The Science of Fatigue at Sea: A Biomathematical Model for Recreational Sailing

GALVANIC
WORKS

Contents

1. The Problem No One Talks About

Maritime accident investigation bodies around the world identify fatigue as a contributing factor in the majority of serious incidents at sea. The UK Marine Accident Investigation Branch (MAIB) has consistently found that 70–80% of maritime accidents are attributable to human error, and in the majority of these cases, fatigue is identified as a major contributory link (MAIB, 2024). A US Coast Guard analysis of marine casualty reports found that crew fatigue was a causal or contributing factor in 33% of personnel injuries and 16% of critical vessel casualties (McCallum, Raby & Rothblum, 1996). Bayesian network analysis of grounding incidents has shown that fatigue raises the probability of grounding by approximately 23% (Hu et al., 2020).

The pattern is consistent across accident types and geographies. MAIB analysis of 23 groundings found that most occurred between 0400–0500 and around 2300 — times corresponding precisely to the circadian trough and the onset of sleep-pressure-related impairment (MAIB, 2005). The US National Transportation Safety Board's investigation of the fishing vessel Tenacious found that the captain had been awake for 19.5 hours at the time of grounding, with acute fatigue compounded by chronic sleep debt identified as the probable cause (NTSB, 2022). These are not isolated incidents; systematic reviews of maritime accident investigations identify fatigue as one of the most underreported contributing factors, appearing explicitly in only 5.6% of 1,011 official marine casualty reports examined across European, US, Australian and Canadian investigation bodies, despite being implicated far more broadly (Crestelo Moreno et al., 2026).

This is not a problem confined to commercial shipping. Recreational sailors are, if anything, more vulnerable. Commercial mariners operate under the International Convention on Standards of Training, Certification and Watchkeeping (STCW), which mandates minimum rest periods: at least 10 hours in any 24-hour period, with no more than 14 hours of continuous wakefulness (IMO, 2010). Recreational sailors are bound by no such regulation. A couple on a 120-nautical-mile overnight passage — entirely routine in the Mediterranean — will commonly exceed these professional limits before they sight their destination.

Research on seafarer fatigue confirms that even professional mariners, operating within regulatory frameworks designed to protect them, experience significant fatigue-related impairment. Sanquist, Raby, Forsythe and Carvalhais (1997) found that merchant marine personnel averaged less than 6.6 hours of sleep per day at sea, with frequent interruptions. Allen, Wadsworth and Smith (2008), in a comprehensive review of seafarer fatigue, concluded that the maritime industry suffers from endemic fatigue levels that would not be tolerated in aviation or road transport. Dohrmann and Leppin (2017), in a systematic review of 19 studies on seafarer fatigue determinants, found that working the night watch was the single most fatiguing factor, and that the 6-on/6-off watch system consistently produced the worst fatigue outcomes.

The question is not whether fatigue affects recreational sailors. It is whether they understand how profoundly it does.

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2. Fatigue and Alcohol: The Equivalence That Changed the Conversation

2.1 The Dawson & Reid Study (1997)

The foundational research linking fatigue to measurable cognitive impairment was published in Nature by Drew Dawson and Kathryn Reid of the University of South Australia. Their study compared the performance of 40 subjects on a tracking task under two conditions: progressive sleep deprivation, and progressive alcohol intoxication (Dawson & Reid, 1997).

The results were striking:

- After **17 hours** of sustained wakefulness, performance on cognitive and motor tasks deteriorated to a level equivalent to a blood alcohol concentration (BAC) of **0.05%** — the legal driving limit in Australia, most of Europe, and the UK.
- After **24 hours**, performance reached equivalence with a BAC of **0.10%** — well past the legal limit for operating any vehicle in any jurisdiction.

The elegance of this study lies in its methodology. By testing the same subjects under both conditions and using the same performance metrics, Dawson and Reid created a direct, quantitative bridge between two forms of impairment that are otherwise difficult to compare. The BAC equivalence is not a metaphor. It is a measured correspondence in reaction time, accuracy, and cognitive throughput.

2.2 Independent Corroboration

Three years later, Ann Williamson and Anne-Marie Feyer replicated and extended these findings in a study published in Occupational and Environmental Medicine. Working with 39 subjects drawn from the transport industry and military, they tested cognitive and motor performance under controlled sleep deprivation and alcohol intoxication conditions (Williamson & Feyer, 2000).

Their results confirmed the Dawson & Reid findings:

- After **17–19 hours** without sleep, performance on some tests was equivalent to or worse than at 0.05% BAC.
- Response speeds were **up to 50% slower** for sleep-deprived subjects compared to rested baselines.
- After longer periods of deprivation, performance reached levels equivalent to **0.10% BAC**.

The Williamson & Feyer study is particularly relevant to sailing because their subject pool included operational workers accustomed to shift work — people who, like experienced sailors, believe they have adapted to irregular sleep. The data showed that this belief is largely unfounded. Subjective assessments of alertness diverged sharply from objective performance measurements.

Subsequent meta-analytic work has further solidified these findings. Lim and Dinges (2010), in a comprehensive meta-analysis of 70 studies encompassing over 1,500 participants, confirmed that short-term sleep deprivation produces large, reliable deficits in sustained attention, working memory, and cognitive throughput. The effect sizes were comparable to moderate alcohol intoxication across all cognitive domains measured. Pilcher and Huffcutt (1996), in an earlier meta-analysis of 19 studies, found that sleep-deprived subjects performed worse than 84% of non-deprived subjects on cognitive tasks.

2.3 Field Confirmation: Fatigue in Solo Sailing

The laboratory findings have been directly confirmed at sea. Hurdiel, Van Dongen, Aron, McCauley, Jacolot and Theunynck (2014) conducted a field study during solo Figaro sailing races, measuring reaction time performance using the psychomotor vigilance test (PVT) — the same instrument used in the Dawson & Reid laboratory studies. Solo sailors, sleeping an average of 4.1–4.6 hours per 24-hour period in fragmented naps, showed severe degradation in reaction time performance that tracked closely with the laboratory predictions.

Filardi and colleagues (2020), in a study of 42 solo offshore sailors competing in the Mini Transat, found that 55% adopted some form of pre-race sleep management strategy — most commonly sleep extension (52%), followed by polyphasic sleep (26%) and sleep deprivation (22%). However, no significant difference emerged in final race times between sailors who adopted strategies and those who did not. Solo sailors were predominantly morning-type (40%) or intermediate-type (60%) chronotypes, with no evening-type sailors observed in the cohort — suggesting a self-selection effect for the chronotype best suited to fragmented sleep at sea.

