brazil.

For instance, between 05:00 and 05:59 we propose 11 hours of duty, since this value is also adopted in CAO's-48 (one or two sectors) and in the Brazilian regulation (with a negligible night shift attenuation of 7.5 minutes).

On the other hand, for the interval between 06:00 and 06:59, CAO's-48 adopts 12 hours, while in the Brazilian Regulation we have 11 hours. We do not recommend any increase in the current limit in the amber regions without a dedicated experiment and propose to maintain 11 hours in this case.

For the check-in interval between 14:00 and 15:59 CAO's-48 adopts 12 to 11 hours, against a limit close to 10 hours adopted in Brazil nowadays. It is important to make salient that a 12-hour duty period that starts around 15:00 is likely to finish within the WOCL (final approach and landing). This finding is not taken into account in CAO's-48 and do support our proposal to maintain a 10-hour duty limit for flights under this circumstance. After applying this mitigation the respective hazard areas within 14:00 and 15:59 go to zero and the check-in ranges return to the green band.

The final results are presented in Figure 28B and in Table W.

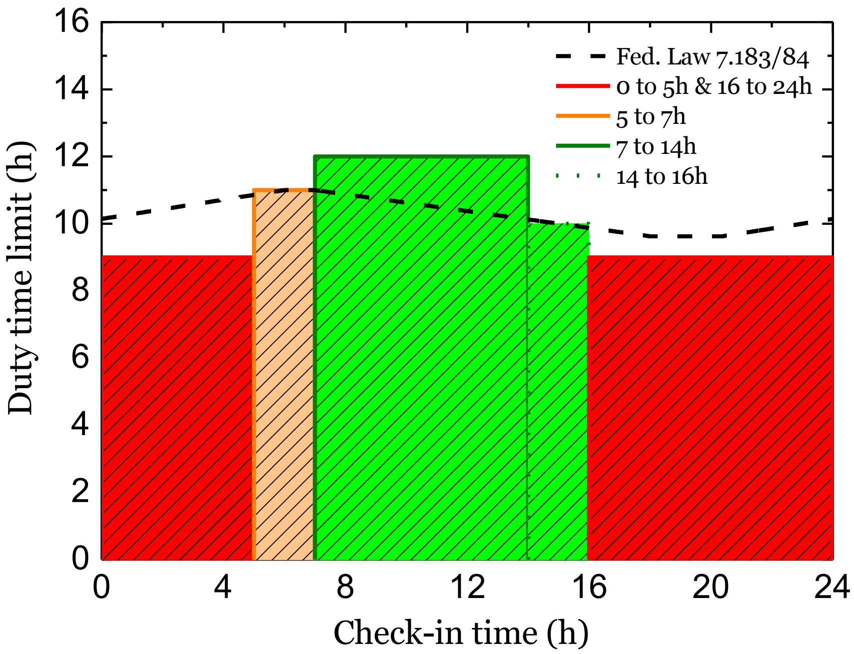

Figure 28B: Duty Time limits after steps 1 through 4 (histograms) in comparison with the current limits (dashed line). Details in the text.

Duty time limits (1 or 2 sectors) in scenarios 2 and 4* with Δ = 2 hours				
Check-in (h)	Initial condition label	Maximum duty time (h)	Average risk	Hazard area (h)
0500-0559	M10	11	0.965	0
0600-0659	M42A(*)	12 → 11	0.928	0
0700-0759	M46A(*)	12	0.894	0
0800-1059	M50A(*)	12	0.860	0
1100-1359	M14	12	0.876	0
1400-1459	M18	12 → 10	0.891	0.018 → 0
1500-1559	M26	11 → 10	0.893	0.018 → 0
1600-2259	M30	9	1.079	0.568
2300-0459	M2	9	1.140	1.179

Table W: Steps 1 through 4 are included.

Step 5: Including the effect of three or more sectors in the same duty period

Since workload effects do play an important role in fatigue, it is crucial to estimate the impact of flying three or more sectors on the prescriptive limits of table W, since they refer to one or two sectors only. In order to evaluate this effect, we have split our problem in three categories: (1) rosters with three or four sectors, (2) rosters with five or six sectors and, (3) rosters with seven or more sectors.

Step 5.1: duty time limits for rosters with three or four sectors:

5.1.1: In the cases where the check-in intervals were qualified in the red band we adopted the limit of nine hours of duty. This approach is in line with the limits adopted in the Project Law 8255/14, which restricts the rosters to four sectors and nine hours of duty for Operators without an FRMS.
5.1.2: In the cases where the check-in intervals were qualified in the amber band we adopted the same relative attenuation used in CAO's-48, rounding the results to the nearest 15 minutes. The relative attenuation factors are shown in Table 16 and the final values in Table 17.

Duty time attenuation factors for 3 or 4 sectors		
Check-in time (h)	Number of sectors	
	1-2	3-4
0500-0559	1	0,909
0600-0659	1	0,917

Table 16: Relative duty time attenuation factors as a function of the number of sectors. The factors were taken from CAO-48 prescriptive limits and are normalized by the limits for 1 and 2 sectors.

Duty Time limits (h)		
Check-in time (h)	Number of sectors	
	1-2	3-4
0500-0559	11	10
0600-0659	11	10

Table 17: Maximum duty time limits for three or four sectors. Details in the text.

5.1.3. In the cases where the check-in intervals were qualified in the green band, we adopted the same limits of CAO's-48, but limited to 12 hours and to the value found for one or two sectors (Table W). After this step we end up with Table 18.

Duty Time Limits (h)		
Check-in time (h)	Number of sectors	
	1-2	3-4
0000-0459	9	9
0500-0559	11	10
0600-0659	11	10
0700-0759	12	12
0800-1059	12	12
1100-1359	12	12
1400-1459	10	10
1500-1559	10	10
1600-2359	9	9

Table 18: Duty Time limits up to four sectors. Details in the text.

Step 5.2: duty time limits for rosters with five or six sectors

The corrections in the maximum duty times for five or six sectors were based on three independent researches carried out in charter and short haul operations (Spencer & Robertson, 2000; Spencer & Robertson, 2002; Robertson & Spencer, 2003). These studies include 4, 5 and 6 sectors, but most of the data were concentrated in 4 sectors only. The researchers concluded that the effect of an additional sector on fatigue is of the same magnitude of increasing the duty period by 37.5 minutes. So, applying this parameter and rounding the results to the nearest 15-minute interval we finally obtain Table 18A.

Duty Time Limits (h)				
Check-in time (h)	Number of Sectors			
	1-2	3-4	5	6
0000-0459	9	9	8¼	7¾
0500-0559	11	10	9¼	8¾
0600-0659	11	10	9¼	8¾
0700-0759	12	12	11¼	10¾
0800-1059	12	12	11¼	10¾
1100-1359	12	12	11¼	10¾
1400-1459	10	10	9¼	8¾
1500-1559	10	10	9¼	8¾
1600-2359	9	9	8¼	7¾

Table 18A: Duty Time Limits (in hours) as a function of the number of sectors.

Step 5.2: duty time limits for rosters with seven or more sectors

Considering that the available data (Spencer & Robertson, 2000; Spencer & Robertson, 2002; Robertson & Spencer, 2003) do not include seven or more sectors, **we do not recommend** extrapolating the previous attenuation factor of 37.5 minutes for seven sectors or more. For these cases, we do recommend that the operator should apply a safety case and implement a full FRMS.

Step 6: Flight Time Limitations

The risk analysis depicted in this document does not take into account the flight time, but only the flight duty time. For this reason, we propose the same flight time limitations adopted in CAO's-48 as far as they do not exceed the duty time limits of Table 18A subtracted by one hour.

The final results are then presented in Table Zulu for acclimatized minimum crew.

Brazilian proposal – maximum duty time (flight time)				
Check-in time (h)	Number of sectors			
	1-2	3-4	5	6
0000-0459	9 (8)	9 (8)	8:15 (7:15)	7:45 (6:45)
0500-0559	11 (9)	10 (8)	9:15 (8)	8:45 (7:45)
0600-0659	11 (9)	10 (9)	9:15 (8)	8:45 (7:45)
0700-0759	12 (9:30)	12 (9)	11:15 (9)	10:45 (9)
0800-1059	12 (10)	12 (9:30)	11:15 (9)	10:45 (9)
1100-1359	12 (9:30)	12 (9)	11:15 (9)	10:45 (9)
1400-1459	10 (9)	10 (9)	9:15 (8)	8:45 (7:45)
1500-1559	10 (9)	10 (8)	9:15 (8)	8:45 (7:45)
1600-2359	9 (8)	9 (8)	8:15 (7:15)	7:45 (6:45)

Table Z: Pilots proposal for the Brazilian flight and duty time limitations. The flight time limits are presented in parentheses.

4.4 The effects of successive early-starts.

As described in section 4.1, flight schedules with successive early-starts play a major role in fatigue (Licati *et al.*, 2015), requiring mitigating procedures by the operators, as well as the Brazilian Regulator ANAC.

A recent research from the University of South Australia (Roach *et al.*, 2012) pointed out that the rosters with check-in times between 0400 and 1000 are the main cause of fatigue in short haul operations. The study was done with 70 Australian pilots that flew B-737 and B-767 in short duties. Their analyses combined actigraph objective measurements with sleep/work diaries and SPS fatigue scores (Samn & Perelli, 1982) in the beginning of the shift work.

The average duty and flight times of the Australian experiment were 7.6 ± 3.0 (h) and 4.9 ± 2.4 (h), respectively. These numbers are very similar to the Brazilian situation, where we have a duty time limit of 11 hours with an average flight time per day of roughly 4 hours. However, regarding the average number of flight sectors, the Brazilian scenario is much more challenging (50% higher) with 3.1 ± 1.2 operations per work day, compared with the number found in Australia (2.0 ± 1.0). The situation is depicted in Figure 29.

