The Analysis of Occurrences Associated with Air Traffic Volume and Air Traffic Controllers' Alertness for Fatigue Risk Management

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ABSTRACT: Fatigue is an inevitable hazard in the provision of air traffic services and it has the potential to degrade human performance leading to occurrences. The International Civil Aviation Organization (ICAO) requires air navigation services which providers establish fatigue risk management systems (FRMS) based on scientific principles for the purpose of managing fatigue. To develop effective FRMSs, it is important to investigate the relationship between traffic volume, air traffic management occurrences, and fatigue. Fifty-seven qualified ATCOs from a European Air Navigation Services provider participated in this research by providing data indicating their alertness levels over the course of a 24-hour period. ATCOs' fatigue data were compared against the total of 153 occurrences and 962,328 air traffic volumes from the Eurocontrol TOKAI incident database in 2019. The result demonstrated that ATCO fatigue levels are not the main contributory factor associated with air traffic management occurrences, although fatigue did impact ATCOs' performance. High traffic volume increases ATCO cognitive task load that can surpass available attention resources leading to occurrences. Furthermore, human resilience drives ATCOs to maintain operational safety though they suffer from circadian fatigue. Consequently, FRMS appropriately implemented can be used to mitigate the effects of fatigue. First-line countermeasure strategies should focus on enough rest breaks and roster schedule optimization; secondary strategies should focus on monitoring ATCOs' task loads that may induce fatigue. It is vital to consider traffic volume and ATCOs' alertness levels when implementing effective fatigue risk management protocols.

KEY WORDS: Air traffic services; circadian rhythm; fatigue risk management; human performance; traffic volume

1. INTRODUCTION

Fatigue is a physiological state of reduced mental or physical performance capability resulting from sleep loss, extended wakefulness, circadian phase, mental, or physical workload that can impair a person's alertness and ability to perform safety-related operational duties (ICAO, 2016). ATCOs suffer from fatigue during night shifts due to a lower body temperature and circadian dysrhythmia (Tirilly, 2004). To improve aviation safety, the International Civil Aviation Organization (ICAO) requires air navigation services providers (ANSPs) to implement

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fatigue risk management systems (FRMS) from 2020. An FRMS is a data-driven means of continuously monitoring and managing fatigue-related safety risks, based on scientific principles, knowledge, and operational experience, which aims to ensure that relevant personnel are performing at adequate levels of alertness (ICAO, 2016). The U.S. National Transportation Safety Board has listed fatigue as one of its "most wanted" safety improvements continually since 1996. Extrapolating this to the wider aviation domain, it means that all staff are vulnerable to the negative effects of fatigue and are generally the worst placed to identify the problem. Fatigue risk management has demonstrated potential in preventing operational errors, incidents, and accidents within flight operations in airlines for many years (Balkin, Horrey, Graeber, Czeisler, & Dinges, 2011; Cabon et al., 2012), but thus far has not been widely implemented in ANSPs. Standardization of fatigue reporting tools and shared experiences should provide benefits across the aviation industry, enhancing the safety of operations based on shared learnings and processes. ANSPs will be able to have a better understanding of fatigue-related occurrences permitting them to develop effective fatigue mitigation strategies. The aims of this research are to evaluate air traffic controller officers' (ATCOs) operational flexibility, manage the risks related to fatigue, and improve ATCOs' safety performance based on guidelines from FRM.

2. LITERATURE REVIEW

2.1. Circadian Rhythm and Alertness

The factor influencing ATCO fatigue levels may be the amount of sleeping time lost as a result of early morning or night shifts (Roach, Sargent, Darwent, & Dawson, 2012; Samel, Vejvoda, & Maass, 2004). Specifically, human operators are estimated to lose between 15 and 30 minutes of sleep if their shift work commences prior to 09:00 in the morning (Roach et al., 2012). Moreover, if a pilot has several consecutive days of early duties, the detrimental effects of sleep loss escalate quickly, as pilots reported that they were unable to achieve good-quality sleep to compensate for the early morning duties (Samel et al., 2004). Consequently, pilots who are assigned to extended duty periods and long-haul flights beginning in the morning may be fatigued and their performance impaired during the approach and landing phases of flight if fatigue countermeasures are not implemented. The Civil aviation Authority (CAA, 2014) conducted several studies related to fatigue, various types of scheduling (day and night), and operational demands. It considered the influences of time of day, time on duty, number of flight sectors in one trip, the timing of sleep prior to duty, and the effect of consecutive late finishes on fatigue.

Subjective sleepiness can best be described as the perceived experience of the propensity to fall asleep. The experience of alertness at any given time can be defined as the capacity of the mind at that moment to respond appropriately to external and internal stimuli and may vary from moment to moment. Increasing sleepiness can also be an indicator of reduced alertness in social functioning and task performance (Moller, Devins, Shen, & Shapiro, 2006). Alertness implies a physical and mental state to process sensory information in accordance with the task demands and the goals to be achieved. Appropriate alertness allows operators an adequate degree of vigilance to be able to respond quickly to unexpected events. It has been widely recognized that low alertness or high fatigue contribute to human performance accidents in many 24/7 industries (Åkerstedt, Connor, Gray, & Kecklund, 2008; Sallinen et al., 2017), and commercial aviation is no different (Gander et al., 2013, 2015; Roach et al., 2012; Vejvoda et al., 2014). Sleep shortage and sleep disorder caused by shift work is closely associated with operator fatigue and decreasing alertness that augment the risks of accident and injury (Folkard, Lombardi, & Tucker, 2005; Mulhall et al., 2019). Across 24/7 industries, the timing and duration of work are the most critical determinants of operators' fatigue and alertness (Sallinen & Hublin, 2015; Sallinen & Kecklund, 2010). Furthermore, alertness may be affected by task difficulty and time pressure (Galy, Cariou, & Mélan, 2012). Based on the Wickens resource model (Wickens, 1984), energy or resources are needed during task performance and these resources are limited in their availability. Resource models have not only been considered in general task performance, but may also be applied to sustained attention or alertness research (Matthews & Davies, 2001; Smit, Eling, & Coenen, 2004) and adapted to aviation.