Bruno and colleagues (2023), in a survey of 190 teams in the 151 Miglia overnight crewed regatta, found that the self-management of sleep/wake timing emerged as the most successful strategy overall. Among teams that adopted shift-based scheduling, shorter night shifts (i.e., 2 h) significantly predicted better race placement than longer ones — suggesting that for short overnight events, frequent rotation may matter more than longer consolidated rest blocks.

2.4 Beyond Reaction Time: Higher-Order Cognitive Impairment

The BAC equivalence framework captures impairment in reaction time and vigilance — but the effects of sleep deprivation extend far beyond these metrics.

Harrison and Horne (1999) demonstrated that a single night of sleep loss significantly impairs **innovative thinking and flexible decision-making** — the capacity to respond to novel, unexpected situations. Subjects performed comparably to rested controls on well-practised, routine tasks, but deteriorated dramatically when tasks required updating plans, integrating new information, or managing competing priorities. In a subsequent review, Harrison and Horne (2000) argued that the prefrontal cortex — responsible for executive function, risk assessment, and impulse control — is disproportionately vulnerable to sleep loss.

This distinction between routine and novel performance is critical for sailors. Helming in steady conditions on a well-known route may remain adequate even when fatigued. But responding to an unexpected encounter — a vessel on a collision course, a sudden wind shift near a lee shore, an equipment failure requiring immediate decision-making — demands exactly the cognitive flexibility that fatigue degrades first. Fatigued mariners don't stop seeing hazards; they stop responding to them appropriately.

Durmer and Dinges (2005), in their review of the neurocognitive consequences of sleep deprivation, summarised the evidence as follows: sleep loss produces "an overall slowing of cognition, with lapses in attention, reduced working memory capacity, impaired divergent thinking, and poor behavioural flexibility." These are precisely the cognitive functions demanded by night-time watchkeeping — the ability to detect an approaching vessel, assess whether a collision risk exists, formulate a response plan, and execute it reliably.

Banks and Dinges (2007) provided additional evidence from controlled laboratory studies that even moderate sleep restriction — limiting sleep to 6 hours per night, a common experience on passage — produces significant deficits in psychomotor vigilance, with performance continuing to degrade across successive days of restriction.

2.5 Why the BAC Equivalence Matters at Sea

The practical significance of these findings for sailors is this: the cognitive tasks degraded by fatigue are precisely the tasks required for safe watchkeeping.

COLREG Rule 5 requires every vessel to maintain "a proper look-out by sight and hearing as well as by all available means appropriate in the prevailing circumstances and conditions so as to make a full appraisal of the situation and of the risk of collision." This demands sustained visual scanning, auditory monitoring, situation assessment, and decision-making — all functions that deteriorate measurably after 17 hours of wakefulness.

A solo sailor who departs at 0600 after a normal night's sleep begins to cross the 0.05% BAC equivalence threshold around 2300 that evening. By 0600 the following morning — exactly 24 hours in — they are operating at a level equivalent to legal intoxication. If they are still on passage, every navigational decision, every assessment of a developing situation, every response to an alarm is being made with the cognitive resources of someone who has been drinking.

No competent sailor would stand watch after five drinks. But many routinely stand watch after 24 hours without sleep, unaware that the impairment is equivalent.

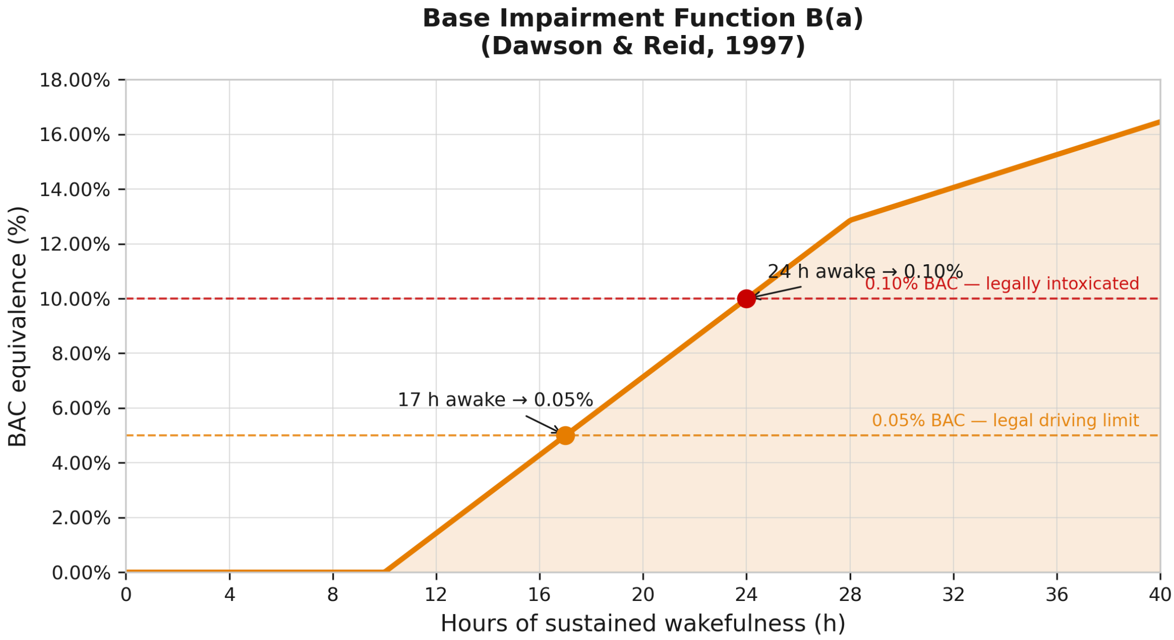

Figure 1: Base impairment function B(a) — BAC equivalence as a function of hours of sustained wakefulness. The piecewise linear model reaches 0.05% (legal driving limit) at 17 hours and 0.10% (legal intoxication) at 24 hours. Derived from Dawson & Reid (1997).

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3. The Circadian Dimension: Why 3 AM Is Not Like 3 PM

3.1 The Three-Process Model of Alertness

Fatigue is not simply a linear function of time awake. It is modulated by the body's circadian rhythm — the roughly 24-hour internal clock that regulates cycles of alertness and sleepiness independent of how long a person has been awake.

The most widely used framework for modelling this interaction is the three-process model developed by Simon Folkard and Torbjörn Åkerstedt, first published in 1987 and refined in 1997 (Folkard & Åkerstedt, 1987; Folkard & Åkerstedt, 1997). The model describes alertness as the product of three interacting processes:

1. **Process S (Homeostatic sleep pressure):** A monotonically increasing drive toward sleep that accumulates during wakefulness and dissipates during sleep.
2. **Process C (Circadian rhythm):** A sinusoidal oscillation in alertness driven by the suprachiasmatic nucleus of the hypothalamus, independent of sleep history.
3. **Process W (Sleep inertia):** A transient reduction in alertness immediately after waking, typically lasting 15–30 minutes.