The check-in times of the rosters analyzed by Roach *et al.* (2012) were more frequently distributed within 04 and 10h (47.6%) and between 10 and 16h (33.6%). Figure 30 presents one example that combines actigraph data with pilot's reports regarding work, sleep and wakefulness.

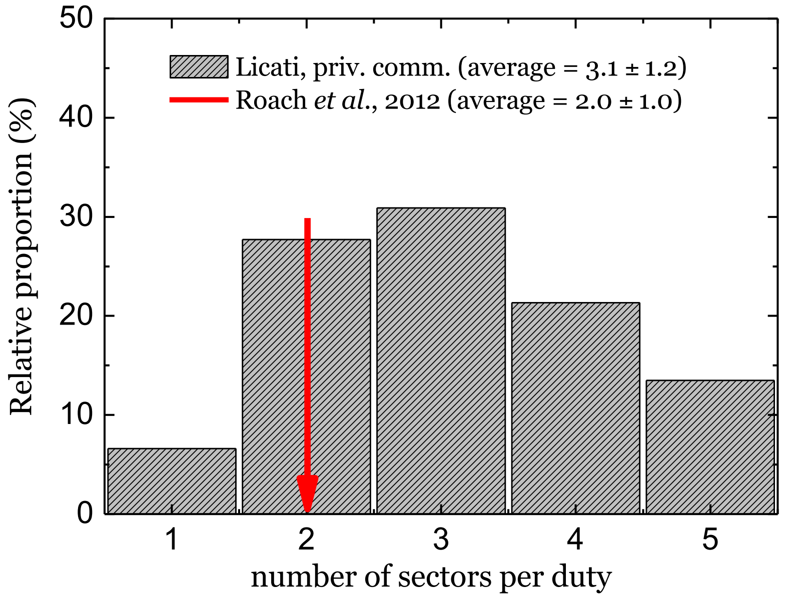

Figure 29: Distribution of the number of sectors (gray histogram) and its respective average value found in the Brazilian survey (Licati, private communication). The result found by Roach *et al.* (2012) is shown by the red arrow.

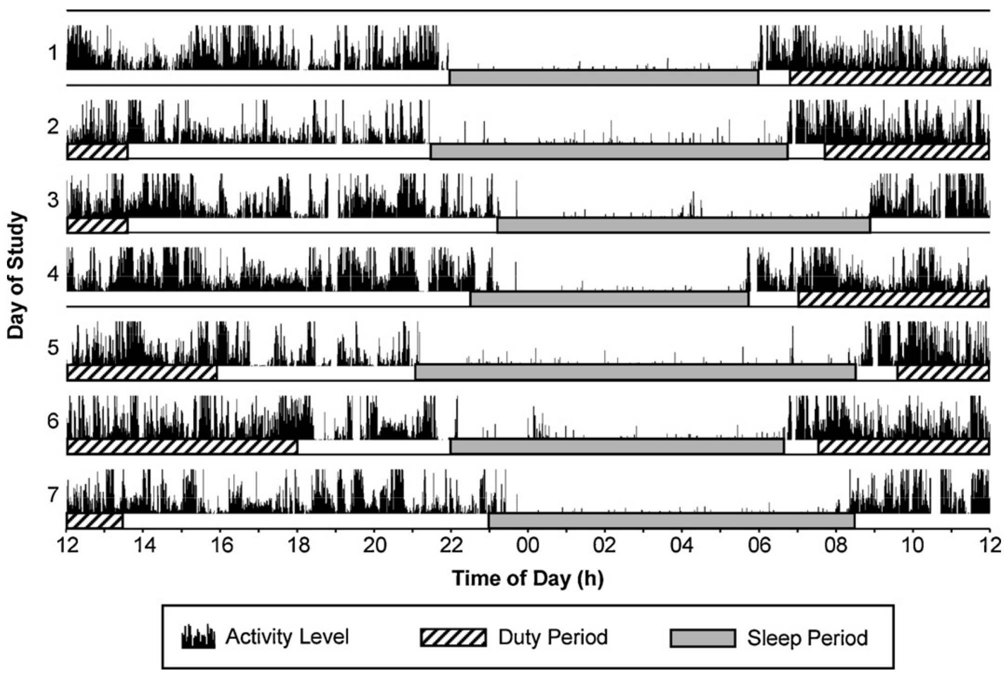

Figure 30: Picture with actigraph data extracted from Roach *et al.* (2012). Details in the text.

From the inspection of Figure 30 it is verified that the sleep periods are lower for duty periods that start early in the morning, since they reduce the amount of recovery sleep.

Another interesting result is the average time spent from the start of wakefulness and the check-in, which is close to one hour in the situation that the check-in happens early in the morning. This scenario is completely different in Brazil, where the crewmembers are required to wake-up several hours (three or maybe even four hours) before the check-in in huge metropoles.

Figure 31 shows the distribution of the sleep hours within the 12-hour period before the check-in for the Australian pilots. The average amount of sleep was 6 hours (orange arrow), while in the Brazilian survey we found only 5 hours (blue arrow). It is worth mentioning, however, that this difference is even higher considering that in the Brazilian experiment the amount of sleep was referred to the 24-hour period before fatigue sensation, instead of the Australian experiment that considered a lower 12-hour period prior to check-in.

This difference in the amount of sleep could be related with the deficiencies in the Brazilian infrastructure, the operations that take place in two different airports at the same metropolis, and the huge density of consecutive flights early in the morning.

Figure 32 shows the correlation between the amount of sleep and the start of the duty, where one easily observes that the lowest sleep amount (~5.5 h) occurs for the check-in interval between 4 and 5 in the morning, while the highest amount of sleep (~6.7 h) occurs when the start of the duty is between 09 and 10 h.

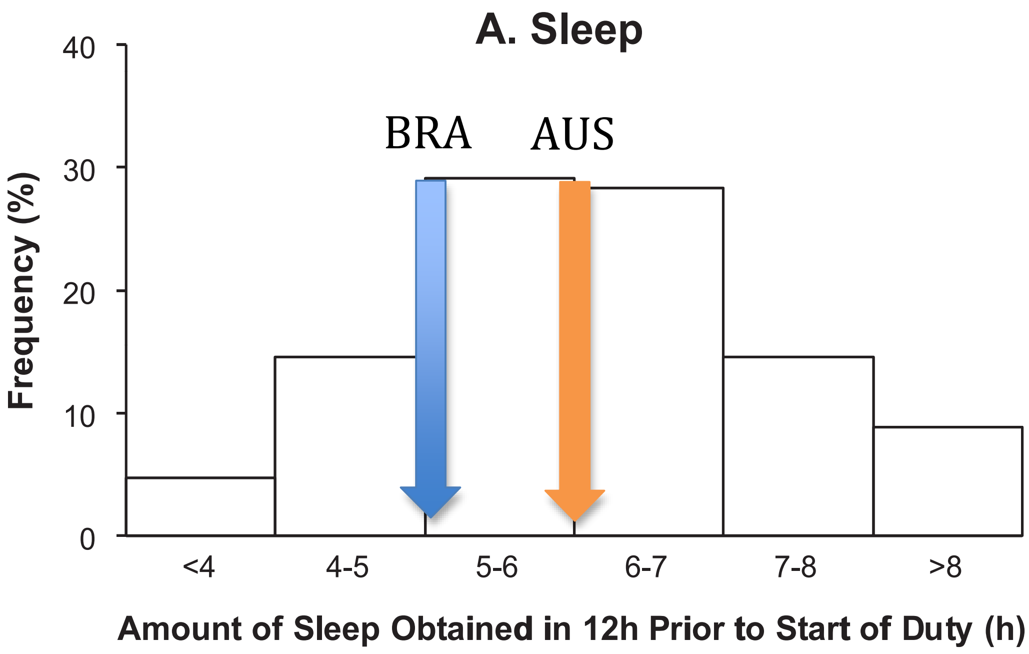

Figure 31: Histogram with the total amount of sleep in the 12-hour period prior to the check-in, taken from (Roach *et al.*, 2012). The blue and orange arrows represent the average values obtained by the Brazilian (Licati *et al.*, 2015) and Australian experiments, respectively.

As a consequence of this sleep deficit, the researchers also found the worse SP fatigue scores within 04 and 05 in the morning (Figure 33).

It is quite evident from the Australian experiment that the earlier is the check-in the lower is the amount of sleep and the higher is the fatigue.

On the other hand, laboratory studies have shown that individuals with partial sleep deprivation similar to the worst case in the Australian experiment (start of duty within 4 and 5 in the morning) do not show a significant reduction in the cognitive performance during the first day of duty, but are largely affected if this condition is maintained for two or three consecutive days (Belenky *et al.*, 2003; Dinges *et al.*, 1997).