2.2. Cognitive Load Associated with Safety Performance

The definition of air traffic volume is the maximum number of aircraft entering a sector in a given length of time (Moon, Yoo, & Choi, 2011). A heavy

traffic volume may present an excessively heavy task load to an ATCO (Malakis, Kontogiannis, & Kirwan, 2010) increasing the risk of a decrease in human performance leading to an accident or incident (Rodgers, Mogford, & Mogford, 1998). United States Federal Aviation Administration (FAA) has also reported that if supplementary manpower in ATC is not provided in a timely manner, and this leads to a heavy task load, there can be an increase in accidents (FAA, 2007). Furthermore, increased traffic volumes are considered as intrinsic cognitive loads and obstructed to situation awareness, and thus to influence ATCO safety performance further (Galy et al., 2012). The process of Air Traffic Control is cognitively complex, changes in task load can have significant impacts on ATCO performance. In aviation, there have been several studies and solutions to deal with issues related to an imbalance between heavy task load and safety performance that allow senior management to be aware of the current situation and support decision making related to determining whether actions are required to further mitigate safety risks (Benitez, Del Corte Valiente, & Lanzi, 2018; ICAO, 2018; Mansikka, Virtanen, Harris, & Simola, 2016). However, there is a paucity of research in the ATC domain on human factors and task load compared with flight operations. Given that there is an increasing trend of aircraft movements, the relationship between ATCO cognitive load and safety performance deserves more attention and research (Kaber, Perry, Segall, & Sheik-Nainar, 2007; Parasuraman, Sheridan, & Wickens, 2000).

Excessive task load will occupy more attention resources leading to a decline in both task performance and safety effectiveness. There are multiple psychological and physiological mechanisms involved in attention distribution including arousal that is resulting from various inputs; activation that is defined in terms of physical readiness to respond; and effort that coordinates arousal and activation. The challenge to ATCOs is to stay awake and perform a monotonous monitoring task that requires mental effort and can deplete the pool of cognitive resources fast (Parasuraman, 1985; Pribram & McGuinness, 1975). There is an inverted U-shape relationship between task load and performance as proposed by Yerkes and Dodson (1908). With task loads increasing from easy to complex, an individual's performance will increase up to a certain point after which performance starts to decrease at the point of overloading. Many accidents or occurrences in aviation have been attributed to human performance issues

such as physical, mental, and emotional responses of the human operators who are vulnerable to organizational management issues, operational environment, and task demands (Li, Harris, & Yu, 2008; Wiegmann & Shappell, 2001). Constant increases in air traffic volumes impose demands on ATCO's cognitive load to resolve unexpected events under time pressure. Furthermore, enhanced air traffic management (ATM) systems are often promoted as the solution to accommodating expanding traffic volumes, but these often induce new challenges for the ATCO on cognitive load, fatigue, and human performance issues (Rupp, Garbarino, Guglielmi, & Lanteri, 2013).

2.3. Fatigue Mitigation for Safety Intervention

The interaction of lack of sleep and circadian factors can be especially troubling and circadian rhythms influence almost every aspect of performance (J. A. Caldwell, J. L. Caldwell, & Schmidt, 2008; Van Dongen & Dinges, 2005). In general, the quality of performance follows the pattern of our internal body temperature (a standard marker of the biological clock) in that low body temperature (often observed between the hours of 03:00 and 05:00) is associated with lower alertness, slower reaction times, and poorer accuracy than periods of higher body temperature. ATCOs performing monotonous monitoring tasks cause the aversive experience of mental effort and depleted physical resources over time. Compensating for these natural variations in body activation requires mental effort and controlled mental processing and attention. That resource might be only available for short durations (Kurzban, Duckworth, Kable, & Myers, 2013; Pribram & McGuinness, 1975). It is not surprising that night workers often perform more poorly than their daytime counterparts (Folkard & Tucker, 2003; Pribram & McGuinness, 1975). Alertness can vary in parallel with the circadian biological clock and sleep-wake cycle (Baek & Choi-Kwon, 2017; Mulhall et al., 2019). Within a 24-hour period, the output of the circadian pacemaker and the drive for sleep interact to determine the level of alertness and performance (Borbély, Daan, Wirz-Justice, & Deboer, 2016). Furthermore, due to the influence of the circadian rhythm on alertness, operator's performance can also vary from hour to hour and day to day (Lee et al., 2016; Lenné, Triggs, & Redman, 1998). For example, driving performance can vary with time of day, with performance becoming increasingly impaired during the early hours of the morning, around the time night

shift workers are commuting home (Lenné et al., 1998; Matthews et al., 2012).

Studies examining the benefits of napping, with naps from a matter of 30 seconds up to two hours, have indicated that benefits accrue to the person including maintaining cognitive performance as well as reducing sleepiness (Hartzler, 2014). Sleep loss may cause malfunctioning of arousal and activation. If this malfunctioning is not corrected by effort, there is a decrement in the performance (Sanders, 1983). Traditional explanations of the decrement of performance have addressed decreasing arousal and rising fatigue over time. The effects of time-on-task and time of test demonstrated that the effect of sleep loss is generally stronger during the afternoon and during the second session (between 10th and 20th minutes), and sleep loss affects the strategy of allocating more attention resources to the most probable location by leveling the allocation priorities (Sanders & Reitsma, 1982). Monotony on monitoring task requires compensation to stay awake. Therefore, a short break will relieve the mental effort so that it can recuperate over time. Appropriate breaks in aviation are recommended as effective in promoting fatigue recovery. Just 10–20 minutes of napping have demonstrated many positive effects on the performance, alertness, health, and happiness. Allowing a 20 minute power nap midshift will enhance memory, alertness, productivity, and creativity and will increase employees the ability to achieve optimum performance (Autumn, Monica, Jitendra, & Bharat, 2016). Several breaks under suitable circumstances with appropriate safeguards can help to ensure operational safety. However, handovers between controllers during shift change or for a break, for example, may increase the risk of occurrences. Breaks should be viewed as a fatigue risk management tool for ATCOs and the supervision of handovers for a break needs careful supervision within air traffic control units. Efforts are undertaken at many air traffic control units to reduce occurrences at these handover times that can be defined as the passing of control authority from one outgoing ATCO to another takeover ATCO (Eurocontrol, 2016; IAA, 2019). Based on the literature review, both traffic volume and ATCOs' fatigue levels have impacts on ATCOs' safety performance leading to occurrences. The specific definition of occurrence is any safety-related event that could endanger an aircraft, its occupants, or any other person and includes in particular an accident or serious incident

Table I. Frequency and Percentages of Participants' Demographical Variables Consisted with Ages, Working Experiences, and Gender

	Category	Frequency	Percentage
Age	23–30	6	10.53%
	31–40	17	29.82%
	41–50	29	50.88%
	Over 50	5	8.77%
Gender	Male	47	82.46%
	Female	10	17.54%
Experience	1–10 years	26	39.39%
	11–20 years	16	24.24%
	21–30 years	12	18.18%
	Over 30 years	4	6.06%

(Patriarca, Cioponea, Di Gravio, & Licu, 2018). There is a need to investigate the relationship between traffic volume, occurrences, and fatigue to develop effective FRMS in air traffic management.