For passage planning, Processes S and C are the critical factors. Process S determines the baseline rate of impairment accumulation. Process C determines when that impairment hits hardest.

3.2 The Circadian Trough: 0200–0600

The circadian rhythm produces a pronounced dip in alertness during the biological night, with the nadir occurring between approximately 0200 and 0600. This is not a matter of conditioning or habit — it is a neurobiological reality driven by melatonin secretion and core body temperature cycles (Wright et al., 2013).

Schmidt, Collette, Cajochen and Peigneux (2007), in a comprehensive review of circadian influences on cognition, demonstrated that virtually every measurable cognitive function — attention, executive control, memory retrieval, and psychomotor speed — exhibits circadian variation, with the worst performance consistently occurring during the biological night. These effects persist even when total sleep time is controlled, confirming that the circadian trough is an independent source of impairment, not merely a consequence of sleep loss.

The maritime accident record confirms this pattern directly. MAIB analysis of groundings found that incidents clustered heavily between 0400–0500 — the deepest point of the circadian trough (MAIB, 2005). The NTSB investigation of the

Tenacious grounding documented that the captain fell asleep at the helm during this same window (NTSB, 2022). Phillips (2004), in a content analysis of maritime incident reports, found a clear time-of-day pattern in fatigue-related accidents, with the circadian trough window accounting for a disproportionate share.

The interaction between homeostatic sleep pressure and circadian phase is multiplicative, not additive. Boivin, Boudreau and Kosmadopoulos (2022) have shown that the performance decrement during the circadian trough is amplified by concurrent sleep deprivation, producing impairment levels greater than either factor alone would predict. This means that the 0200–0600 window on the second night of a passage — when both sleep debt and circadian trough are at their deepest — represents a period of extreme vulnerability.

Research aboard naval vessels has confirmed that non-standard watch rotations can exacerbate circadian disruption. Marando et al. (2023), in a scoping review of 13 studies on submariner watchkeeping schedules, found that longer off-watch periods were associated with better cognitive performance, that circadian misalignment was greater for non-24-hour schedules, and that 4-hour-on / 8-hour-off and 8-hour-on / 16-hour-off schedules represent the best compromise between human risk factors and operational demands. Erez et al. (2025), studying Israeli Navy submariners on a 20-hour rotating watch schedule, demonstrated that this non-24-hour schedule creates daily circadian misalignment “akin to experiencing 4 h of jet lag” — producing fragmented sleep, evening alertness deficits, morning mood disturbance, and elevated afternoon risk-taking propensity.

In the fatigue model, the circadian modulation ranges from approximately **0.65** (reduced impairment during the circadian peak, typically mid-afternoon) to **1.35** (amplified impairment during the circadian trough). This means that the effective impairment at 0300 can be roughly **double** the impairment at 1500 for the same number of hours awake.

3.3 Mathematical Representation

The circadian modulation is modelled using a dual-cosine function, following the harmonic structure proposed by Folkard and Åkerstedt:

$$C(t) = 1.0 - 0.18\cos\left(\frac{(t-15)\pi}{12}\right) - 0.08\cos\left(\frac{(t-14)\pi}{6}\right)$$

Where t is the hour of day (0–24). The first cosine term captures the primary 24-hour circadian cycle, with its peak near 1500. The second term adds the secondary harmonic that sharpens the nocturnal trough and accounts for the brief post-lunch dip in alertness — the so-called “post-prandial dip,” which is a genuine circadian phenomenon independent of food intake (Schmidt et al., 2007).

The function is clamped to the range [0.65, 1.35] to prevent physiologically implausible extreme values.

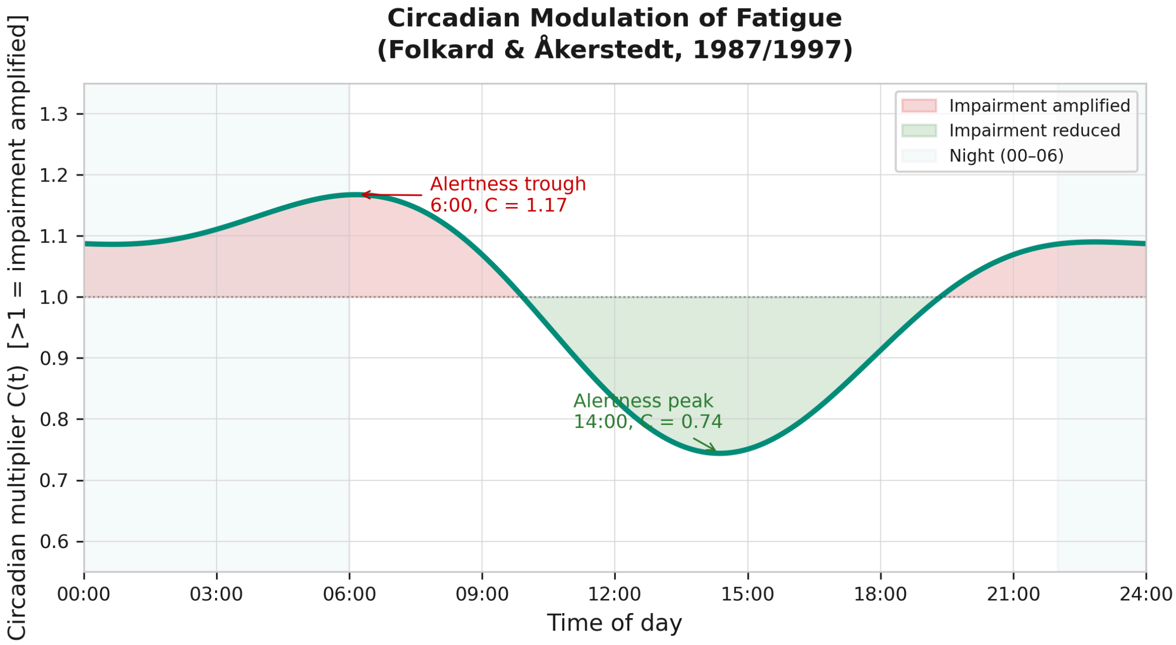

Figure 2: Circadian modulation of fatigue C(t) over a 24-hour period. The multiplier amplifies impairment during the biological night (alertness trough at approximately 06:00, C = 1.17) and reduces it during the afternoon (alertness peak at approximately 14:00, C = 0.74). Based on the dual-cosine model of Folkard & Åkerstedt (1987, 1997).

