*Human Factors in Design, Engineering, and Computing*, Vol. 238, 2026, 2432–2440
https://doi.org/10.54941/ahfe1008468

# A Replicable Two-Phase Field Protocol for Assessing Fatigue Risk in Aircraft Line Maintenance: Design and Operational Applicability

**Mundhir Nasser Ali Al Alawi[1], Ashish Kumar Singh[2], Noraisikin Sabani[3], and Jundika Candra Kurnia[4,5]**

[1]Faculty of Engineering and Science, Curtin University Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia
[2]Department of Design, Indian Institute of Technology Kanpur, Uttar Pradesh 208016, India
[3]General Studies Department, Faculty of Humanities and Health Sciences, Curtin University Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia
[4]Department of Mechanical and Mechatronic Engineering, Faculty of Engineering and Science, Curtin University Malaysia, CDT 250, 98009 Miri, Sarawak, Malaysia
[5]Centre of New and Sustainable Energy Research and Ventures (CoNSERV), Curtin University, CDT 250, 98009 Miri, Sarawak, Malaysia

## ABSTRACT

Fatigue is a recognised contributor to error in aircraft maintenance, yet operators lack a practical, standardised way to assess it, and fatigue research has concentrated on flight crew rather than on maintenance personnel. This paper presents the design of a replicable two-phase field protocol for assessing fatigue risk in aircraft line maintenance and sets out the operating conditions under which it is most valuable. The protocol was developed in an Omani line-maintenance context and is designed to transfer to other operators; this paper presents the method, not country-specific data. Phase 1 is an environmental field-measurement procedure: twenty-one pre-flight inspection checkpoints on the Airbus A320, drawn from the Aircraft Maintenance Manual and grouped into three zones, are assessed for sound pressure level and illuminance using calibrated instruments against recognised occupational limits. Phase 2 is a structured self-report survey pairing two validated instruments, the Epworth Sleepiness Scale and the Fatigue Severity Scale, with exposure items across four domains (roster, sleep/wake, environmental and psychosocial), scored into a fatigue-likelihood index. The protocol is low-cost, tool-light and reproducible by an operator's own safety team. We describe the instruments, checkpoint mapping, scoring logic and data-handling steps, and set out where the approach applies best: hot-climate, high-daylight line operations implementing safety management systems. The protocol has since been executed in full across ten aircraft and 236 maintenance workers, demonstrating operator-scale feasibility; the empirical results are reported separately in companion manuscripts. It offers maintenance organisations a first step toward a fatigue risk management system for line maintenance.

**Keywords:** Fatigue risk management, FRMS, Aircraft maintenance, Field measurement, Occupational safety, Safety management systems, Human factors

Received September 22, 2026; Revised October 24, 2026; Accepted November 5, 2026; Available online December 1, 2026

© 2026 The Authors. This work is licensed under a Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 License.
For more information, see https://creativecommons.org/licenses/by-nc-nd/4.0/

## INTRODUCTION

Aircraft maintenance is safety-critical work carried out around the clock, and fatigue has long been recognised as a contributor to maintenance error (Gramopadhye & Drury, 2000; Hobbs et al., 2011). Maintenance error remains a recurrent factor in accidents and serious incidents (Hobbs et al., 2011; Marais & Robichaud, 2012). Yet most of what is known about fatigue in aviation comes from the flight deck. Studies of the maintenance workforce remain few, and the maintenance environment is still less well described than the flight deck (da Silva et al., 2024).

The response to fatigue risk in safety-critical industries is well established. A fatigue risk management system (FRMS) treats fatigue as a hazard to be managed through rostering, organisational controls and monitoring, not through working-hour limits alone (Lerman et al., 2012; Sprajcer et al., 2025). Aviation has adopted this approach within its safety management framework (International Civil Aviation Organization, 2016), but largely for pilots and cabin crew; the safety performance indicators and biomathematical models in use were built around flight-duty patterns (Gander et al., 2014; Devine et al., 2025). Maintenance organisations have been offered principles and countermeasures (Hobbs et al., 2011; Miller et al., 2023). What they have not been given is a field procedure: a way for an operator to measure its own inspection environment and its own workforce with its own staff. Practical guidance of that kind is limited (Hobbs et al., 2011; da Silva et al., 2024).