3. METHOD

3.1. Participants

Fifty-seven qualified ATCOs from a European Air Navigation Services provider participated in this research. The ages of participants ranged between 23 and 58 years of age ($M = 41.18$, $SD = 6.52$), and their work experience varied from 1 to 38 years ($M = 17.00$, $SD = 8.10$). All participants were licensed rated air traffic controllers. The demographical variables of participants are shown in Table I.

3.2. Ethics Statement

The approval of the Research Ethic Committee was granted (CURES24702017) in advance of the research taking place. Participants were briefed that the purpose of the research was ATCO's alertness levels at controller working positions to assess fatigue and safe operations. Participants signed a consent form indicating their willingness to participate in the research. Participants were guaranteed the right to withdraw from the research at any stage. All collected data are only available to the research team and stored in accordance to the United Kingdom Ethical Code and the Data Protection Act.

Degree of Alertness	Scale Rating
Feeling active, vital, alert	7 (the highest level of alertness)
Functioning at high levels, but not fully alert	6
Awake, but relaxed; responsive but not fully alert	5
Somewhat foggy, let down	4
Foggy; losing interest in remaining awake; slowed down	3
Sleepy, woozy, fighting sleep; prefer to lie down	2
No longer fighting sleep	1 (the lowest level of alertness)

3.3. Material

3.3.1. Stanford Sleepiness Scale

The Stanford Sleepiness Scale (SSS) as developed by Hoddes, Deement, and Zarcone (1972) was used to evaluate ATCO 24-hour alertness level at the air traffic controller working positions (CWPs). SSS is used to evaluate the subjective alertness level versus sleepiness level in research and clinical settings, and it has been validated for general populations. It is a one-item self-report form to evaluate ATCO's alertness levels on task performance during each working hour, and the scale can be used repeatedly at different time intervals for measuring the effects of interventions. This research adapted the SSS to evaluate one-item (alertness level) using scoring ranges from 7 for the highest alertness to 1 for sleep onset soon (Table II). Furthermore, ATCOs were encouraged to add their comments in terms of their views of what effective countermeasures to fatigue might be and also to indicate any safety concerns at the end of the evaluation form.

3.3.2. TOKAI

The tool kit for ATM occurrence investigations (TOKAIs) is a Eurocontrol validated, web-based application that enables ATCOs to report, investigate, and take corrective actions following incidents and accidents, known as "occurrences." TOKAI is a web-based application that helps air navigation service providers (ANSPs) manage the entire air traffic safety incident investigation process: notification, investigation, storage, analysis, and reporting.

An added benefit is that TOKAI users automatically comply with EU Regulations, in particular Regulation No 376/2014 on reporting occurrences in civil aviation and Regulation No 390/2014 on the performance. Furthermore, TOKAI provides a number of statistical functions ideal for reporting, thus making it the central tool within ANSP Safety Management System (SMS). The appealing feature is that the analysis is steered by investigators who can select the occurrence data for a specific period of time, such as screening the occurrences by hours, days, months, or years.

3.4. Research Design

3.4.1. Hypotheses

Air Traffic volume and circadian rhythm may affect ATCO alertness level that has a direct impact on operational safety and the volume of accidents/incidents occurrences at certain times of the day. ATCOs are required to provide air traffic services to aircraft on 24/7 basis on five consecutive duty working days. The average of an ATCOs' alertness level shall be evaluated over a 24-hour basis and compared to the traffic volume and volume of incidents/accidents occurrences. Therefore, there are six hypotheses to be tested as follows:

> H1: There is a significant correlation between traffic volume and occurrences.
> H2: There is a significant correlation between ATCOs' alertness level and occurrences.
> H3: There is a significant correlation between traffic volume and ATCOs' alertness level.
> H4: There is a significant correlation between traffic volume and occurrences, while adjusting ATCOs' alertness level.
> H5: There is a significant correlation between ATCOs' alertness level and occurrences, while adjusting traffic volume.
> H6: There is a significant correlation between traffic volume and ATCOs' alertness level, while adjusting occurrences.

3.4.2. Procedures for Collecting ATCOs' Alertness by Focus Group

Participants were invited to join a group briefing (4-6 ATCOs per session) on the aims of this research and to complete a consent form. Participants then completed a self-reporting SSS form that recorded

their own alertness levels hourly on the working position retrospectively. After completion of the SSS, ATCOs participated in focus groups that provided qualitative research consisting of a discussion regarding their experiences, perceptions, opinions, beliefs, and attitudes toward their task loads (traffic volume), alertness level, and any safety concerns related to the new regulation on fatigue risk management from ICAO. This study conducted 12 focus group sessions and collected 57 ATCOs' operational experiences and opinions on developing FRMS related to traffic volumes and circadian rhythm. Each focus group session consisted of a new set of ATCOs (between four and six) who were encouraged to express their concerns regarding their fatigue experiences and alertness levels on working positions, the impacts of fatigue to the safety of operations and their lives and what actions, in their view, should be taken to deal with their concerns using FRMS.

The structured topics of the focus groups consisted of three main dimensions related to fatigue risk management in air traffic services domain based upon the ripple model (Morley & Harris, 2006). The first dimension "Concerns" were associated with threats to the needs of the individual ATCO and worries about meeting the requirements placed on them, including task demands, station manager responsibility, traffic volume, circadian rhythm, and experiences of error or incidents. The second dimension "Influences" were concerned with the factors that dictated the approaches by which safety requirements could be accomplished, including mitigating the negative effects of fatigue by meal breaks and fatigue breaks, roster flexibility, balance between duty hours, and personal time. The third dimension "Actions" were related to ATCOs' communication and responses to their concerns that directly impacted upon operational safety in either a positive or negative manner, including how to provide ATCOs with education and training to increase alertness levels, how to develop an suitable FRMS, and how to seek available supports for fatigue interventions. Participants were encouraged to express their "Concerns," "Influences," and "Actions" for developing an effective FRMS from different points of view including line operators, middle management, senior management, and the industry regulator as a whole (Fig. 1). This collected information was then compared with accidents/incidents reports from the TOKAI system based on 24 hours of occurrence data.
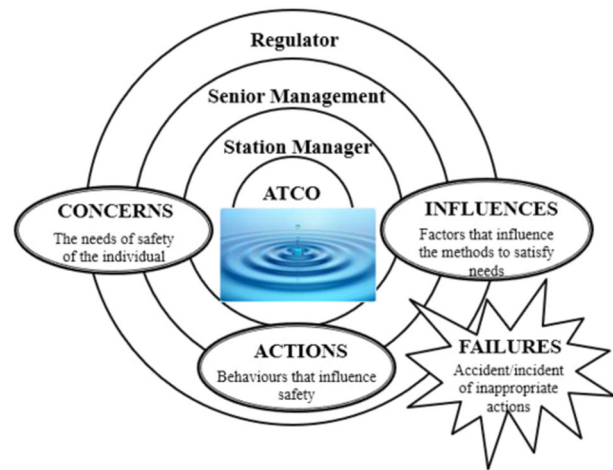