4. Sleep Recovery: Not All Rest Is Equal

4.1 The Architecture of Sleep

Human sleep is not a uniform state. It cycles through distinct stages in approximately 90-minute periods, a pattern first identified by William Dement and Nathaniel Kleitman in their landmark 1957 electroencephalographic study (Dement & Kleitman, 1957). Each cycle progresses through light sleep (Stages N1 and N2), deep slow-wave sleep (Stage N3), and rapid eye movement (REM) sleep. Kleitman (1963) later proposed that this ~90-minute rhythm — which he termed the Basic Rest-Activity Cycle (BRAC) — operates not only during sleep but as a fundamental organising principle of human alertness across the entire 24-hour day.

These stages serve different restorative functions. Slow-wave sleep, predominant in the first half of the night, is associated with physical restoration, immune function, and memory consolidation. REM sleep, predominant in the latter half, is critical for emotional regulation and procedural memory. Both are necessary for full cognitive recovery (Durmer & Dinges, 2005).

The ~90-minute cycle length has important implications for watchkeeping schedules. A 90-minute off-watch period allows one complete sleep cycle; a 45-minute period does not. This is not a minor distinction — it determines whether sleep produces meaningful cognitive restoration or merely superficial drowsiness reduction.

4.2 Sleep Fragmentation

Research by Bonnet and Arand (2003) has demonstrated that fragmented sleep — sleep interrupted by awakenings — is substantially less restorative than consolidated sleep of equal duration. Their review of sleep fragmentation studies found that:

- Fragmented sleep produces **next-day sleepiness and cognitive impairment comparable to partial sleep deprivation**, even when total sleep time is preserved.
- The restorative value of sleep depends not only on duration but on **continuity**. A 6-hour uninterrupted sleep period is substantially more restorative than 6 hours of sleep accumulated in 90-minute fragments.
- Sleep interruptions as brief as **5–10 seconds** (sufficient to trigger an arousal on EEG) can degrade sleep quality, even if the sleeper does not recall waking.

Earlier work by Bonnet (1987) quantified this effect more precisely, finding that periodic awakenings reduced the restorative value of sleep in proportion to their frequency, with fragmented sleep recovering approximately **55–60%** of the cognitive capacity restored by equivalent consolidated sleep. Stepanski, Lamphere, Badia, Zorick and Roth (1984) confirmed this in clinical populations, demonstrating a dose-response relationship between the number of sleep interruptions and next-day sleepiness.

Martin, Wraith, Deary and Douglas (1997) showed that even “nonvisible” sleep fragmentation — brief arousals detectable only on EEG, which the sleeper does not consciously experience — produces measurable impairment in daytime cognitive function. This finding is particularly relevant to sleep at sea, where the constant motion and noise of a sailing vessel produce continuous sub-threshold arousals that degrade sleep quality without the sailor’s awareness.

Polysomnographic data from ships at sea confirms this. Kerkamm and colleagues (2023) conducted the first ambulatory polysomnographic study aboard merchant vessels on the open ocean, measuring actual sleep architecture with clinical-grade instruments. They found that watchkeepers achieved only **78.3% sleep efficiency** — meaning that for every hour in a bunk, only 47 minutes consisted of actual sleep. The remaining time was spent in wakefulness, light drowsiness, or sub-arousal states triggered by vessel motion, noise, and vibration.

Djonlagic, Saboisky, Carusona, Stickgold and Malhotra (2012) demonstrated that sleep fragmentation specifically impairs the **offline consolidation of motor memories** — the process by which skills practised during wakefulness are strengthened during sleep. For sailors, this means that the procedural skills required for watch handovers, sail trim, and emergency responses may be less reliable after fragmented sleep, even if the sailor feels rested.

For sailors, these findings are directly relevant. On most two-person watch schedules, the off-watch period is 3–6 hours. But time off watch is not time asleep. It takes time to go below, time to fall asleep, time to reawaken and dress before the next watch. A 4-hour off-watch period may yield only 2.5–3 hours of actual sleep — consistent with the 78.3% efficiency measured by Kerkamm et al. (2023). If that sleep is further fragmented by alarms, weather changes, or anxiety, its restorative value diminishes further.

4.3 The Deep Sleep Threshold

In the fatigue model, sleep periods are classified as either “deep” (≥2 hours of continuous off-watch time, allowing at least one complete sleep cycle) or “shallow” (<2 hours). Based on the sleep fragmentation literature:

- **Deep sleep** (≥2 hours continuous): approximately **85%** recovery efficiency relative to fully consolidated sleep.
- **Shallow sleep** (<2 hours continuous): approximately **55%** recovery efficiency.

These values are conservative estimates derived from the Bonnet (1987), Bonnet & Arand (2003), and Stepanski et al. (1984) findings, calibrated against the polysomnographic data from Kerkamm et al. (2023) and adjusted for the operational reality that even “off-watch” sleep at sea is inherently lighter than sleep ashore.

5. The Sea State Factor: Why Your Bunk Is Not Your Bed

5.1 Environmental Degradation of Sleep Quality

The maritime environment presents unique challenges to sleep quality that have no analogue ashore. Ship motion, engine noise, vibration, ambient temperature, and the psychological awareness that one is sleeping aboard a moving vessel all contribute to degraded sleep.

Research by Hystad and Eid (2016), studying seafarers aboard merchant vessels, found that **91.6%** of participants reported their sleep was disturbed by environmental factors, including vessel motion, vibration, and noise. Their analysis identified duration at sea, psychological capital, and environmental stressors as significant predictors of fatigue, with vessel motion ranking among the most disruptive factors. A subsequent systematic review by Kerkamm and colleagues (2021) of measurement methods for fatigue and sleepiness aboard ships also documented noise, ship motion, and vibration as significant environmental stressors affecting sleep on board across multiple study designs and vessel types.

Jepsen, Zhao and van Leeuwen (2015), in a comprehensive review of seafarer fatigue for International Maritime Health, identified six categories of fatigue risk factors at sea: sleep-related factors, work-related factors, environmental factors, health-related factors, operational factors, and organizational factors. Of these, environmental factors — particularly motion-induced sleep disruption — were among the most consistently reported across studies and vessel types.

Oldenburg, Jensen, Latza and Baur (2009) studied stress factors aboard merchant and passenger ships, finding that physical environmental stressors — noise, vibration, and vessel motion — were identified by seafarers as the most significant impediments to rest, exceeding even psychosocial stressors such as separation from family or interpersonal conflict. Oldenburg, Hogan and Jensen (2013), in a systematic review of 109 maritime field studies, confirmed that environmental disruption of sleep was the most common physical complaint, reported across all vessel types and crew roles.