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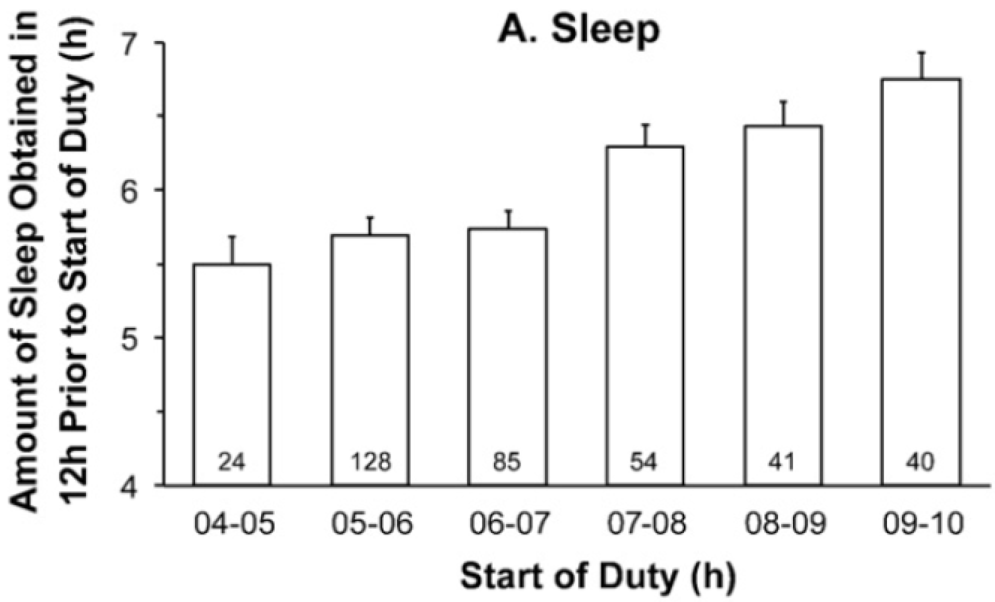

Figure 32: Total amount of sleep as a function of the start of duty, extracted from Roach *et al*. (2012).

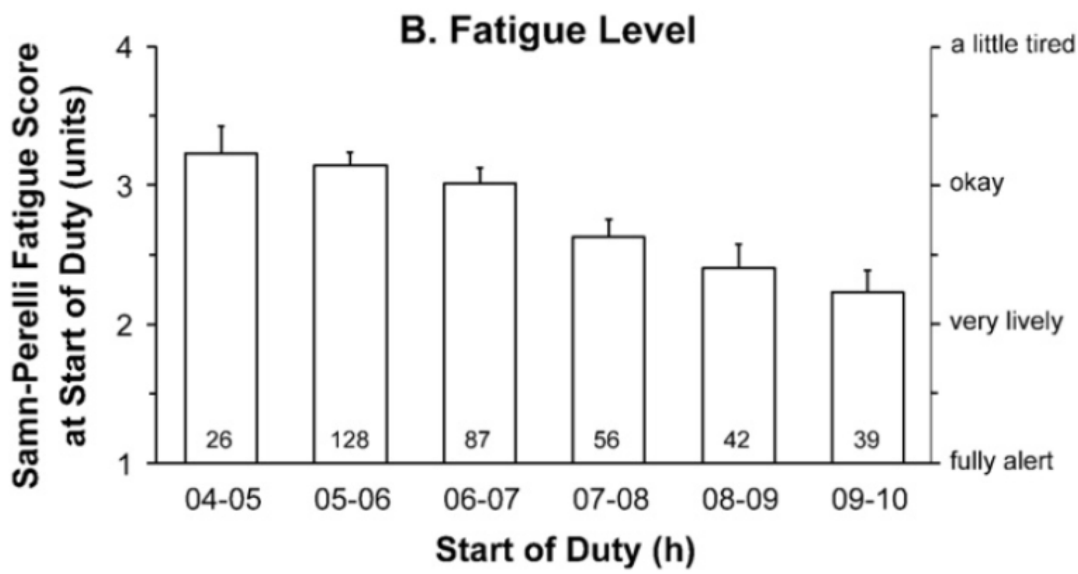

Figure 33: SP fatigue scores at the start of the duty as a function of the check-in time, extracted from Roach *et al*. (2012).

In one attempt to quantify the crewmember fatigue in successive early starts, we present in table 19 one study based on the SAFTE-FAST model that applies the scenarios proposed in section 4.3.1 for rosters starting within 06 and 11 h. The maximum duty times were taken from the "Brazilian" proposal (Table Z).

Average SAFTE-FAST effectiveness (%) (Δ = 2 hours)							
Check-in (h)	Duty time (h)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
06:00 - 06:59	11	91.71	89.11	88.21	87.52	86.96	86.52
07:00 - 07:59	12	94.86	93.62	93.17	92.85	92.64	92.47

Table 19: SAFTE-FAST average effectiveness (%) in successive early-morning shift works with Δ = 2 hours. Details in the text.

The green and amber bands of table 19 follow the same criterion adopted in figure 23. As observed, the average effectiveness falls systematically for flight schedules before 0700 in the morning but remains reasonably unchanged until the 6th day for duties that start after this period. It is worth mentioning, however, that table 19 refers to Δ = 2 hours, which does not cover the realistic situation found for large metropolis and in huge traffic jams. So, in order to account for a more realistic situation, we show in tables 20A and 20B the results found for Δ = 3 and 4 hours, respectively.

Average SAFTE-FAST effectiveness (%) (Δ = 3 hours)							
Check-in (h)	Duty time (h)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
06:00 - 06:59	11	88.44	83.90	82.21	80.88	79.74	78.79
07:00 - 07:59	12	92.04	89.53	88.55	87.82	87.25	86.81
08:00 - 10:59	12	97.14	94.59	93.01	91.93	91.15	90.60

Table 20A: SAFTE-FAST average effectiveness (%) in successive early-morning shift works with Δ = 3 hours. Details in the text.

Check-in (h)							
Check-in (h)	Duty time (h)	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6
08:00 - 10:59	12	94.81	88.37	84.25	81.25	78.94	77.11

Table 20B: SAFTE-FAST average effectiveness (%) in successive early-morning shift works with Δ = 4 hours. Details in the text.

For Δ = 3 hours (Table 20A) we verify that the average effectiveness decrease progressively (and always below 90%) for consecutive workdays before 07:00 (amber band). For workdays before 08:00, on the other hand, the effectiveness scores drop below 90% only after the second consecutive workday.

Considering the check-in intervals between 08:00 and 10:59 we found effectiveness scores below 90% only for Δ = 4 hours. This huge commuting parameter of 4 hours may reflect more realistically the situation found in huge cities where the crewmembers are supposed to show up for the shifts in two or more airports.

Another interesting point that should be further investigated is the calibration of bio-mathematical models for early-starts scenarios.

Some of the laboratory sleep-deprivation studies (Belenky *et al.*, 2003; Dinges *et al.*, 1997) usually postpone the bed time of the individuals in such a way of reducing the actual amount of sleep per night in comparison with the controlled group (baseline) that has a “normal” sleep dose of typically 8 to 9 hours per night. For instance, in order to have a 5-hour sleep group, the researchers postpone the bed time of the individuals to 02:00 and let them sleep until 07:00. This procedure assures that each group has its correct sleep amount but with a common wake-up time of 07:00.

In real world situation, however, the crewmembers try to go to bed earlier and wake-up in the middle of the recovery sleep during dawn. For this reason, one can argue that the situation found during actual flight operations may not be completely reproduced by the laboratory experiments, which, in turn, have been used to calibrate the models.

Consequently, we strongly recommend that the effects of early-starts should be measured in more realistic circumstances, providing a more reliable calibration to the bio-mathematical models and a more precise framework for the fatigue risk mitigation. The Operators should avoid rosters with successive early-starts since they play a major role for the accumulation of sleep deficit.

As pointed out by Roach *et al.* (2012), one of the main components of the FRMS should be the construction of rosters in such a way that early-starts be executed only if absolutely necessary, but preferably avoiding consecutive flights.

There are a large number of rosters that start very early in the morning in Brazil, which requires that the operators manage the risks through a careful analysis of the following factors:

1) **Duty-time limits:** these limits should take into account the huge commuting and the deficiencies in the Brazilian infrastructure. All these factors reduce the sleep opportunity of the crewmembers and should be tested by operators and the Regulator (ANAC) preferably through objective measurements (PVT and actigraphs). The pairing and rostering optimizers usually search the solutions close to the optimal in such a way of building all the flight schedules under the prescribed limits. In the event that we have a decrease in the maximum duty time (such as during the night period and early-starts, table Z) the pairings will still be produced, but with a different combination and probably with a reduced number of flight sectors. According with Powell *et al.* (2007) the fatigue scores are much higher comparing a five-sector flight with flights up to two sectors. **Consequently, the restrictions in the duty times proposed in this document for early-starts shall provide the first effective mitigation for the fatigue risks;**
2) **The structure of the rosters:** In the event that the rosters contain early-starts, they should be organized clockwise. **A counter-clockwise structure during successive early starts should be strongly avoided** since it decreases the sleep opportunity and is likely to cause fatigue;
3) **Check-in in huge metropoles:** The FRMS criteria established by the Regulator should take into account an adequate concept for contractual basis. For huge metropoles with two or more airports, such CGH/GRU, SDU/GIG,

CNF/PLU, and other similar configurations in the future, it is required that the operators define one airport as the contractual basis. In the event that the crewmember is scheduled to start or finish his duty in a different airport, the rest time before (or after) the flight should be increased. In these cases, we recommend that the operators take into account the realistic conditions depicted in Tables 20A and 20B;

4) **Check-in in airports close to the rest facilities:** In the event that the crewmember is scheduled for a flight in an airport less than 30 minutes away from the hotel designated for the rest period we recommend that the operators adopt table 19 (Δ = 2 hours).

4.5 Recovery during off days (acclimatized crew)

This section describes the recovery profile for the crewmembers during off days based on SAFTE-FAST model predictions.

Figure 34 shows a typical recovery after the second night shift at 0200 with Δ = 2 hours (M2). In this case, the crewmember spends almost four nights for a complete recovery. In fact, 36 hours after the end of the duty (at 00:00 on 04/11) the individual effectiveness is around 85% but with a steep descent trend due to the WOCL. This effectiveness of 85% is also found at 06:00 on 04/11, but at this time with a significant positive derivative, reaching the top value of 92% around 10:00 on 04/11.