Fig 1. The structured topics on focus group comprised with three dimensions: concerns, influences, and actions to develop effective fatigue risk management system.

3.4.3. *Algorithms of Occurrences on 24 Hours Basis*

TOKAI has a user-management system and allows users to be allocated to a specific role, such as investigator, viewer, administrator, reporter, etc. There is a large degree of flexibility in defining these roles and there is practically no limit to drawing up reporting and investigation templates. ATCOs fill in these templates with their occurrence data, which are then stored in a database. Investigators can then use this information to make further statistical analyses and create periodic or individual reports including time and date of occurrences, contributing factors, the nature of occurrences, and circumstances of the event. In this case, the main interest of the analysis algorithm is the time of these 153 occurrences in 962,328 flights on 24 hours basis for the year 2019. The algorithm of occurrences includes five safety performance indicators, separation minima infringements, runway incursions, aircraft deviations from ATC clearance, level busts, and airspace infringements. The rates refer to occurrences defined per 100,000 flight hours for separation minima infringements, aircraft deviations from ATC clearance, level busts and airspace infringements, and per 100,000 movements for runway incursions.

3.5. Statistics Analysis

The paired correlation among ATCO alertness, traffic volume, and occurrences (H_1, H_2, and H_3)

Table III. ATCOs' Alertness Levels, Occurrences, and Traffic Volume Divided into 24 Hours

Hour	Alertness Level	Occurrences (Total)	Traffic Volume (Average)	Annual Traffic Volume (Total)
1	4.09	0	12.5	4,563
2	3.71	0	22	8,030
3	3.35	3	54	19,710
4	2.95	4	109	39,785
5	3.91	8	125	45,625
6	5.00	8	181	66,065
7	5.34	8	168.5	61,503
8	5.95	6	160	58,400
9	6.17	16	168.5	61,503
10	6.31	16	177.5	64,788
11	6.45	8	198	72,270
12	6.45	9	168	61,320
13	6.36	6	173.5	63,328
14	6.26	12	142	51,830
15	6.25	9	130.5	47,633
16	6.20	13	124.5	45,443
17	6.07	9	121	44,165
18	5.97	5	107	39,055
19	5.81	5	85	31,025
20	5.53	3	70.5	25,733
21	5.00	2	58.5	21,353
22	4.82	2	39.5	14,418
23	4.51	1	22.5	8,213
24	4.26	0	18	6,570
M	5.28	6.38	109.85	40,097
SD	1.09	4.73	59.86	21,847.84

was tested using the Pearson correlation analysis. Moreover, the normality assumptions of three variables were tested by quantile–quantile (Q-Q) plots (Gnanadesikan & Wilk, 1968). However, a strong Pearson correlation does not necessarily mean that there is a strong direct correlation between two variables (Kenett, Huang, Vodenska, Havlin, & Stanley, 2015). For example, ATCO alertness level and traffic volume over the 24 hour period can both be related to occurrences. To investigate the direct effects of correlation between ATCO alertness and occurrences, the common factor traffic volume should be controlled. Partial correlation can quantify the correlation between two variables when conditioned on one or several other variables, as partial correlation is a measure of the strength and direction of a linear relationship between two continuous variables while controlling for the effect of additional variables (Baba, Shibata, & Sibuya, 2004). Therefore, partial correlation analyses were carried out to explore the key factors related to occurrences as the main indicator of safety performance (H_4, H_5, and H_6).

4. RESULTS

4.1. Sample Characteristics

There are three variables including ATCO alertness level (V1), occurrences (V2), and traffic volume (V3) per working hour (Table III). The alertness levels of 57 ATCOs' self-reported SSS rating are $M = 5.28$, $SD = 1.09$. The traffic volume extracted from the official EUROCONTROL Network Manager archive ($M = 109.85$, $SD = 59.86$), and TOKAI data for occurrences ($M = 6.38$, $SD = 4.73$) in a 24-hour basis. According to the Q-Q plot tests, the plotted dots of 24-hour alertness level (i), occurrences (ii), and traffic volume (ii) face with the reference line (red) (Fig. 2), which indicates that these three variables meet the normality assumption approximately (Das & Imon, 2016).