Wadsworth, Allen, McNamara and Smith (2008) found that fatigue levels among seafarers were significantly associated with vessel type — with smaller vessels, which experience greater motion, producing higher fatigue scores. Abrahamsen and colleagues (2023), studying fishermen in the North Atlantic, documented the combined effects of vessel motion, short watch cycles, and extreme environmental conditions on crew fatigue, finding that working environment factors explained a significant proportion of variance in fatigue scores beyond work hours alone.

Gander, van den Berg and Signal (2008), studying fishermen on rotating watch schedules, documented severe sleep restriction at sea (averaging 4.5 hours per 24-hour period), with sleep quality further degraded by vessel motion. Their findings are particularly relevant to recreational sailors, whose vessels are typically smaller and subject to greater sea-induced motion than the commercial fishing boats studied.

While these studies were conducted in commercial maritime settings, the conditions aboard a sailing yacht are typically worse. Commercial vessels are large enough to dampen much of the sea's motion. A 40-foot sailing yacht in moderate seas experiences accelerations and roll angles several times greater than a commercial ship, compounded by the unpredictable motion characteristics of wind-driven sailing.

5.2 Sea State and Sleep Quality Coefficients

The fatigue model applies a sea state multiplier to the base sleep recovery rate, reflecting the empirically observed degradation of sleep quality in progressively worse conditions:

Sea State	Sleep Quality Coefficient	Interpretation
Calm		Sleep quality approaches shore-based quality. Full recovery potential.
Moderate		Noticeable motion and noise. Sleep is lighter, with more frequent brief arousals. Recovery is reduced by approximately 20%.
Rough		Significant motion requiring bracing even in a bunk. Sleep is shallow and frequently interrupted. Less than 60% of normal recovery.
Storm		Severe conditions. Sleep is barely possible. What sleep occurs provides minimal cognitive recovery.

These coefficients are derived from the maritime sleep quality literature (Hystad & Eid, 2016; Jepsen et al., 2015; Oldenburg et al., 2009; Wadsworth et al., 2008; Kerkamm et al., 2023; Abrahamsen et al., 2024) and calibrated against the experiential reports of long-distance sailors. They are applied multiplicatively to the base sleep recovery rate, meaning that in rough conditions, a 4-hour off-watch period provides the cognitive recovery equivalent of approximately 2.2 hours of consolidated sleep ashore.

6. Cumulative Sleep Debt: The Hidden Danger of Multi-Day Passages

6.1 The Van Dongen Study (2003)

Perhaps the most alarming finding in fatigue research — and the most relevant to offshore sailing — comes from a study by Hans Van Dongen and colleagues at the University of Pennsylvania, published in Sleep (Van Dongen, Maislin, Mullington & Dinges, 2003).

The study restricted subjects to either 4, 6, or 8 hours of sleep per night for 14 consecutive nights, measuring cognitive performance daily. The results demonstrated that:

- **Sleep debt is cumulative.** Restricting sleep to 6 hours per night for two weeks produced cognitive impairment equivalent to **two consecutive nights of total sleep deprivation** — a level corresponding to approximately 0.10% BAC.
- **The accumulation is linear and relentless.** There was no plateau, no adaptation. Performance continued to degrade across all 14 days.
- **Subjects did not perceive their own impairment.** Self-rated sleepiness levelled off after a few days of restriction, while objective performance continued to deteriorate. Participants genuinely believed they had adapted; the data showed they had not.

6.2 Corroborating Evidence

Belenky, Wesensten, Thorne and colleagues (2003) conducted a parallel sleep dose-response study at the Walter Reed Army Institute of Research, restricting subjects to 3, 5, 7, or 9 hours of sleep for seven consecutive nights, followed by three nights of recovery sleep. Their findings complemented Van Dongen et al.:

- Performance degraded progressively across all restriction conditions except the 9-hour control.
- At 3 hours per night, performance was **severely impaired** by day 7, with PVT lapse rates increasing approximately 15-fold relative to baseline.
- Critically, **three nights of recovery sleep did not fully restore performance** in the 3-hour and 5-hour groups. Sleep debt, once incurred, takes longer to repay than to accumulate.

Cohen, Wang, Wyatt and colleagues (2010), in a study published in Science Translational Medicine, demonstrated that chronic sleep loss produces **residual cognitive impairment that persists even after subjects feel fully recovered**. Using a forced desynchrony protocol, they showed that subjective recovery outpaces objective recovery — individuals report feeling rested while still carrying measurable performance deficits. This finding directly challenges the common belief among offshore sailors that “I’ll catch up on sleep when we arrive.”

Rupp, Wesensten, Bliese and Balkin (2009) investigated whether sleep can be “banked” — that is, whether extended sleep before a period of restriction provides a protective buffer. Their results were encouraging: subjects who obtained extended sleep (10 hours per night) for one week before a period of restriction showed significantly less performance degradation than control subjects. This provides a scientific basis for the common-sense recommendation that sailors should prioritise sleep in the days before departure. Filardi et al. (2020) documented that 52% of solo offshore sailors in the Mini Transat adopted sleep extension as their primary pre-race strategy, although their study found no significant difference in final race times between sailors who adopted any sleep management strategy and those who did not — highlighting that the relationship between pre-race sleep loading and race-day performance in solo offshore sailing remains an open question.

6.3 Field Data from Offshore Racing

The cumulative sleep debt findings from the laboratory have been directly confirmed in offshore sailing. Hurdiel et al. (2014) documented the progressive deterioration of reaction times across solo sailing races, with performance degradation tracking the predictions of the Van Dongen model. The sailors’ average sleep of 4.1–4.6 hours per day is comparable to the 4-hour restriction condition in the Van Dongen study — a condition that produced impairment equivalent to two nights of total sleep deprivation over 14 days.

Ceccanti and colleagues (2026), in a PRISMA systematic review of 16 studies on offshore sailing regattas, concluded that partial sleep deprivation impairs cognition and reaction speed, increasing technical errors. They identified two main strategies: “banking sleep” before short regattas, and split sleep of 4.5–5.5 hours per day in 30-minute to 1-hour episodes during long races — highlighting that no universal sleep-management approach exists across race lengths and crew sizes.

6.4 The Metacognitive Failure

The most dangerous aspect of cumulative sleep debt is the divergence between subjective and objective impairment. Van Dongen, Baynard, Maislin and Dinges (2004) demonstrated that this divergence reflects **systematic individual differences**

in vulnerability to sleep loss that are trait-like and stable over time. Some individuals are consistently more vulnerable to sleep deprivation than others, but neither group can accurately assess their own level of impairment.