So, for a complete recovery after M2 one needs four nights of sleep. Nonetheless, a marginal recovery can be reached with a single off day provided the crewmember wakes up in the work day naturally (around 08:00). Indeed, the sleep amount inserted in the FAST software during recovery is nine hours (bed time is 23:00), which is a consolidated parameter for the IBR team.

In the aviation industry it is unfeasible that all the off days are grouped in three (with four nights of sleep), even though this would be the best scenario from the physiological perspective. Consequently, for the cases where a single day off is needed, the operators should guarantee that the crewmember do not show to work before 10:00 in the following day. This criterion is intended to mitigate the risks of fatigue for single days by taking advantage of the circadian boost around 10:00.

Figure 34: SAFTE-FAST predicted effectiveness during two successive night duties (solid lines) and the respective recovery profile during off days. The calculation was performed by Lauren Waggoner, PhD (IBR).

In order to quantify this criterion we calculate using FAST software the crewmember effectiveness at 10:00 during the recovery days (first, second and third) after some typical workdays. The results as a function of the elapsed time since checkout are presented in Figure 35.

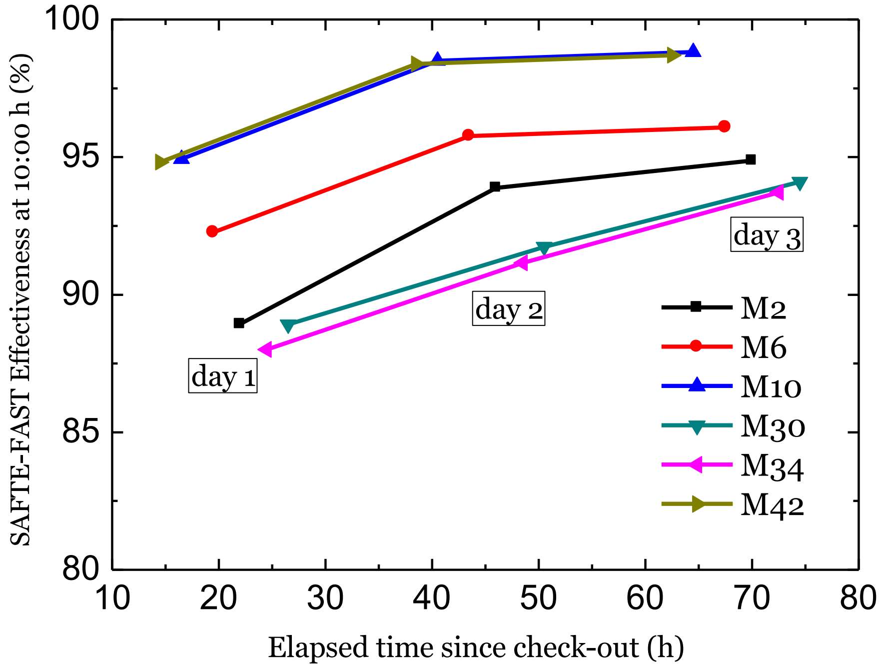

Figure 35: SAFTE-FAST effectiveness at 10:00h in the first, second and third days after the end of the duty. The notation for M2 through M42 is the same adopted for the work shift scenarios of section 4.3.1.

Figure 36 presents the average effectiveness (at 10:00h) considering the different initial conditions together with a linear regression (red line) that shows the increase of 2.3% on the Effectiveness by each recovery day.

Such a finding clearly demonstrates that the off days should be assigned in groups in order to guarantee an adequate recovery against fatigue. Single days off should be avoided whenever possible.

Another important result refers to the recovery after consecutive night flights. In these cases we recommend a minimum of 48 hours free of duty, with the subsequent check-in not before 10:00h.

In this regard, after a shift work during the night **we recommend a period of at least two consecutive days off or that the**

subsequent duty is not assigned before 10:00h after a single day off.

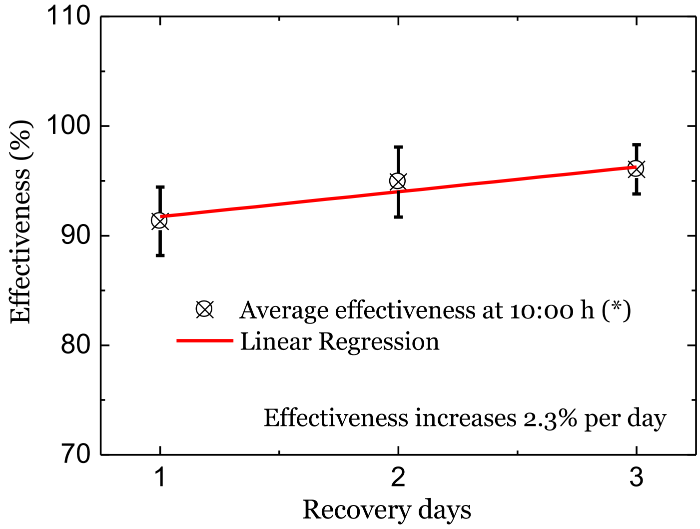

Figure 36: Average effectiveness at 10:00h for the initial conditions shown in Figure 35. Details in the text.

4.6 The effect of commuting

Commuting is certainly one important factor that should be taken into account by the new FRMS regulations.

A recent survey (Giustina *et al.*, 2013) showed that 34% of the crewmembers of a major Brazilian airline live in São Paulo, while 66% are from other cities, such as Porto Alegre (15%), Rio de Janeiro (9%), Curitiba (4%), Florianópolis (4%), Brasilia (2%), Guarulhos (2%) and others (30%).

Since 35% of these individuals go to work by plane, one can estimate that the majority of the air displacements are concentrated in flights from POA, RJ, CWB, FLN and BSB (total of 34%) to São Paulo.

So, about 65% of the responders do not use air displacements, while 36% live either in São Paulo or Guarulhos. Consequently, about 29% of the responders live in the cities nearby São Paulo (country side of the São Paulo State, south of Minas Gerais, etc...) and go to work via ground displacements.

In this regard, one can assume that 1/3 of the crewmembers live in São Paulo, 1/3 live in the cities nearby São Paulo (and use ground displacements) and 1/3 are distributed among POA, RJ, CWB, FLN, BSB, etc...

As presented in section 4.3.1, the parameter Δ can be very useful for the evaluation of the effectiveness since it is generally linked with the start of the wakefulness. This connection between Δ and the start of wakefulness gets weaker when the check-in is typically after 10:00h, mainly because the individuals are likely to wake-up naturally under these circumstances. As pointed out in the analysis of FAR-117 and CAO-48 duty time limitations, we have adopted Δ

= 2 hours in all situations, even for shift-works that start around 09:30h or in the end of the afternoon, when the ground displacements become hard in the huge metropoles, such as São Paulo, Rio de Janeiro and Belo Horizonte. Under these circumstances a more realistic parameter would be 3 or even 4 hours.

Nonetheless, as our duty time limits are supposed to work for all conceivable situations and all over the country, we decided to use Δ = 2 hours (section 4.3.4). On the other hand, we also propose some recommendations to mitigate the risks either during the second night flight or during consecutive early-starts. The latter, for instance, are quite sensitive to the Δ parameter and for this reason it is very important that the operators do consider the two different conditions that are suitable for the operations in airports close to the hotel (Δ = 2 hours, table 19) or in airports different from the contractual basis airport in huge cities (Δ = 3 or 4 hours, tables 20A and 20B).

Figure 37 shows the effect on the effectiveness by switching the Δ parameter from 2 hours (black line) to 3 hours (red line). The average effectiveness along the duty decreases from 78.92 to 77.69%, while the average risk goes slightly up (~1%).

Consequently, the increase of one hour in the commuting during the first workday at 02:00 (M3 x M1) increases by 1% the average fatigue risk. This effect is considerably higher comparing the second night shift (M4 x M2), where the average fatigue risk is increased by 14% (table 8).

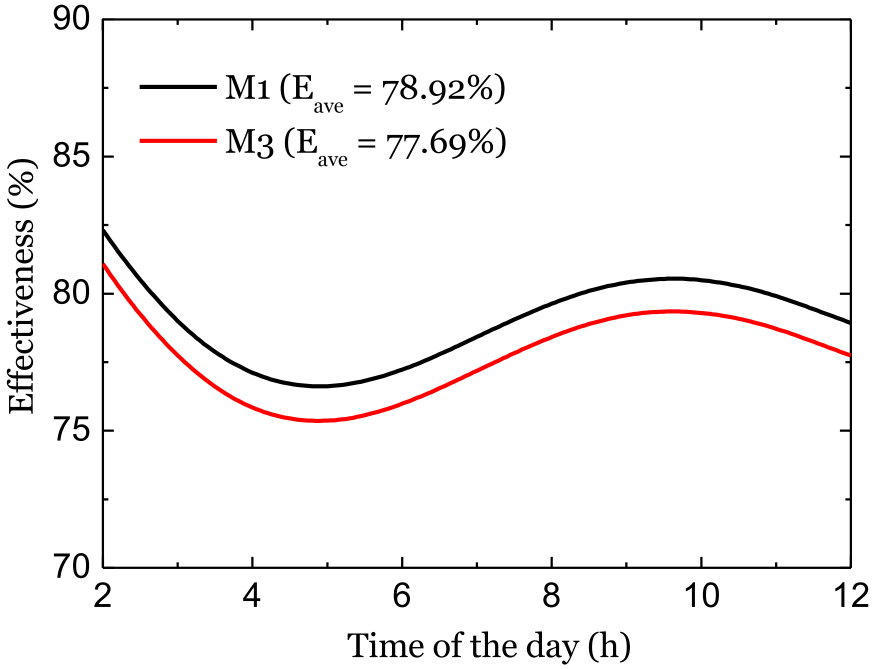

Figure 37: SAFTE-FAST predicted effectiveness assuming Δ = 2 h (M1, black line) and Δ = 3 h (M3, red line).