ATCOs' alertness levels vary over the 24-hour cycle depending on the influence of the circadian biological clock. Generally, ATCOs have lower alertness levels during the late night and early morning
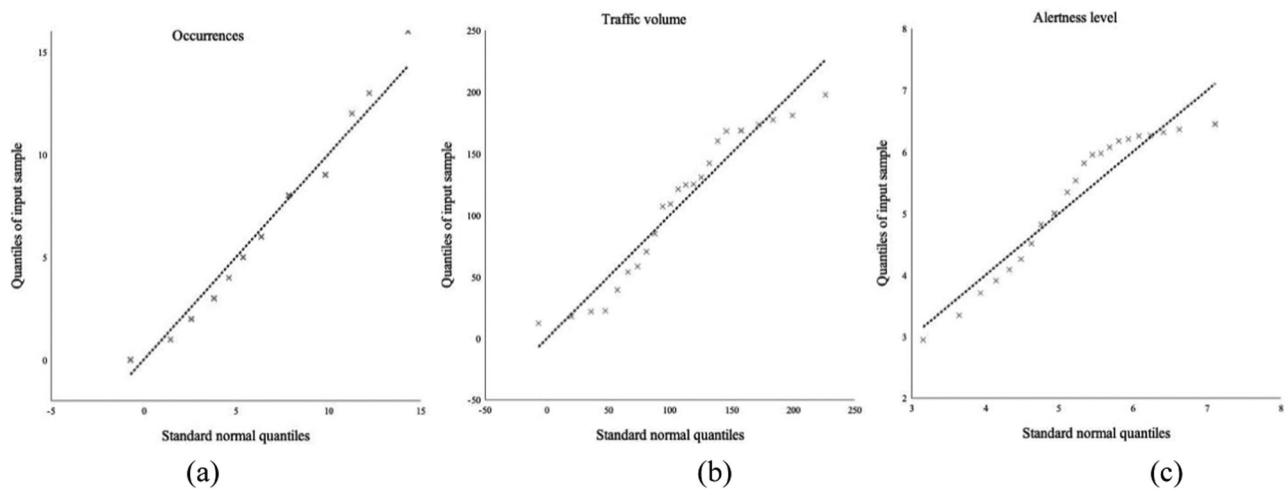
Fig 2. Normal Q-Q plots of sample data versus theoretical distribution of occurrences (a), traffic volume (b), and alertness level (c). The *X*-axis shows the quantile of the standardized normal distribution, *Y*-axis shows the quantiles of sample data distribution, and the reference line represents approximately standardized normal distribution. The dots compare the quantiles of sample data distribution with the quantiles of the theoretical normal distribution. In these three normal Q-Q plots, the plotted dots lie close to and approximately distribute evenly on both sides of the reference line, which indicates that these data sets met the normal distributions.
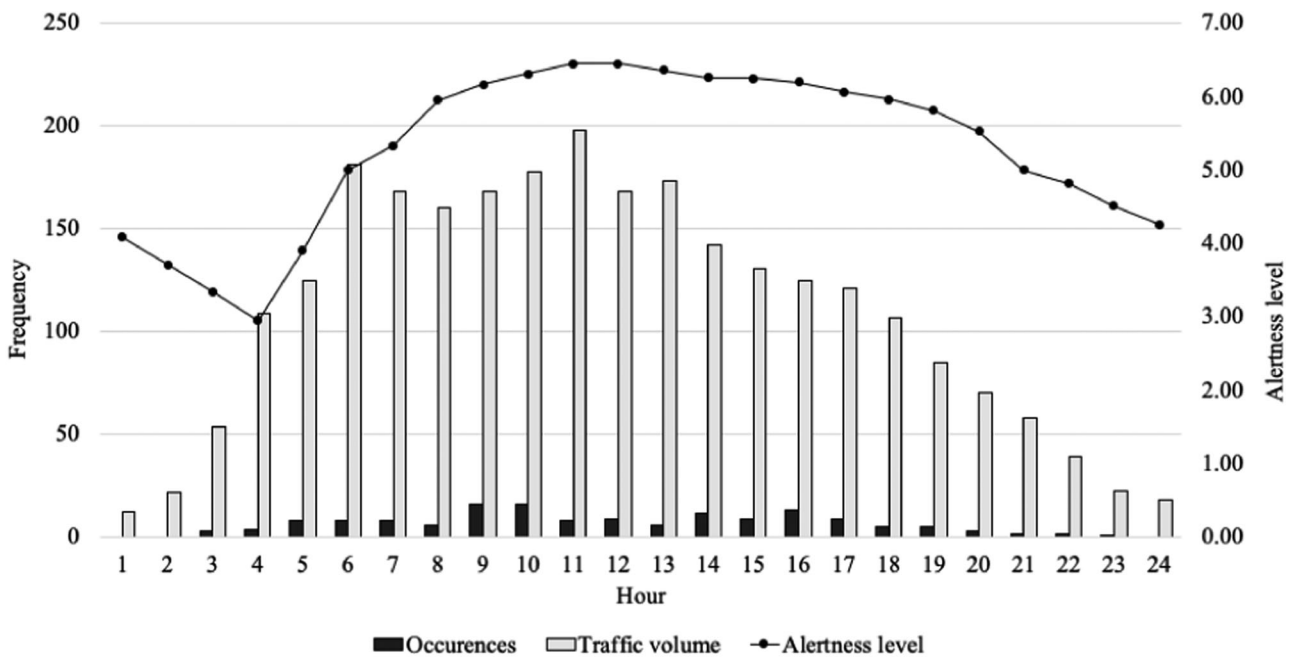

Fig 3. The fluctuation of traffic volume (gray column), occurrences (black column), and ATCOs' alertness level (black dot) in 24 hours. Traffic volume related to cognitive loads and alertness levels represent circadian rhythm, both traffic volume and ATCOs' alertness have to be considered to develop effective FRMS.

(Table III). However, ATCOs must provide air traffic services on a 24 hour basis, occurrences over this period (black bar in Fig. 3) may relate to low alertness and high fatigue levels at night (dotted line in Fig. 3) and high traffic volumes during the day (gray bar in Fig. 3). To develop effective FRMS, it is essential to investigate the relationship between traffic volume and fatigue associated with occurrences.
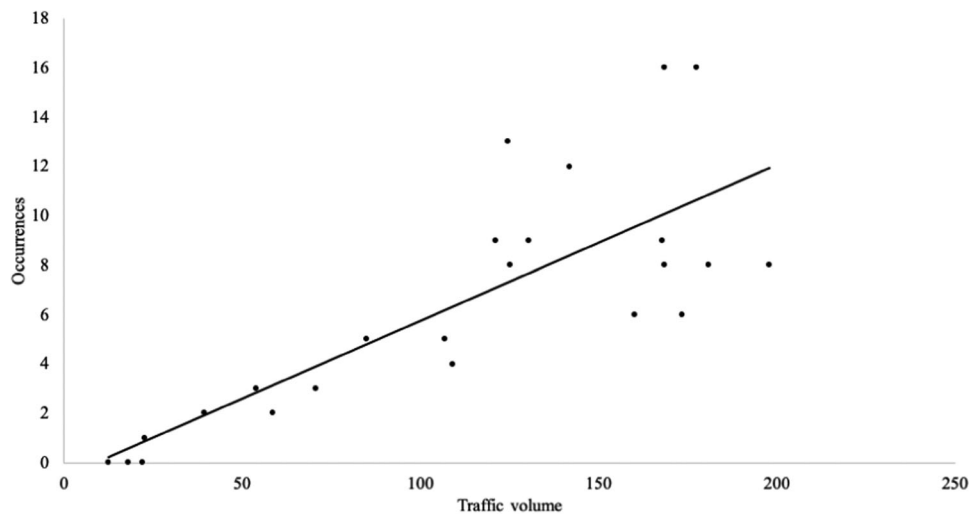
Fig 4. The scatterplots of traffic volume and occurrences: the plotted dots show the traffic volume (*X*-axis) and occurrences (*Y*-axis) distributed evenly on both sides of the straight trend line, which demonstrates a positive linear correlation between traffic volume and occurrence.