Pilcher and Huffcutt (1996) found in their meta-analysis that self-rated mood and affect — the subjective sense of being alert or tired — showed only modest correlations with objective performance under sleep deprivation. The human brain is, in effect, the last system to recognise its own degradation.

For sailors, this creates a dangerous feedback loop. On day three of an offshore passage, both crew members may genuinely believe they are performing adequately. The research says they almost certainly are not — and the longer the passage continues, the wider the gap between their perception and their reality.

6.5 Modelling Cumulative Debt

In the fatigue model, cumulative sleep debt is represented as a day factor that increases base impairment by approximately **8% per day** after the first 24 hours:

$$D(h) = 1 + \max\left(0, \left(\frac{h}{24} - 1\right) \times 0.08\right)$$

Where h is the total elapsed passage time in hours. This is a conservative linear approximation of the degradation observed by Van Dongen et al. (2003) and Belenky et al. (2003). On a 72-hour passage, the cumulative day factor is approximately 1.16, meaning base impairment is amplified by 16% — a meaningful increase layered on top of acute sleep deprivation and circadian effects.

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7. The Integrated Fatigue Model

7.1 The Biomathematical Approach

Biomathematical fatigue models — computational tools that predict alertness and impairment from sleep-wake schedules — have been used in aviation, military operations, and road transport for over two decades. Mallis, Mejdal, Nguyen and Dinges (2004) reviewed seven such models, including the Sleep, Activity, Fatigue, and Task Effectiveness model (SAFTE; Hursh, Redmond, Johnson et al., 2004), the Fatigue Audit InterDyne (FAID; Roach, Fletcher & Dawson, 2004), and the three-process model of alertness (Folkard & Åkerstedt, 1997). All share a common architecture: a homeostatic sleep-pressure component, a circadian oscillator, and a recovery function.

Dawson, Noy, Härmä, Åkerstedt and Belenky (2011), in a review for Accident Analysis & Prevention, assessed the use of fatigue models in work settings and concluded that while no model perfectly predicts individual impairment, they provide “a rational, defensible framework for managing fatigue risk” that is superior to subjective assessment or fixed hour-of-service rules alone. The European Commission’s Project MARTHA, a €3.4 million study involving over 1,000 seafarers, applied biomathematical fatigue modelling specifically to the maritime sector and developed improved prediction models calibrated for shipboard conditions (Van Leeuwen et al., 2011).

The fatigue model described in this paper follows the same general architecture, adapted for the specific constraints of offshore sailing.

7.2 Bringing It Together

The model combines four components into a single impairment estimate, expressed as a BAC equivalence:

$$\text{BAC}_{\text{eq}}(t) = B(a) \times D(t) \times C(t_{\text{day}})$$

Where:

- **B(a)** is the base impairment from hours awake, derived from Dawson & Reid (1997)
- **D(t)** is the cumulative day factor from Van Dongen et al. (2003) and Belenky et al. (2003)
- **C(t_day)** is the circadian modulation from Folkard & Åkerstedt (1987, 1997)

The base impairment function B(a) is defined as:

$$B(a) = \begin{cases} 0 & \text{if } \ a \leq 10 \\ 0.00714 \times (a - 10) & \text{if } \ 10 < a \leq 28 \\ 0.1286 + 0.003 \times (a - 28) & \text{if } \ a > 28 \end{cases}$$

This piecewise linear function produces: - **0.00% BAC** at 10 hours awake (no measurable impairment) - **0.05% BAC** at 17 hours awake (Dawson & Reid threshold) - **0.10% BAC** at approximately 24 hours awake - A reduced rate of increase beyond 28 hours, reflecting the asymptotic behaviour observed in extreme sleep deprivation studies (Lim & Dinges, 2010)

7.3 Sleep Recovery Mechanics

When a sailor goes off watch, their accumulated hours-awake counter decreases according to the sleep recovery function:

$$R(s, q, d) = s \times e \times q \times 1.5$$

Where:

- **s** is hours of actual sleep obtained during the off-watch period
- **e** is sleep efficiency: 0.85 for deep sleep (≥2 hours) or 0.55 for fragmented sleep (<2 hours), per Bonnet (1987) and Bonnet & Arand

  (2003)
- **q** is the sea state quality coefficient (1.0, 0.8, 0.55, or 0.3), derived from the maritime sleep literature (Hystad & Eid, 2016; Kerkamm et al., 2023)
- **1.5** is an acceleration factor reflecting that even partial sleep produces disproportionate recovery in the early hours, consistent with the initial rapid phase of Process S dissipation (Folkard & Åkerstedt,

  1997)

The recovery value is subtracted from the running hours-awake counter, modelling the partial reset that off-watch sleep provides. This means that on a well-structured watch system, the hours-awake counter oscillates rather than monotonically increasing — but it never fully resets to zero, because off-watch sleep at sea never fully replaces the sleep it would have been ashore (Belenky et al., 2003; Cohen et al., 2010).

7.4 What the Model Shows

The integrated model produces several insights that are not intuitive:

1. **Departure time matters enormously.** Departing at 0600 versus 1800 can shift the onset of impairment by several hours, because the circadian trough either coincides with or opposes the accumulating sleep debt (Folkard & Åkerstedt, 1997; Schmidt et al., 2007).
2. **Adding one crew member is often more valuable than any other intervention.** Going from 2 crew to 3 increases off-watch time from 50% to 67% of the passage, allowing substantially more — and deeper — sleep. Paul and Love (2022), evaluating six different Royal Canadian Navy watch systems, found that the 1-in-3 straight 8-h shift schedule produced the best fatigue and quality-of-life outcomes — a system that maximises off-watch time relative to on-watch time.
3. **Short watch rotations (3 on / 3 off) can outperform longer ones (6 on / 6 off),** because they cap the maximum continuous wakefulness at 3 hours plus however long the sailor has been awake before their watch. However, this advantage is partially offset by reduced sleep depth from shorter off-watch periods (Bonnet & Arand, 2003). Dohrmann and Leppin (2017) found that the 6-on/6-off system consistently produced the worst fatigue outcomes in their systematic review.
4. **Sea state has a compounding effect.** In rough weather, every off-watch period provides less recovery, meaning impairment accumulates faster — precisely when cognitive demand is highest (Hystad & Eid, 2016; Abrahamsen et al., 2023).
5. **Self-assessment is unreliable.** Consistent with Van Dongen et al. (2003; 2004) and Pilcher & Huffcutt (1996), sailors' subjective sense of their own alertness is a poor predictor of their actual cognitive performance after the first 24 hours.