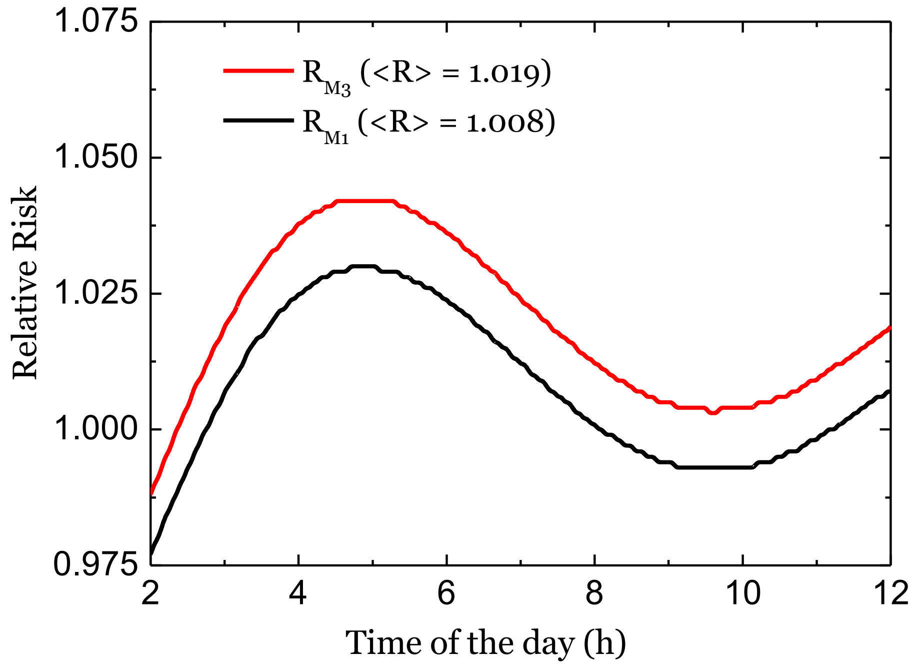

Figure 38: Relative risk in the first night shift assuming Δ = 2 h (M1, black line) and Δ = 3 h (M3, red line).

In summary, considering the technical issues described above, the social-economical aspects of the major Brazilian airlines that employ crewmembers of all states, as well as the Brazilian Constitution and Work Agreements, we point out some plausible measures that could largely mitigate the risks inherent to the commuting:

1. **Operational basis:** Differently from the US, the Brazilian aviation is very concentrated in the Southeast with roughly 1/3 of the crewmembers taking air displacements in order to check-in for their schedules. For this reason, it would be important that the operators expand their bases (either physically or virtually) all over the country. It is well known that modern softwares are able to generate balanced basis by the coupling of the available crew with the respective pairings of the basis. By doing this, operators will improve the covering of those airports with local crews with extra savings with hotel accommodation and food allowance;
2. **Airports located in huge metropoles:** The operator shall establish one airport as the contractual basis of the crewmember in the event that this airport is inserted in a metropole with two or more airports. This procedure will decrease quite substantially the effect of the commuting in ground displacements. In the event that the crewmember is assigned to an airport that does not corresponds to his contractual basis airport **we strongly recommend that the operators arrange the rosters according with tables 20A and 20B**;
3. **Unrestricted free pass for crewmembers:** Since 1/3 of the crewmembers go to work by plane we also recommend

that the operators eliminate the current restrictions for the free pass. This step will increase the options for the crewmembers and reduce the fatigue as a consequence of the increased sleep opportunity;

4. **Shared responsibilities:** flight and cabin crew shall inform their employers of any event that could adversely affect his (her) compliance of the fatigue risk management policy defined by the operator, as well as the compliance of the prescriptive limits and criteria established by the Civil Aviation Authority. Events that could affect the cognitive performance of the crewmember include the lack of recovery sleep prior to the flight and/or excessive commuting that could adversely affect the sleep opportunity.

5. Conclusions

This report proposes a scientific approach based on the SAFTE-FAST bio-mathematical model for the identification of the potential hazards and effective mitigations for the fatigue risk management in the Brazilian civil aviation. The work was accomplished via the collaboration between SNA, ABRAPAC, ASAGOL and ATT, with the support of the University of São Paulo and the Institutes for Behavior Resources (IBR).

The work is intended to provide a broad and consistent picture of fatigue in the Brazilian civil aviation, comparing important parameters found in Brazil, USA and Australia that could impact the aviation industry.

The report presents some prescriptive limits/criteria that could contribute for the achievement of a mature and science based FRMS regulatory framework by the Brazilian Civil Aviation Authority (ANAC).

Regarding the Brazilian data it is worth-mentioning that: (i) pilot errors per hours are 50% more frequent during night shifts (Mello *et al.* 2008), (ii) fatigue was confirmed in 3/4 of the FOQA level III events in a major Brazilian airline (Quito, 2012), (iii) Licati *et al.* (2015) found strong evidences for chronic fatigue. As a consequence, the relative risk in Brazil is around 13.6% higher than in the USA (Roma *et al.*, 2012).

The proposed research took into account 61 different initial conditions suitable for the Brazilian case that were analyzed using the SAFTE-FAST bio-mathematical model with the help of the IBR team.

The analysis propitiated the extraction of the crewmember effectiveness as a function of the time of the day during the duty, allowing a new concept related with the evaluation of the hazard area. This new and consistent approach showed that: (i) the fatigue hazard area during the second consecutive night flight starting at 0200 is about ten times higher than during the first shift, (ii) the daily averaged hazard area for a completely recovered crewmember is 20% higher for FAR-117 than CAO-48 prescriptive limits, (iii) the daily averaged hazard area during the second night flight and in the sixth consecutive early-start is 2.6% higher for FAR-117 than CAO-48 prescriptive limits, (iv) some frequent initial conditions found in Brazil either under FAR-117 or CAO-48 duty time prescriptive limits generate unaccepted relative risks (danger zone) with magnitudes compatible with the analyses of the Guantanamo Bay (AIA 808) and Comair 5191 accidents, (v) the average number of sectors in Brazil (Licati *et al.*, 2015) is approximately 50% higher than in Australia (Roach *et al.*, 2012), and (vi) the average amount of sleep in Brazil is about 5 hours, compared with 6 hours found in Australia.

So, after this careful analysis, **the representative institutions SNA, ABRAPAC, ASAGOL and ATT recommend** that the following limits/criteria are included in future FRMS regulations: (i) maximum duty and flight time limitations for acclimatized and minimum crew as shown by **Table Z**, (ii) maximum of two consecutive night flights as far as at least one duty does not exceed two hours in the period from 0000 to 0600 and always respecting the clockwise criterion for successive shifts. **We do not recommend take-off and/or landing operations during the second night shift within the WOCL (from 0200 to**

0500), (iii) consecutive early-starts should be avoided and if needed should respect the clockwise criterion. The parameters shown in Tables 19, 20A and 20B should be further investigated through a dedicated Brazilian experiment, (iv) avoidance of single off days whenever possible. In the event that a single day off needs to be planned, **the crewmember should not be assigned before 1000 in the next day**.

At the end, we make salient that our research has two limitations, as it does not include the risk increase as a function of the increase in the number of sectors, as well as the effects of de-synchronization due to multiple zonetime crossing. Since those effects have adverse impacts either on the crewmember cognitive performance, or the higher risk exposure (caused by multiple sectors), we consider that the parameters and the criteria presented in this report are interpreted as upper limits for an FRMS. These effects, as well as the adverse effect of workload in the individual effectiveness should be taken into account in the future.

In the event that the operators are willing to extrapolate the limits proposed in this report, we recommend a dedicated experiment (safety case) performed with actigraphs and PVT's in order to quantitatively determine the level of fatigue and that the crewmembers are performing under an acceptable level of safety.

6. Acknowledgments

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Annex I: considerations about adequate food services within 02:00 to 07:00

Airline crewmembers maybe subject to a diet high in sugar, especially during night shifts, as a strategy to quickly obtain enough energy for their tasks. It is important to understand that different food cause different and distinct effects in the organism.

The carbohydrates (simple and complex) are the main sources of energy in the organism and can be found in breads, cereals, tubers, pasta, fruits, processed foods and sweets.

Simple carbohydrates are highly absorbed and deliver insulin. As a consequence, they do not satisfy all the nutritional needs, being closely related with weight gain and diabetes type II. This type of food should be avoided whenever possible in all phases of the day and can be consumed in small portions few days of a week.

Simple carbohydrate includes:

- White bread;
- White rice;
- Regular pasta;
- Cakes, sweets and other products with refined sugar, honey, dextrose and maltodestrin.

Complex carbohydrate, also called low glicemic foods, have high fiber content in his composition. As a consequence, the digestions take longer and generate less insulin release, helping in weight control. They are recommended foods for daily consumption at any meal.

Complex carbohydrates includes:

- Vegetables such as peas and lentils;

- Whole grain breads;
- Full noodles;
- Brown rice;
- Vegetables with starch such as potatoes and corn.

It has been proven by the scientific community that a balanced diet can help improve the concentration at work, reduce the fatigue and stress, improve the quality of the memory and reduce the risk of depression, anxiety and aggressiveness (Korol, 1998; Morris, 1998).