4.2. Relationships between Traffic Volume and Occurrences

The results of Pearson correlation analysis show that there is a strong, positive relation between traffic volume and occurrences, r (22) = 0.799, $p < 0.001$. Therefore, the "H_1: there is a significant correlation between traffic volume and occurrences" is supported. Furthermore, a partial correlation analysis was run to determine the direct relationship between traffic volume and occurrences while controlling for ATCOs' alertness level. It does suggest some influence of positive partial correlation between traffic volume and occurrences while controlling for alertness level, r (21) = 0.649, $p < 0.01$. Therefore, the "H_4: there is a significant correlation between traffic volume and occurrences, while adjusting ATCOs' alertness level" is supported. The correlation between traffic volume and occurrences is shown in Fig. 4.

4.3. Relationships between ATCOs' Alertness Level and Occurrences

According to Pearson correlation analysis, there is a significant positive correlation between ATCOs' alertness and occurrences, r (22) = 0.654, $p < 0.01$. Therefore, the "H_2: there is a significant correlation between ATCOs' alertness level and occurrences" is supported. Furthermore, the result of partial correlation, r (21) = 0.292, $p = 0.177$, demonstrates no sig-

nificant correlation. Therefore, the "H_5: there is a significant correlation between ATCOs' alertness level and occurrences, while adjusting traffic volume" is not supported. The correlation between occurrences and ATCOs' alertness is shown in Fig. 5.

4.4. Relationships between Traffic Volume and ATCOs' Alertness Level

There is a significant correlation coefficient between traffic volume and ATCOs' alertness level, r (22) = 0.652, $p < 0.01$. Therefore, the "H_3: there is a significant correlation between traffic volume and ATCOs' alertness level" is supported. Furthermore, a partial correlation analysis was carried out to test the direct relationship between traffic volume and alertness level while controlling for occurrences. The result shows that there is no significant correlation, r (21) = 0.285, $p = 0.187$. Therefore, the "H_6: there is a significant correlation between traffic volume and ATCOs' alertness level, while adjusting occurrences" is not supported. The correlation between traffic volume and alertness level is shown in Fig. 6.

4.5. Summary of Fatigue Risk Management on Focus Groups

ATCOs must provide air traffic services on a 24-hour basis against the circadian rhythm; however, task demands related to traffic volumes diverge throughout the day with different challenging
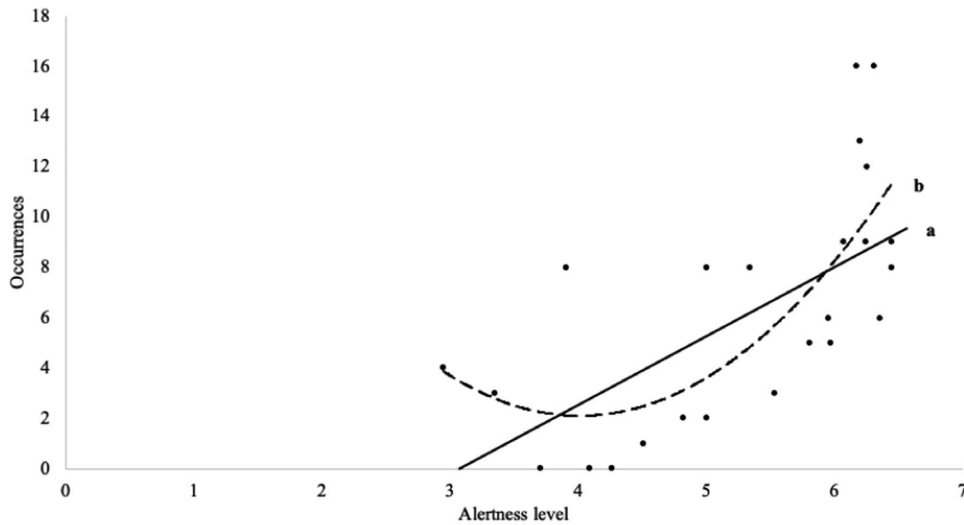
Fig 5. The scatterplots of alertness level and occurrences: the plotted dots show the alertness level (*X*-axis) and occurrences (*Y*-axis) distributed evenly on both sides of the straight trend line (solid line, a), which indicates a positive linear correlation between alertness level and occurrences; however, partial correlation analysis shows a nonlinear correlation between alertness level and occurrences essentially. Therefore, the correlation between these two variables can be plotted more appropriately as a multinomial distributed trend line (dashed line, b).
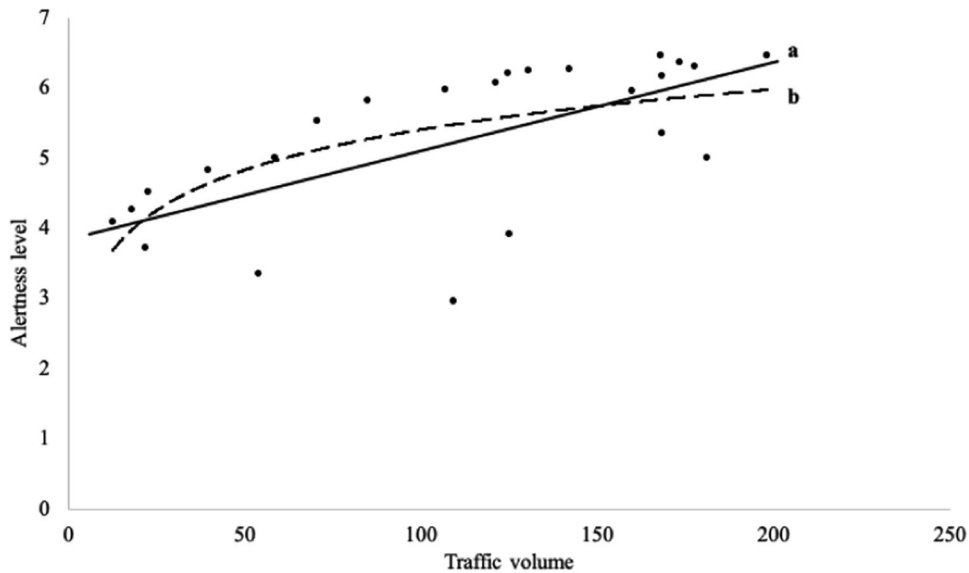

Fig 6. The scatterplots of traffic volume and alertness level: the plotted dots show the traffic volume (*X*-axis) and alertness level (*Y*-axis) distributed evenly on both sides of the straight trend line (solid line, a), which indicate a positive linear correlation between traffic volume and alertness level; however, partial correlation analysis shows nonlinear correlation between traffic volume and alertness essentially. Therefore, the correlation between these two variables can be plotted more appropriately as a multinomial distributed trend line (dashed line, b).

scenarios. FRMS permits ATCOs' opinions to be integrated into scheduling systems and policies. ATCOs expressed their concerns and interests related to fatigue risk management during focus group sessions.