These insights are valuable precisely because they are not intuitive — which is why the model must be made accessible through a tool that performs the calculations automatically, presents results visually, and allows sailors to explore different passage configurations interactively.

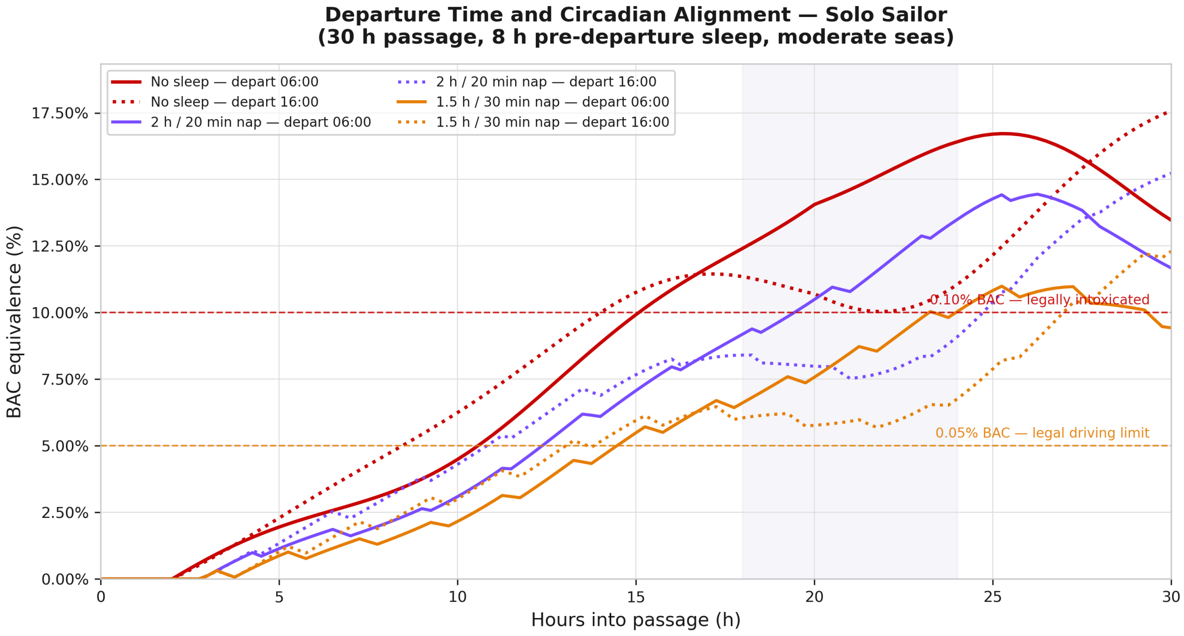

Figure 3: Effect of departure time on fatigue trajectory for a solo sailor on a 30-hour passage in moderate seas, with 8 hours of pre-departure sleep. Three nap schedules are compared (no sleep, 2 h on / 20 min nap, and 1.5 h on / 30 min nap), each at departure times of 06:00 (solid) and 16:00 (dotted). Short naps slow fatigue accumulation but cannot prevent it. The circadian trough amplifies impairment differently depending on departure time.

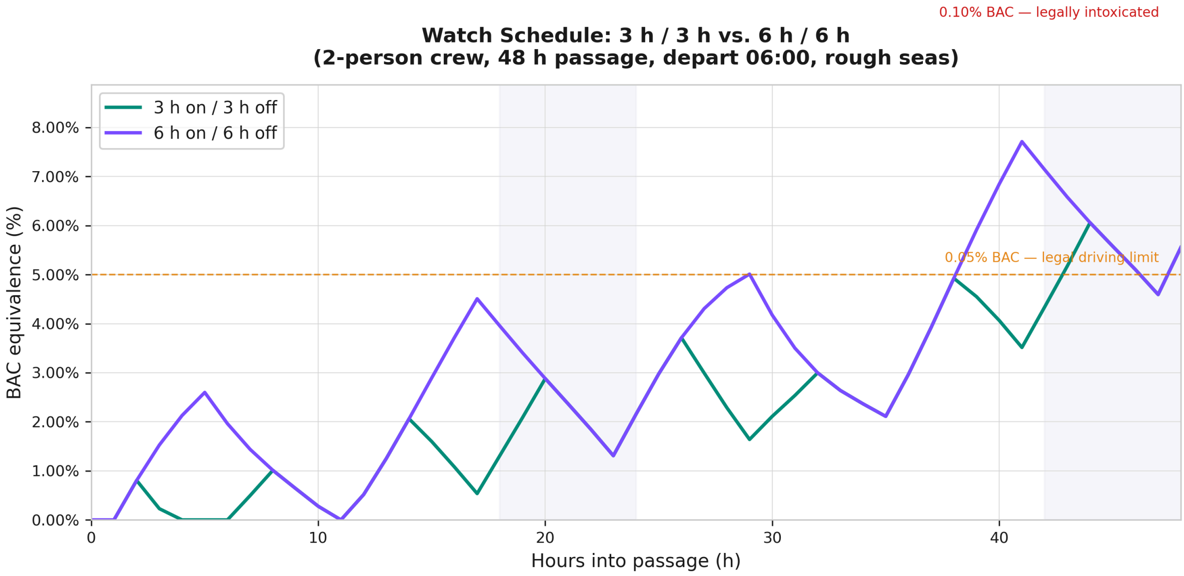

Figure 4: Watch schedule comparison — 3 h on / 3 h off vs. 6 h on / 6 h off for a 2-person crew on a 48-hour passage in rough seas. The 6/6 schedule produces higher peak BAC values within each cycle due to longer continuous wakefulness, despite identical total on-watch time. Both schedules show progressive fatigue accumulation when rough seas degrade sleep recovery. Shaded bands indicate night periods (00:00–06:00).