This is due to the influence of neurotransmitters, chemicals that convey information from one brain cell to another using the power components coming feedstock.

Nutrients from food help produce various neurotransmitters. As a main example, the tryptophan is an amino acid food which is converted into serotonin, calming chemical substance that induces relaxation and controls sleep, appetite, memory, learning, body temperature, libido, mood, cardiovascular function, muscle contraction, and endocrine regulation (Prasad, 1998).

Excessive intake of foods high in simple carbohydrates, like candies, increases tryptophan levels in the brain and, consequently, increases the synthesis and release of the neurotransmitter serotonin, bringing feeling of relaxation and sleepness. (Wurtman, 1996).

Therefore, complex carbohydrates are preferable in the daily diet with attention to nighttime as to improve the cognitive ability of the crew, as well as to help prevent chronic diseases such as diabetes, obesity, high cholesterol, hypertension, and the larger aggregates risks to air operations called human fatigue.

Foods with a high glycemic index (especially sweets high in sugar, soft drinks and so on) should be avoided. This should contribute to a better quality of life, prevention and control of pre-existing diseases and improve of the performance, including during night shifts, where the phenomena described tend to be enhanced due to the window of circadian low.

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Annex II: Flight Duty Time and Flight Time limits for augmented crew.

According to Simons & Spencer (2007), the extensions to the flight duty period (FDP) in augmented crew due to in-flight relief should be proportional to the rest periods available to the pilots, to the environment which is available for rest, and whether the crew member is acclimatized or not.

In this work, the researchers considered that the total rest period in a flight is equal to the *extended FDP* minus 3 (three) hours. In this regard, the difference between augmented L' (in hours) and non-augmented L limits should be proportional to the extended limit L' divided by the number of rest periods, such that:

$$L' - L = \frac{pq(L'-3)}{R}, \qquad (1)$$

with p reflecting the sleep quality, q the acclimatization factor (q = 1 for acclimatized and 0.8 for non-acclimatized crew) and R one parameter that reflects the number of pilots in the flight (R = 2 for four pilots and R = 3 for three pilots). The factor “-3” represents the reduction of the extended FDP (L') due to the operational constraints that reduce the sleep opportunity (from check-in up to the top of climb and from the start of the decent briefing until the check-out). Although not mentioned by the authors (Simons & Spencer, 2007), it is unlikely that the three hour reduction parameter in Eq. (1) can account for multiple sectors in the same duty period and for this reason we recommend that this formula is restricted only to single sector flights.

The factor p depends on the rest facility, such that p = 0.75 for Class I, p = 0.56 for Class II and p = 0.25 for Class III. The details and criteria to achieve theses parameters can be found elsewhere (Simon & Spencer, 2007).

In this regard, one can extend Eq. (1) for multiple sectors by considering a penalty (herein taken as two hours) in the sleep opportunity for each additional sector. By doing this, Eq. (1) can be generalized in the form:

$$L' - L = \frac{pq[L' - 3 - 2(S-1)]}{R}, \qquad (2)$$

with S being the number of sectors.

Re-writing Eq. (2) in terms of L (non-augmented FDP), one finds:

$$L'R - LR = pqL' - 3pq - 2pq(S-1)$$
$$L'(R - pq) = LR + Lpq - Lpq - 3pq - 2pq(S-1)$$
$$L'(R - pq) = L(R - pq) + pq[L - 3 - 2(S-1)]$$
$$L' = L + pq\frac{[L - 3 - 2(S-1)]}{R - pq}$$

$$\therefore L' - L = \Delta L = pq\frac{[L - 3 - 2(S-1)]}{R - pq}. \qquad (3)$$

In fact, Eq. (3) is identical to the formula adopted by Simons & Spencer (2007) for the specific case where S = 1 (single sector). One useful strategy is to re-write Eq. (3) in terms of two parameters that do not depend on the un-augmented FDP (L), such that:

$$\Delta L = A(p,q,R)L + B(p,q,R,S)$$

with

$$A = \frac{pq}{R - pq}$$

and

$$B = -pq\frac{[3+2(S-1)]}{R-pq}. \qquad (4)$$

With this new parameterization one can calculate A and B considering a 3 (herein denoted C) or 4-pilot (denoted R) crew in three different rest facilities (I, II and III). The results are presented in the following tables.

FDP Extension: $\Delta L = AL + B$			
Single sector		A	B
Acclimatized	C1	0.333	-1
	C2	0.23	-0.689
	C3	0.091	-0.273
	R1	0.6	-1.8
	R2	0.389	-1.167
	R3	0.143	-0.429
Non-acclimatized	C1	0.25	-0.75
	C2	0.176	-0.527
	C3	0.071	-0.214
	R1	0.429	-1.286
	R2	0.289	-0.866
	R3	0.111	-0.333

Table 1: FDP extension parameters for S = 1.

FDP Extension: $\Delta L = AL + B$			
Two sectors		A	B
Acclimatized	C1	0.333	-1.667
	C2	0.23	-1.148
	C3	0.091	-0.455
	R1	0.6	-3
	R2	0.389	-1.944
	R3	0.143	-0.714
Non-acclimatized	C1	0.25	-1.25
	C2	0.176	-0.878
	C3	0.071	-0.357
	R1	0.429	-2.143
	R2	0.289	-1.443
	R3	0.111	-0.556

Table 2: FDP extension parameters for S = 2.

FDP Extension: $\Delta L = AL + B$			
Three sectors		A	B
Acclimatized	C1	0.333	-2.333
	C2	0.23	-1.607
	C3	0.091	-0.636
	R1	0.6	-4.2
	R2	0.389	-2.722
	R3	0.143	-1
Non-acclimatized	C1	0.25	-1.75
	C2	0.176	-1.229
	C3	0.071	-0.5
	R1	0.429	-3
	R2	0.289	-2.021
	R3	0.111	-0.778

Table 3: FDP extension parameters for $S = 3$.

The plots shown below represent the extended FDP (in hours) for augmented crew ($L + \Delta L$) taking the interval $9 \leq L \leq 12$h.

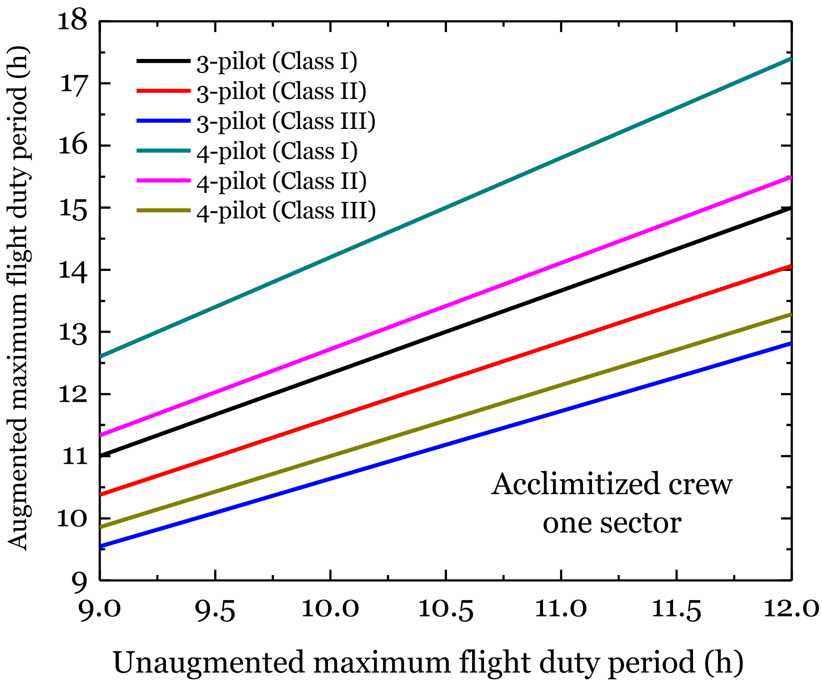

Figure 1: Extended FDP for acclimatized crew with $S = 1$.

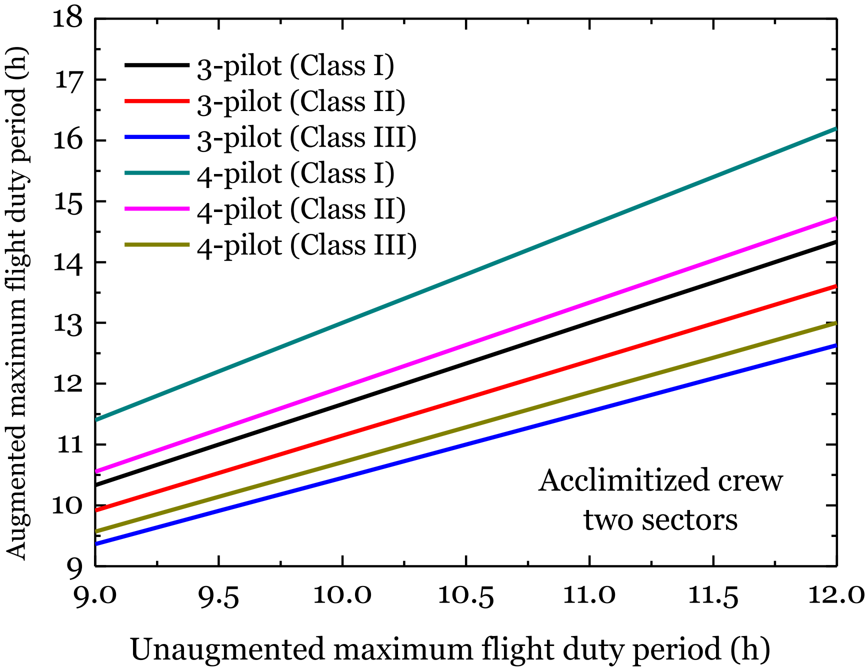

Figure 2: Extended FDP for acclimatized crew with $S = 2$.