Two obstacles remain. The first is that maintenance fatigue has several causes at once. Roster structure and sleep restriction act on the worker, while noise and lighting in the working environment, which often fall outside recommended levels, act on the task itself (Bosley et al., 2005). No single measure captures the combination. The second is practical. Operators lack a standardised, affordable procedure they can run without consultants or a laboratory. This paper addresses the second obstacle. It sets out the design of a two-phase field protocol for assessing fatigue risk in aircraft line maintenance: an environmental measurement phase for the shared workplace and a survey phase for the individual worker. It then describes where the protocol is most useful. The empirical results are reported separately; the contribution here is the method and the case for using it.

## OVERVIEW OF THE TWO-PHASE PROTOCOL

The protocol separates the shared physical environment from the individual worker. Phase 1 measures the noise and lighting conditions of inspection at fixed checkpoints on the aircraft, independent of any individual. Phase 2 records each worker's exposure, sleep/wake history and psychosocial load in a short, structured survey and combines them into a fatigue-likelihood index. The two phases are separate so that an operator can run Phase 1 once, to characterise its fleet, and then repeat the low-burden Phase 2 survey at intervals. Both phases use inexpensive, widely available instruments, and

an operator's own safety or human-factors team can run them without a laboratory. Because the checkpoints and instruments are standardised, the protocol is intended to transfer to other line-maintenance operators. Table 1 summarises the instruments, measurement points and outputs of each phase.

**Table 1:** Summary of the two-phase field protocol.

| Element | What is Measured | Instrument / Tool | Reference Standard |
|---|---|---|---|
| Phase 1 – noise | Mean SPL at 21 checkpoints (3 zones), four directions at ear level | Calibrated Type 2 sound level meter | NIOSH REL 85 dBA (8-h TWA); OSHA PEL 90 dBA |
| Phase 1 – light | Illuminance at each checkpoint, morning / afternoon / evening | Calibrated illuminance meter | EN 12464-1 maintained illuminance (500 lx, general inspection) |
| Phase 2 – outcomes | Daytime sleepiness; fatigue severity | ESS; FSS (self-report) | ESS ≥ 10; FSS mean ≥ 4 |
| Phase 2 – exposure | Roster, sleep/wake, environmental, psychosocial items | Structured questionnaire | Study-defined 0–1–2 scoring |
| Output | Fatigue-likelihood index (four domain sub-scores) | Spreadsheet / survey platform | Screening aid (not fitness-for-duty) |

## PHASE 1: ENVIRONMENTAL FIELD MEASUREMENT

Phase 1 measures sound pressure level (SPL) and illuminance at standardised pre-flight inspection checkpoints. Twenty-one checkpoints were selected from the 73 pre-flight inspection items in the Airbus A320 Aircraft Maintenance Manual (Airbus, 2017). Three criteria were used: each item is inspected on every aircraft, the set is spaced along the walk-round, and together the items cover the whole aircraft. The checkpoints are grouped into three physical zones by their position on the aircraft (Figure 1, Table 2). Zone 1 covers the nose and forward fuselage; Zone 2 the wings, engines, mid-fuselage and landing gear; and Zone 3 the aft fuselage, tail and auxiliary power unit (APU) compartment. Measuring at fixed, manual-referenced checkpoints, rather than at arbitrary positions, makes the procedure reproducible across aircraft and between operators.