Furthermore, ATCOs propose the ideal actions and strategies that could be taken at an individual level and organizational level to mitigate fatigue. The following were the key points from the focus groups:

(1) Fatigue-related safety concerns: Shift work is a significant issue to senior ATCOs; the effects of shift work become cumulative and impact their safety and health due to sleep quality and quantity; night shift caused ATCO's cognitive lock up, not able to drive home after shift; rest facilities needed improvement; five shifts and three off roster needed to be more flexible; fatigue symptoms related to incidents needed to be investigated for training purposes; the design of quiet rooms for ATCOs to snooze is critical to operational safety; the transit time to and from work/home at second shift and fifth shift presented safety concerns.

(2) The Influences of fatigue: Fatigue influences everything, both work and domestic issues; traffic volume and circadian rhythm influenced ATCOs fatigue levels; sufficient staffing and scheduling of breaks increased alertness; domestic life impacted fatigue level at works; the balance of shifts influenced competency issues, if ATCOs only did night shifts, they would be not equipped to deal with high-level traffic during day operations; the percentage of gender balance can facilitate better teamwork and a mix of ages on the roster; managers need to understand that fatigue is inevitable.

(3) Actions to mitigate fatigue: Discussions were ongoing at managerial level with regard to installing sleeping pods in rest areas; it would also be a good idea to allow people to get some rest before leaving work and driving long distances home between fourth shift and fifth shift; 20 minutes of nap significantly increased alertness; providing gym fitness training and mindfulness courses to ATCOs; good kitchen facilities for a cup of tea can mitigate fatigue; education required to identify individual fatigue and colleagues suffering from fatigue; positive teamwork can assist in identifying team members who may be suffering fatigue.

5. DISCUSSION

5.1. High Traffic Volume Increasing Cognitive Complexity Leading to Occurrences

Air Traffic controllers must intervene to resolve unexpected disturbances in the working environment and their performance has become one of the most significant elements in preventing events such as runway incursions, aircraft deviations from ATC clearance, level busts, and airspace infringements. Based on the ANSP's statistical analysis (Table III), the average traffic volume deviated from minimum of 12.5 at 1 a.m. to maximum of 198 at 11 a.m. However, the frequency of occurrences fluctuated from 0 at 1 a.m. to the highest of 16 at 10 a.m. It reveals that ATCOs' task load varied significantly over the 24-hour traffic sample. A safety performance indicator is defined in the ICAO Safety Management Manual (ICAO, 2018) as a measure used to represent the level of safety performance achieved in ATM system. They are generally expressed in terms of the frequency of occurrences of harmful event causing damage, e.g., the number of midair crashes, near missed or serious incidents.

The threshold of traffic volume is defined as the average of the flight per hour which is 109 in this study (Table III). The trend of increasing traffic volume starts from 109 flights at 4 a.m. to the peak of 198 flights at 11 a.m., and then gradually decreasing to 121 flights at 5 p.m. Traffic volume is above 150 flights per hour between 6 a.m. and 1 p.m. with the highest occurrence rates of 16 is at both 9 a.m. with 168.5 flight and 10 a.m. with 177.5 flight (Table III). There is a strong positive correlation between traffic volume and occurrences ($r = 0.799$, $p < 0.001$), which means increasing traffic volume means increasing occurrences (Fig. 4). It is arguable that the confounding variable of fatigue might also have a contribution to occurrences (Cabon et al., 2012). To investigate the relationship between traffic volume and occurrences while controlling the effect of ATCOs' fatigue/alertness, the partial correlation is applied to fulfill the objective of measurement. The partial correlation denotes that there is a significant correlation between traffic volume and occurrences while adjusting ATCOs' alertness level ($r = 0.649$, $p < 0.01$). This result suggests that "ATCOs' alertness level" had no influence in the relationship between "traffic volume" and "occurrences," and traffic volume had significant positive association with occurrences. Accurate traffic volume assessment as well as prompt interventions such as the timely opening of more air traffic control sectors and enhanced system tools are proposed as strategies to control traffic volumes.

5.2. Occurrence Correlated with Traffic Volume While Adjusting ATCOs' Alertness

The provision of ATCOs' shift works can drive physical and mental fatigue frequently. However, ATCOs have to maintain high levels of alertness particularly at busy times either in the early morning or late in a day. According to the data retrieved from TOKAI, ATCOs' alertness levels fluctuate with traffic volume and occurrences over a 24-hour basis (Fig. 4). The results confirmed that ATCOs maintained high alertness levels during the highest traffic volumes between 6 a.m. and 2 p.m. This finding indicates busy traffic volumes activated ATCOs' alertness levels and mitigates the impact of fatigue that is consistent with the previous research on three physiological systems proposed by Pribram and McGuinness (1975). Air traffic controllers must provide 24-hour service to international flights. Shift work has disturbed ATCOs' circadian rhythm and causes it to be out of synchrony with the day–night cycle. This can be a significant factor impairing monitoring performance and reducing alertness levels. The impact of disturbed circadian rhythms would have a negative impact on sleep quality, which, in turn, could result in increased chronic fatigue (Barton, Spelten, Totterdell, Smith, & Folkard, 1995) and negatively influence alertness and task performance (Riethmeister, Bültmann, De Boer, Gordijn, & Brouwer, 2018). The nature of ATCOs' shift work induces circadian dysrhythmia and can cause the breakdown of arousal and activation that can impair ATCOs' performance if this breakdown is not be corrected by effort (Pribram & McGuinness, 1975; Sanders, 1983). ATCOs' alertness levels increase from 9 a.m. (6.17) to a peak at 12 p.m. (6.46), and then gradually decrease as the afternoon progresses to 6.07 at 5 p.m. (Table III). This finding conforms with previous research by Sanders and Reitsma (1982), due to the decreasing arousal and raising fatigue over time, the effects of time-on-task, and time of task performance declined during the afternoon and during the second session of work.