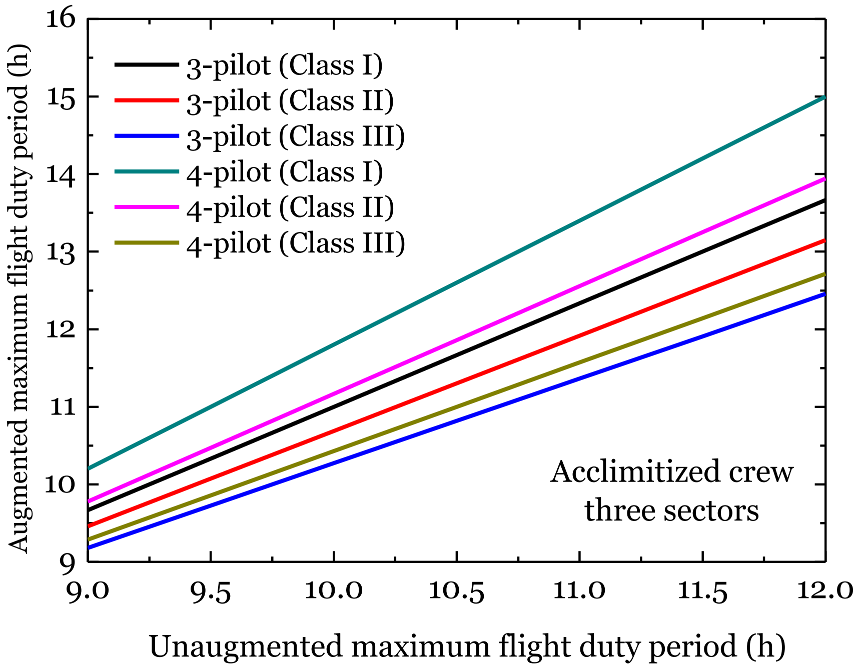

Figure 3: Extended FDP for acclimatized crew with $S = 3$.

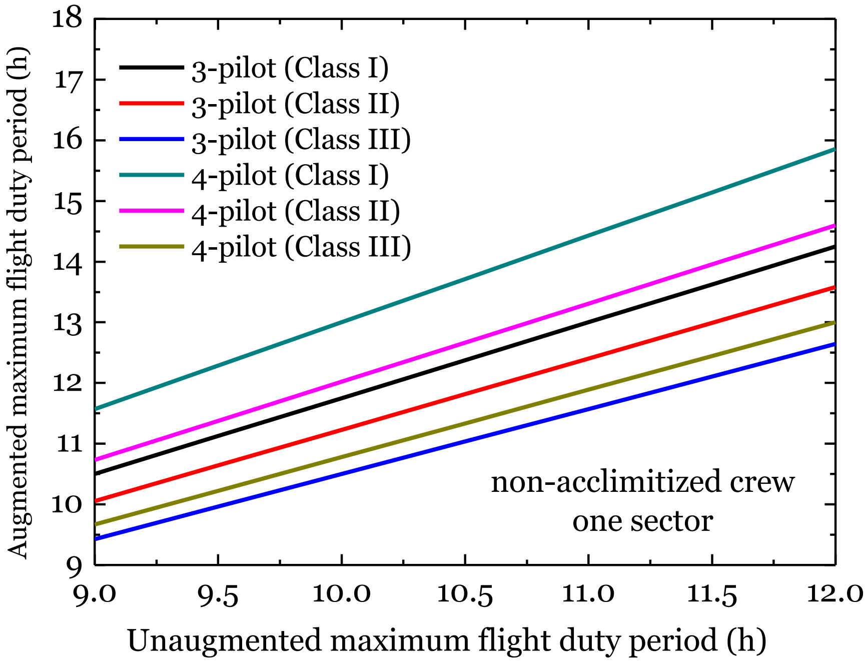

Figure 4: Extended FDP for a non-acclimatized crew with $S = 1$.

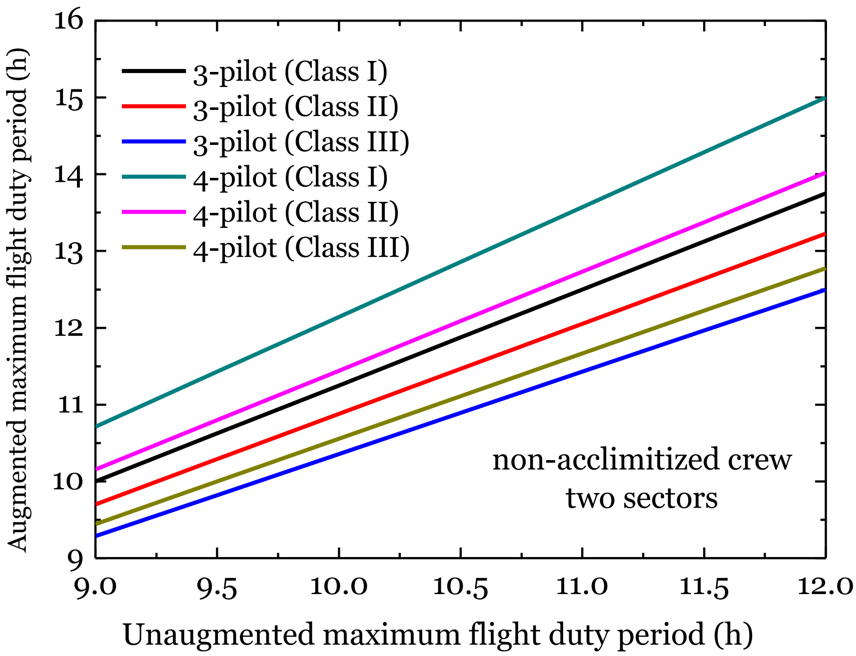

Figure 5: Extended FDP for a non-acclimatized crew with $S = 2$.

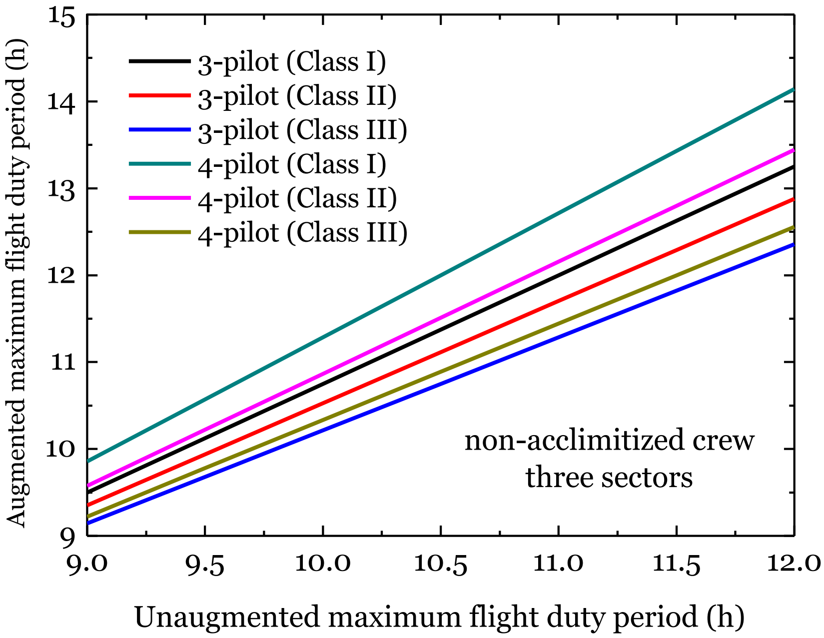

Figure 6: Extended FDP for a non-acclimatized crew with $S = 3$.

So, in order to calculate the maximum flight duty periods for augmented crew (3 and 4-pilots) for all conceivable configurations one needs to adopt the parameters presented in tables 1, 2 and 3 and the proposed limits for un-augmented crew. The latter are presented below for one or two sectors:

Check-in time (acclimatized crew)	Maximum FDP for minimum crew, *L* (h)
0000-0459	9
0500-0659	11
0700-1359	12
1400-1559	10
1600-2359	9

Table 4: Maximum FDP for minimum crew (*L*). Details in the text.

Taking the values of table 4 and the parameters of table 1 one easily obtains the maximum FDP for augmented crew for a single sector flight. The results are then presented in tables 5 (acclimatized) and 6 (non-acclimatized).

Maximum FDP (h) Acclimatized crew – single sector						
Check-in time (h)	Class I		Class II		Class III	
	3-pilot	4-pilot	3-pilot	4-pilot	3-pilot	4-pilot
0000-0459	11	12.6	10.381	11.334	9.546	9.858
0500-0659	13.667	15.8	12.841	14.112	11.728	12.144
0700-1359	15	17.4	14.071	15.501	12.819	13.287
1400-1559	12.333	14.2	11.611	12.723	10.637	11.001
1600-2359	11	12.6	10.381	11.334	9.546	9.858

Table 5: Maximum FDP for acclimatized augmented crew in a single sector flight.

Maximum FDP (h) Non-acclimatized crew – single sector						
Check-in time (h)	Class I		Class II		Class III	
	3-pilot	4-pilot	3-pilot	3-pilot	4-pilot	3-pilot
0000-0459	10.5	11.575	10.057	10.735	9.425	9.667
0500-0659	13	14.433	12.409	13.313	11.567	11.889
0700-1359	14.25	15.862	13.585	14.602	12.638	13
1400-1559	11.75	13.004	11.233	12.024	10.496	10.778
1600-2359	10.5	11.575	10.057	10.735	9.425	9.667

Table 6: Maximum FDP for non-acclimatized augmented crew in a single sector flight.