Sound pressure level is recorded with a calibrated Type 2 sound level meter (Fluke 945; IEC 651 / ANSI S1.4 Type 2), using A-weighting and fast time response. The meter is held at the inspector's ear position, and one reading is taken in each of four directions at every checkpoint. The four readings are averaged (arithmetic mean) to give a single level for that checkpoint. Inspectors move between zones during a pre-flight inspection, so the checkpoint levels are combined into an 8-hour time-weighted average

(TWA) using the time an inspector is expected to spend in each zone and the 3 dB exchange rate recommended by NIOSH. The TWA is a modelled exposure index, not a personal dosimetry record. It is compared with the NIOSH recommended exposure limit (REL) of 85 dBA as an 8-hour TWA (National Institute for Occupational Safety and Health, 1998), with 90 dBA, the OSHA permissible exposure limit (Occupational Safety and Health Administration, 1983), as the upper reference level. Illuminance is recorded with a calibrated illuminance meter (HTC LX-103; range 0 to 100,000 lx, accuracy ±3% + 5 lx) at each checkpoint at three times of day, at about 09:00, 12:00 and 18:00, to capture the change in natural light. Each reading is taken twice. Values are compared with the maintained-illuminance values in EN 12464-1 (European Committee for Standardization, 2021). During readings the aircraft is in its usual pre-flight ground configuration, with the APU, air-conditioning unit and electric pump running. Readings are repeated on ten aircraft of the same configuration so that the profile represents the fleet rather than one airframe. Table 3 gives the procedure step by step. The output is an exposure profile that anchors the environmental scoring in Phase 2. For noise, each zone is classed by its mean level as below 85 dBA, 85 to 90 dBA, or above 90 dBA. For illuminance, the mean at each checkpoint and time of day is classed as below 500 lx, or at or above it, against the maintained illuminance that EN 12464-1 sets for general inspection work. Because daylight varies more with time of day than with position on the aircraft, the illuminance profile is summarised by shift and matched to each worker's usual shift in Phase 2.

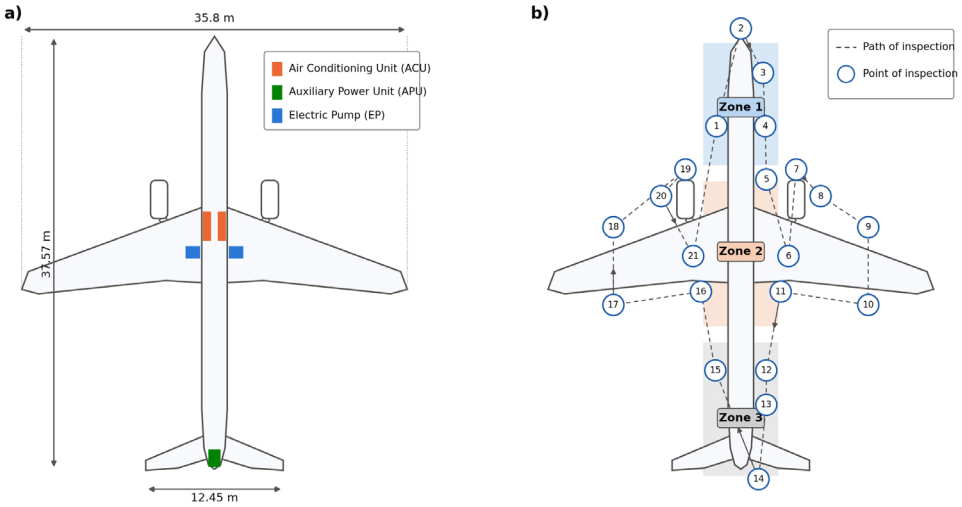



**Figure 1:** (a) A320 principal dimensions and the indicative positions of the ground noise sources; (b) the 21 pre-flight inspection checkpoints in walk-round order, grouped into three zones.

**Table 2:** Checkpoint sampling frame: the 21 A320 pre-flight inspection checkpoints by zone (numbered in walk-round sequence).

| Zone | Checkpoints | Physical Areas Covered | Inspection Categories |
|---|---|---|---|
| Zone 1: nose and forward fuselage | 1 to 4 (4 points) | Nose section; nose landing gear; left- and right-hand forward fuselage | Visual condition and obstruction; gauge reading; security and latching |
| Zone 2: wings, engines, mid-fuselage and landing gear | 5 to 11 and 16 to 21 (13 points) | Lower centre fuselage; left- and right-hand wing leading edge, trailing edge and inner tank area; engines 1 and 2; left- and right-hand main landing gear | Structural surface; leak detection; fluid level; visual condition and obstruction; security and latching; gauge reading |
| Zone 3: aft fuselage, tail and APU compartment | 12 to 15 (4 points) | Left- and right-hand aft fuselage; lower aft fuselage; APU compartment | Security and latching; structural surface; gauge reading |