There is a significant positive correlation between ATCO alertness level and occurrences, which denotes that as ATCO alertness levels increase, occurrences also increase (Fig. 5). The finding is not consistent with previous research that showed that high alertness was related to better performance (Aidman, Chadunow, Johnson, & Reece, 2015; Galy & Mélan, 2015; Sallinen et al., 2017). The result of partial correlation to measure the strength of correlation between ATCO alertness and occurrences while controlling the effect of traffic volumes demonstrated that there is no significant effect. Traffic volume had an influence in adjusting the relationship between "ATCO alertness" and "occurrences." It may be that excessive traffic volumes not only activated ATCOs' alertness levels but also induced high perceived workload thereby jeopardizing safe performance. Previous research demonstrated that there are many human factors issues that contribute to occurrences, such as the concept of "many to one" (Harris & Li, 2019; Reason, 1997). It would be rare for an occurrence to have a single cause of fatigue. Therefore, FRMS should be developed that can support ATCOs' cognitive capacity to deal with shift works and provide appropriate short breaks to recover from depletion.

5.3. Task Demands and Circadian Rhythm Impacted to ATCOs' Alertness

Traffic volume is a direct indicator of ATCO cognitive task demand and this can fluctuate on an hourly basis. ATCO alertness level has been proven to be closely linked with task load and circadian rhythm (Caldwell, et al., 2009). In this research, ATCO alertness patterns were consistent with the variation of human's circadian rhythm showing the maximum alertness level (6.46) at 12 p.m. and the lowest alertness level at 4 a.m. (Table III). Pearson correlation shows a significant effect between traffic volume and ATCOs' alertness ($r = 0.652$, $p < .01$), but no significant effect on partial correlation by adjusting occurrences ($r = 0.285$, $p = 0.187$) (Fig. 6). This result indicates that ATCO alertness levels vary over a 24-hour period independent of traffic volume, and there may be other factors causing the variation of alertness levels, such as circadian rhythm and operational environment (temperature, lighting, noise, and CWP). Previous research has indicated that subjective alertness and fatigue varied in parallel with the circadian biological clock and sleep–wake cycle (Baek & Choi-Kwon, 2017; Mulhall et al., 2019), time-on-task, and time of day (ICAO, 2016). The lowest alertness level (2.95) was detected at 4 a.m., which coincides with a low body temperature as per circadian rhythm, whilst experiencing a challenging traffic volume (109) (Fig. 3). On this basis FRMS should particularly consider the mitigations to support ATCO's during this high risk time. Disturbed circadian rhythms have a negative impact on sleep quality, which, in turn, would result in ATCOs' increased chronic fatigue (Barton et al., 1995).

Current models of sleepiness and alertness in the context of sleep–wake patterns incorporate a two-process model based on circadian and homeostatic processes. These physiological factors may have an impact on ATCOs' safety performance and occurrences. ATCOs can maintain a better level of alertness if they have a general idea of what will be expected of them. Therefore, duty start times should be predictable and consistent while developing fatigue risk management programs (ICAO, 2016). An effective fatigue risk management program should take the impact of shifts worked and the effects of circadian rhythm into account by prescribed limits on hours of work and numbers of breaks during daily work. Methods of boosting alertness such as frequent and adequate breaks should be considered by ANSP's in the development of FRMS as barriers to fatigue. Previous research has indicated that disengagement from monotonous tasks for even short periods can support operators fending off fatigue. When using breaks as a fatigue countermeasure, ATCOs have suggested increasing the numbers of shorter breaks (i.e., 10–15 minutes) that can increase alertness, attention, memory, and achieve the optimum performance. This finding is consistent with previous research proposed by Autumn et al. (2016).

5.4. The Characteristics of Human Performance for Fatigue Risk Management

FRMS need to extend beyond a simple analysis of roster cycles, shift work, sleeping hours, breaks, task load, and circadian rhythm to also consider the overall operational environment of the air traffic management. It offers a way to safely schedule air traffic controllers to provide air traffic services beyond simply complying with existing regulatory limits of duty time and rest period regulation. The findings of this research are in line with the previous research, demonstrating that task difficulty and time pressure were considered as intrinsic cognitive loads and noted to have interactions with alertness (Galy et al., 2012); increasing traffic volume on the peak hour corresponded to a high task demand that could increase ATCO task load and the potential for occurrences (Eurocontrol, 2003; Moon et al., 2011). The statistical analysis demonstrated that there are significant correlations between alertness, traffic volume, and occurrences. However, only traffic volume shows a significant relationship with occurrences while adjusting the variable of alertness. In this study, high traffic volume represents high task load

that has shown positive correlations with occurrences (Fig. 4). Therefore, it implies that high traffic volumes increase task complexity surpassing ATCO's capacity to maintain optimal safety performance and increases the risk of occurrences. FRMS should be integrated with appropriate fatigue countermeasures considering the circadian rhythm of the ATCO beyond the basic roster patterns. Fatigue should be recognized as a factor in the provision of air traffic services. Therefore, it is important that science-based fatigue risk management tools are applied to protect the integrity of the system at all times. Initial countermeasure strategies should focus on sufficient breaks and schedule optimization; secondary strategies should focus on monitoring ATCOs' task loads that may induce fatigue; and finally, FRMS should be balanced between cost and benefits in the ANSPs.

6. CONCLUSION

Fatigue is an inevitable hazard in the provision of air traffic services and fatigue has the potential to degrade human performance and lead to occurrences. ANSPs must establish FRMS that aim to ensure that ATCOs are performing at adequate levels of alertness based on scientific principles and operational experiences. These basic principles should consider traffic volume and circadian effects on human performance, as ATCOs can only work for a limited period of time, after that a fatigue recovery break is required. It is vital to consider traffic volume and ATCOs' alertness levels when implementing effective fatigue risk management protocols. High traffic volumes increase ATCO cognitive task loads sometimes beyond ATCO attentional capacity leading to occurrences. Fatigue risk should be managed to an acceptable level through consideration of circadian effect and applying scientific knowledge to appropriate rostering and scheduling of breaks; controlling suitable traffic volume in a sector; and human-centered design of CWPs. Important considerations for ANSP's are the balance of proper countermeasures to ensure safety of service and the cost benefits of implementation of such measures against continued pressure from regulators and airlines for reduced costs and maintain same level of safety performance.

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DECLARATION OF INTEREST STATEMENT

The authors declared that they have no commercial or associative interest that represents a conflict of interest in connection with the work submitted.

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