Tables 7 and 8 present the maximum FDP rounded to the nearest 15-minute interval.

Maximum FDP (h) Acclimatized crew – single sector						
Check-in time (h)	Class I		Class II		Class III	
	3-pilot	4-pilot	3-pilot	3-pilot	4-pilot	3-pilot
0000-0459	11	12 1/2	10 1/2	11 1/4	9 1/2	9 3/4
0500-0659	13 3/4	15 3/4	12 3/4	14	11 3/4	12 1/4
0700-1359	15	17 1/2	14	15 1/2	12 3/4	13 1/4
1400-1559	12 1/4	14 1/4	11 1/2	12 3/4	10 3/4	11
1600-2359	11	12 1/2	10 1/2	11 1/4	9 1/2	9 3/4

Table 7: Maximum FDP for acclimatized augmented crew (single sector) rounded to the nearest 15-minute interval.

Maximum FDP (h) Non-acclimatized crew – single sector						
Check-in time (h)	Class I		Class II		Class III	
	3-pilot	4-pilot	3-pilot	3-pilot	4-pilot	3-pilot
0000-0459	10 1/2	11 1/2	10	10 3/4	9 1/2	9 3/4
0500-0659	13	14 1/2	12 1/2	13 1/4	11 1/2	12
0700-1359	14 1/4	15 3/4	13 1/2	14 1/2	12 3/4	13
1400-1559	11 3/4	13	11 1/4	12	10 1/2	10 3/4
1600-2359	10 1/2	11 1/2	10	10 3/4	9 1/2	9 3/4

Table 8: Maximum FDP for non-acclimatized augmented crew (single sector) rounded to the nearest 15-minute interval.

The next and final step towards the determination of our proposal for the maximum FDP and FT for augmented crew in Class I rest facilities should take into account the limits being proposed by the project law 8255/14 for 3 (FDP of 12h and FT of 11h) and 4 (FDP of 16h and FT of 14h) pilots. So, assuming these values as the minimum ones, and considering that the flight time limits should be lower or equal than the flight duty period limits subtracted by two hours, one finally arrives to the figures shown in tables 9 and 10.

Maximum FDP (FT) Acclimatized crew – single sector						
Check-in time (h)	Class I		Class II		Class III	
	3-pilot	4-pilot	3-pilot	4-pilot	3-pilot	4-pilot
0000-0459	12 (11)	16 (14)	10 ½ (8 ½)	11 ¼ (9 ¼)	9 ½ (7 ½)	9 ¾ (7 ¾)
0500-0659	13 ¾ (11 ¾)	16 (14)	12 ¾ (10 ¾)	14 (12)	11 ¾ (9 ¾)	12 ¼ (10 ¼)
0700-1359	15 (13)	17 ½ (15 ½)	14 (12)	15 ½ (13 ½)	12 ¾ (10 ¾)	13 ¼ (11 ¼)
1400-1559	12 ¼ (11)	16 (14)	11 ½ (9 ½)	12 ¾ (10 ¾)	10 ¾ (8 ¾)	11 (9)
1600-2359	12 (11)	16 (14)	10 ½ (8 ½)	11 ¼ (9 ¼)	9 ½ (7 ½)	9 ¾ (7 ¾)

Table 9: Maximum FDP and FT for augmented crew (acclimatized – single sector).

Maximum FDP (FT) Non-acclimatized crew – single sector						
Check-in time (h)	Class I		Class II		Class III	
	3-pilot	4-pilot	3-pilot	4-pilot	3-pilot	4-pilot
0000-0459	12 (11)	16 (14)	10 (8)	10 ¾ (8 ¾)	9 ½ (7 ½)	9 ¾ (7 ¾)
0500-0659	13 (11)	16 (14)	12 ½ (10 ½)	13 1/4	11 ½ (9 ½)	12 (10)
0700-1359	14 1/4 (12 ¼)	16 (14)	13 ½ (11 ½)	14 ½ (12 ½)	12 ¾ (10 ¾)	13 (11)
1400-1559	12 (11)	16 (14)	11 ¼ (9 ¼)	12 (10)	10 ½ (8 ½)	10 ¾ (8 ¾)
1600-2359	12 (11)	16 (14)	10 (8)	10 ¾ (8 ¾)	9 ½ (7 ½)	9 ¾ (7 ¾)

Table 10: Maximum FDP and FT for augmented crew (non-acclimatized – single sector).

A similar procedure can be carried out for the cases of two or more sectors, but in theses cases we recommend that the operators implement an FRMS.

In order to provide plausible qualitative estimates for potential industrial/labor impacts in long haul operations in Brazil, we present in Figure 7 a comparison of the current duty time limits (Federal Law 7.183/84) with the proposed limits of table 9 for Class I and the realistic duty times for most of the medium and long haul flights in Brazil.

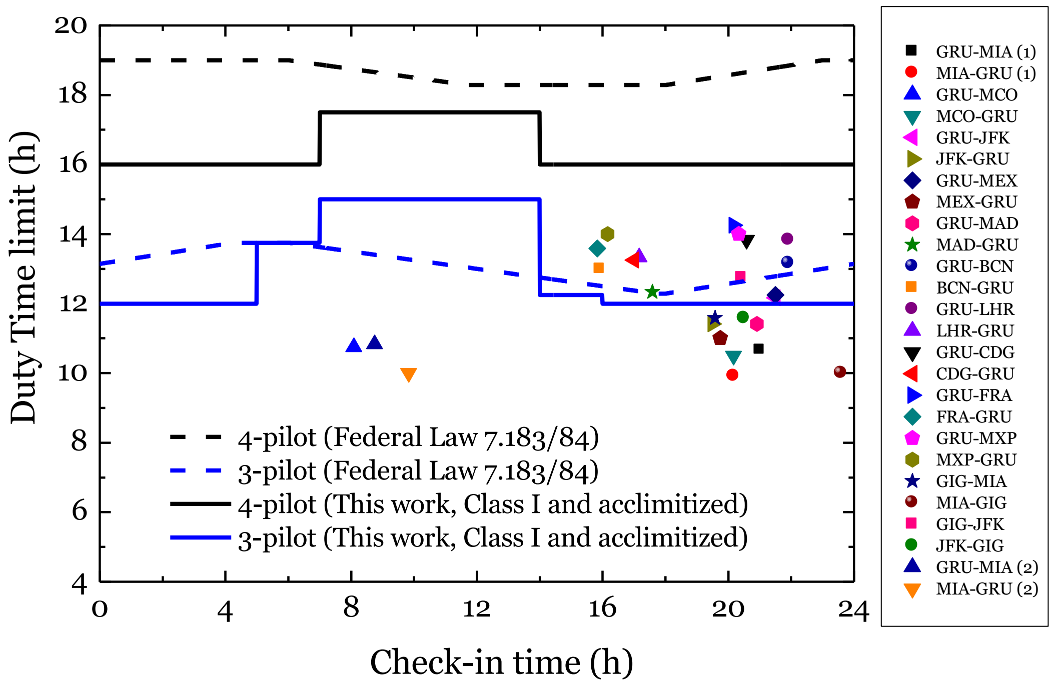

Figure 7: Duty time limits of Federal law 7.183/84 for 4 (dashed black) and 3 (dashed blue) pilots in comparison with the proposed limits for 4 (solid black) and 3 (solid blue) pilots considering Class I rest facilities and acclimatized crew. The data points represent the realistic duty times for 26 medium/long haul flights of the Brazilian air network.

As easily seen, the pilot's proposal has essentially no impact in the current air network, which is highly concentrated within check-in times from 1600 to 2200. Under this interval, the proposed limit is slightly below the current one for a 3-pilot and roughly two hours below for a 4-pilot.

Specifically for a 3-pilot crew, the flights GRU-MIA, MIA-GRU, GRU-MCO and MCO-GRU have a considerably high margin that allows the inclusion of the one hour buffer proposed by the clauses 4.2.10.1 and 4.2.10.2 (FRMS Report, Part I).

The current 4-pilot limits (dashed black line) are higher for less favorable start-times (typically within 22:00 and 06:00), which clearly demonstrates a shape problem in the Brazilian Regulation. On the other hand, the proposed limits (solid black line) do not introduce any additional cost to the operations, letting a buffer of almost two hours for the longest flight in the current scenario (GRU-FRA).

These buffers in all scenarios clearly show that the criteria proposed in sections 4.2.10.1 and 4.2.10.2 (FRMS Report, Part I) are consistently reachable by the airlines. With this new proposal the airlines, the agency and the crews will satisfy the forthcoming regulations even in the event of diverting to an alternate airport. This diversion is not fully covered by the current federal law, since it does not allow extensions in the maximum flight time per day.

It is worth-mentioning however, that the duty-time limits for 3 and 4-pilots were not studied under the context of a risk analysis and for this reason we propose that ANAC adopts the limits of tables 9 and 10 until further studies dedicated to the Brazilian circumstances shed a light on the subject.

We propose the creation of a committee of representatives of workers, airlines and regulatory agency to ensure that this study will be conducted transparently, with appropriate scientific methodology and with a deadline for conclusion.

By doing this, the Brazilian State will move towards a new regulatory framework that could be a reference for future global developments related with fatigue risk management.

Reference:

Simons, M.; Spencer, M. *Extension of flying duty period by in-flight relief*. TNO Defence, Security and Safety. TNO-DV 2007 C362. The Netherlands, 2007.