**Table 3:** Phase 1 measurement procedure.

| Step | Action | Record |
|---|---|---|
| 1 | Confirm the normal pre-flight ground state (auxiliary power unit, air-conditioning unit and electric pump running); note registration, date, time and ambient conditions. | Aircraft, configuration, time, weather |
| 2 | Check that both meters hold current calibration certificates; note make, model and serial number. Check the sound level meter against an acoustic calibrator before and after each session. | Instrument identity; certificate dates; calibrator check values |
| 3 | Walk the 21 checkpoints in the standard inspection sequence (Table 2). | Sequence used |
| 4 | At each checkpoint hold the sound level meter at ear height where the inspector stands; take one reading facing front, back, left and right. | Four SPL readings per checkpoint; checkpoint mean |
| 5 | At each checkpoint take the illuminance reading, repeat it and log the time; complete a sweep at each of the three times of day. | Two illuminance readings per checkpoint and time of day |
| 6 | Repeat steps 1 to 5 on further aircraft of the same configuration until the fleet is represented (ten in the reference application). | Number of aircraft |
| 7 | Average the readings per checkpoint across aircraft; estimate the time an inspector spends in each zone and compute the 8-hour TWA using a 3 dB exchange rate. | Checkpoint means; time-in-zone; TWA |
| 8 | Compare with the reference levels (NIOSH REL 85 dBA; OSHA PEL 90 dBA; EN 12464-1), classify each zone and file the exposure profile for Phase 2. | Zone classes; exposure profile |

## PHASE 2: STRUCTURED FATIGUE SURVEY

Phase 2 is a short self-report survey for line-maintenance personnel. Two validated instruments measure the outcomes. The Epworth Sleepiness Scale (ESS) measures daytime sleepiness; a total of 10 or more counts as excessive sleepiness (Johns, 1991). The Fatigue Severity Scale (FSS) measures the impact of fatigue; a mean item score of 4 or more counts as severe fatigue (Krupp et al., 1989). Exposure is recorded in four domains. The roster domain covers shift time, weekly hours, shift duration, extended shifts, the break between shifts and reset days. The sleep/wake domain covers sleep obtained and hours awake in the previous 24 hours. The environmental domain covers time spent in each measured noise zone, bright-light exposure and illumination quality. The psychosocial domain covers perceived time pressure, support, satisfaction, control and job security. Each exposure item is scored 0, 1 or 2, and the item scores are added within each domain. Table 4 gives the structure of the instrument. Each exposure item in the roster, sleep/wake and environmental domains has three ordered response bands, which map to the scores 0, 1 and 2. The environmental items use banded durations and categorical responses, which are mapped to the same three scores. The psychosocial items use 5-point scales and are summed and then banded. The two outcome scales are used in their published form with their usual thresholds. The band boundaries and the domain weighting are design decisions of the index and are documented, with their empirical evaluation, in a separate paper. Administration is light. The survey runs online (Qualtrics under the university licence; any standard platform will serve), opens with a consent statement, and collects no direct identifiers. It stays open long enough to reach personnel on every roster pattern (about nine weeks), so that every shift type is covered. The analysis includes only personnel with at least one year of maintenance experience.

**Table 4:** Structure of the Phase 2 survey instrument.

| Section | Items | Response Format |
|---|---|---|
| 1. Demographic and work profile | Age; height and weight; nationality; marital status; role; years in role; maintenance experience | Free entry and categorical |
| 2. Roster (six items) | Usual shift time; weekly hours; shift duration; frequency of extension; break between shifts; reset days between blocks | Three ordered bands per item |
| 3. Sleep/wake, previous 24 h (two items) | Sleep obtained; hours awake | Three ordered bands per item |
| 4. Environmental exposure | Daily time in each measured noise zone; lighting type (daylight, mixed, artificial); bright-light exposure duration; perceived illumination problems (adequacy, glare, shadow, colour) | Banded durations; categorical lighting and illumination-quality items |
| 5. Psychosocial (five items) | Time pressure; supervisor and colleague support; job satisfaction; control over tasks; job security | 5-point agreement scale, summed and banded |
| 6. Outcomes | Epworth Sleepiness Scale (eight items); Fatigue Severity Scale (nine items) | ESS 0 to 3 per item, total of 10 or more; FSS 1 to 7 per item, mean of 4 or more |

## COMBINING THE DOMAINS INTO A FATIGUE-LIKELIHOOD INDEX

The four domain sub-scores are added to give a single fatigue-likelihood index. The environmental domain is anchored to the Phase 1 zone measurements, so self-reported time in each zone is weighted by the measured severity of that zone. The index is a screening aid: it flags roster and exposure patterns associated with elevated fatigue. It is not a fitness-for-duty test.

## DATA HANDLING AND REPRODUCIBILITY

The protocol is designed to be reproduced from Table 1 and the procedures above. The rules below fix data handling in advance so that results are comparable across sites and over time. Five rules are fixed before data collection begins. First, only consented responses are kept. Second, a record is analysable only if both outcome scales are complete; partial records are excluded, not imputed. Third, respondents with less than one year of maintenance experience are excluded. Fourth, physiologically implausible entries, such as an out-of-range height or weight, are excluded from the derived variables that depend on them; the rest of the record is kept. Fifth, the export is anonymised and scored by a script (Python, with equivalent SPSS syntax kept), so that the sub-scores and the index are recomputed identically from the raw export. In our study these rules reduced 287 responses to 272 consented and 236 analysable records. Table 5 lists the minimum record set for reproducing both phases.

**Table 5**: Minimum record set for a reproducible application of the protocol.

| Phase | Records to Retain |
|---|---|
| Phase 1 | Aircraft, registration and ground configuration; checkpoint list with manual reference and zone; instrument and calibration dates; SPL and illuminance readings with time stamps; time-in-zone estimates; checkpoint means, TWA and zone class |
| Phase 2 | Instrument version, wording and response bands; platform and survey window; consent/anonymisation method; inclusion rules; scoring script version; response funnel; Phase 1 profile used to anchor the environmental domain |
| Both | Ethics approval reference; protocol version and date; data custodian |

## OPERATIONAL APPLICABILITY

Three features define where the protocol is most useful. First, it is low-cost and needs few tools. The environmental phase needs only calibrated sound and light meters, and the survey runs on any standard platform, so a maintenance organisation can adopt it without external consultants. Second, it suits hot-climate operations. Natural light varies strongly through the day, and ground power and air-conditioning units run all year on hot-climate ramps. The time-of-day illuminance sampling and the zone-based noise mapping capture both. Third, it fits current regulation. Civil aviation authorities are implementing the safety-management-system provisions of ICAO Annex 19 (International Civil Aviation Organization, 2016), and

a standardised protocol gives operators the documented evidence those provisions require. Adoption can be incremental. An operator can begin with Phase 1 to characterise its own hangar and fleet and use the results to target hearing-conservation and task-lighting improvements. It can then add the periodic Phase 2 survey to monitor roster- and work-related fatigue. Because the method is the same at every site, it also supports benchmarking and shared learning between operators. This is a practical step toward the maintenance-specific fatigue risk management that the sector currently lacks. Two limitations should be stated. The protocol was developed across several line-maintenance organisations in Oman, so its fit elsewhere is designed rather than demonstrated. Its checkpoints are A320-specific; transfer to another aircraft type requires re-mapping from that type's maintenance manual, although the zone logic can be generic.

## CONCLUSION

This paper has set out the design of a replicable two-phase field protocol for assessing fatigue risk in aircraft line maintenance, and the operating conditions in which it is most useful. The contribution is methodological and practical: a concrete procedure that an operator's own team can run, and a case for using it as the first step toward a maintenance-specific fatigue risk management system. The empirical results are prepared for journal submission. For line-maintenance operations, above all in hot, high-daylight environments, a shared and documented method gives operators a practical way to measure and manage fatigue, not only to recognise it.

## ETHICS STATEMENT

The environmental measurements involved no human participants. The survey was conducted under Curtin University Human Research Ethics Committee approval (HRE2026-0080), with informed consent from all respondents.

## ACKNOWLEDGMENT

This research was self-funded by the first author. The authors used Claude (Anthropic) to proofread the manuscript for language and grammar; the authors reviewed all content and take full responsibility for it.

## REFERENCES

Airbus. (2017). A320 aircraft maintenance manual: Line check list 2.00, external walk-around diagram (Rev. 7, May 2017). Airbus S.A.S.

Bosley, G. C., Miller, R. M., & Watson, J. (2005). Evaluation of aviation maintenance working environments, fatigue and maintenance errors/accidents (DTFA01-99-C-00088). Federal Aviation Administration.

da Silva, J. C., Barqueira, A., Magalhães, L. B., & Santos, L. F. F. M. (2024). Human fatigue in the aircraft maintenance environment. Safety Science, 180, 106634.

Devine, J. K., Choynowski, J., & Hursh, S. R. (2025). Evaluation of a biomathematical modelling software tool for the prediction of risk in flight schedules compared against incidence of fatigue reports. Safety, 11(1), 4.

European Committee for Standardization. (2021). Light and lighting — Lighting of work places — Part 1: Indoor work places (EN 12464-1:2021).

Gander, P. H., Mangie, J., van den Berg, M. J., Smith, A. A. T., Mulrine, H. M., & Signal, T. L. (2014). Crew fatigue safety performance indicators for fatigue risk management systems. Aviation, Space, and Environmental Medicine, 85(2), 139–147.

Gramopadhye, A. K., & Drury, C. G. (2000). Human factors in aviation maintenance: How we got to where we are. International Journal of Industrial Ergonomics, 26(2), 125–131.

Hobbs, A., Avers, K. B., & Hiles, J. J. (2011). Fatigue risk management in aviation maintenance: Current best practices and potential future countermeasures (DOT/FAA/AM-11/10). Civil Aerospace Medical Institute.

International Civil Aviation Organization. (2016). Annex 19 to the Convention on International Civil Aviation: Safety management (2nd ed.). ICAO.

Johns, M. W. (1991). A new method for measuring daytime sleepiness: The Epworth Sleepiness Scale. Sleep, 14(6), 540–545.

Krupp, L. B., LaRocca, N. G., Muir-Nash, J., & Steinberg, A. D. (1989). The Fatigue Severity Scale: Application to patients with multiple sclerosis and systemic lupus erythematosus. Archives of Neurology, 46(10), 1121–1123.

Lerman, S. E., Eskin, E., Flower, D. J., George, E. C., Gerson, B., Hartenbaum, N., Hursh, S. R., & Moore-Ede, M. (2012). Fatigue risk management in the workplace. Journal of Occupational and Environmental Medicine, 54(2), 231–258.

Marais, K. B., & Robichaud, M. R. (2012). Analysis of trends in aviation maintenance risk: An empirical approach. Reliability Engineering & System Safety, 106, 104–118.

Miller, M., Mrusek, B., & Herbic, J. (2023). Managing fatigue in aviation maintenance while promoting a human factors safety reporting system: A strategic approach to aviation safety. In Safety Management and Human Factors (AHFE Open Access). https://doi.org/10.54941/ahfe1003070

National Institute for Occupational Safety and Health. (1998). Criteria for a recommended standard: Occupational noise exposure (DHHS [NIOSH] Publication No. 98–126).

Occupational Safety and Health Administration. (1983). Occupational noise exposure (29 CFR 1910.95). U.S. Department of Labor.

Sprajcer, M., Vincent, G. E., & Dawson, D. (2025). Creating a fatigue risk management system. Current Sleep Medicine Reports, 11(1), 25. https://doi.org/10.1007/s40675-025-00338-8