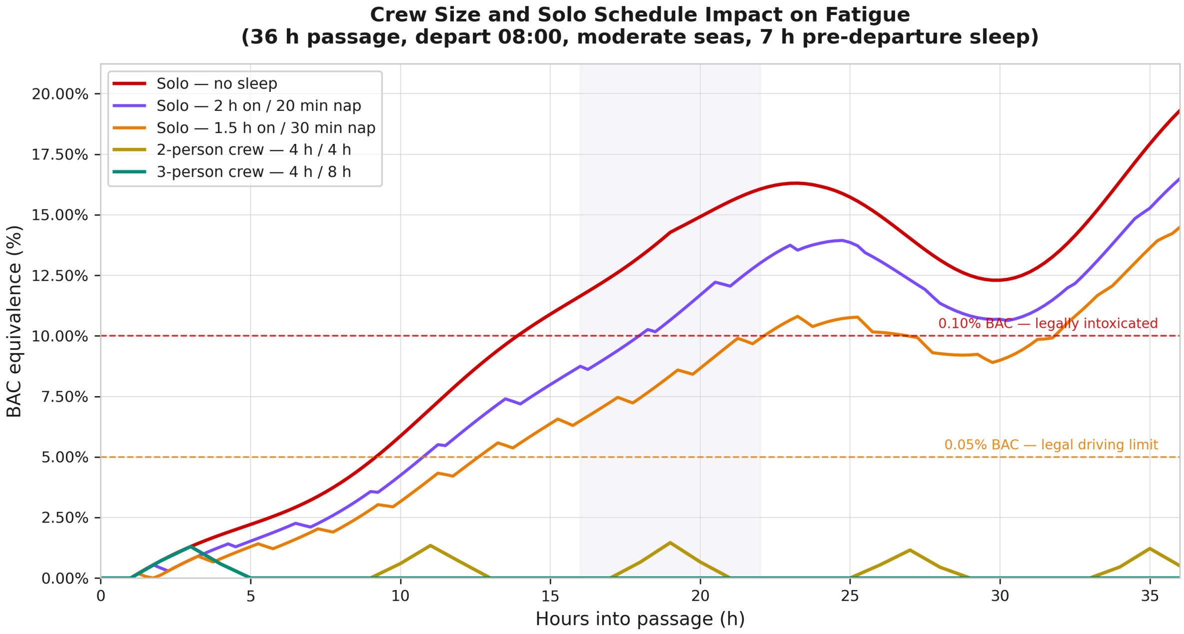

Figure 5: Crew size and solo nap schedule impact on fatigue over a 36-hour passage in moderate seas. Solo sailors accumulate severe impairment regardless of nap strategy — short naps (20–30 min) slow the decline but cannot prevent it. A 2-person crew with 4 h / 4 h watches stays mostly below 2% BAC equivalence. A 3-person crew with 4 h / 8 h watches remains near zero. Adding a second crew member is the single most effective fatigue mitigation.

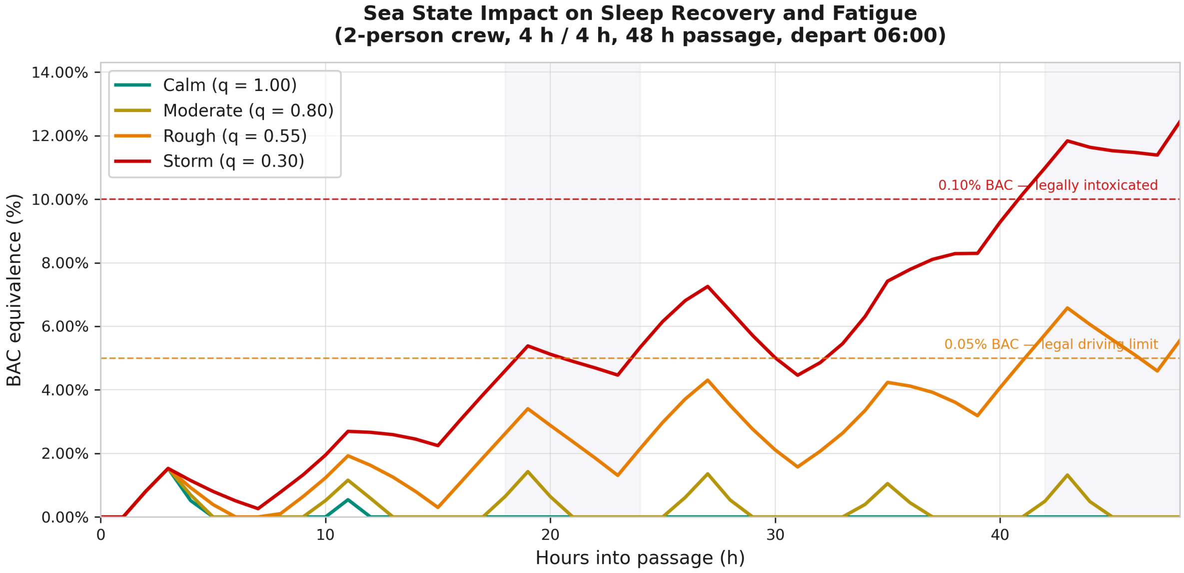

Figure 6: Sea state impact on fatigue accumulation for a 2-person crew (4 h / 4 h watches) on a 48-hour passage. In calm seas, sleep recovery fully compensates for on-watch fatigue. As conditions worsen, degraded sleep quality causes progressive fatigue accumulation — in storm conditions (q = 0.30), BAC equivalence exceeds 0.10% by hour 42. Sea state coefficients derived from Hystad & Eid (2016), Kerkamm et al. (2023), and Abrahamsen et al. (2023).

8. From Model to Application: A Reference Implementation

8.1 Design Philosophy

A fatigue model is only useful if sailors actually use it. The biomathematical framework described in the preceding sections — while grounded in decades of peer-reviewed research — involves piecewise linear functions, dual-cosine circadian oscillators, and multiplicative interaction terms that are impractical for manual calculation. The research consistently shows that subjective self-assessment of fatigue is unreliable (Van Dongen et al., 2003; Pilcher & Huffcutt, 1996). What is needed is a tool that performs these calculations automatically, presents results in an intuitive format, and is accessible to any sailor with a smartphone or web browser.

A reference implementation of the model — a passage fatigue calculator — was developed to fill this gap. It implements every formula, constant, and coefficient described in this paper — the Dawson & Reid base impairment function (Section 7.2), the Folkard & Åkerstedt circadian modulation (Section 3.3), the Bonnet sleep fragmentation efficiencies (Section 4.3), the sea state quality coefficients (Section 5.2), and the Van Dongen cumulative day factor (Section 6.5) — in a deterministic, hour-by-hour simulation engine. No approximations or simplifications were introduced during implementation; the application faithfully reproduces the model as described.

8.2 Technical Implementation

The calculator was built as a cross-platform application, deployed on Android, iOS, and the web from a single codebase. All computation is performed client-side. No data is transmitted to any server, no account is required, and the tool is freely available. This architecture was chosen deliberately: a sailor planning a passage at anchor in a remote bay with intermittent connectivity should be able to use the tool without relying on cloud infrastructure.

The simulation engine runs an hour-by-hour loop over the passage duration. For each hour, it determines whether the sailor is on watch (based on the selected watch schedule), updates the hours-awake counter (incrementing during watches, applying the sleep recovery function during off-watch periods), computes the three model components (base impairment, circadian modulation, cumulative day factor), and outputs the composite BAC equivalence. The reactive state management architecture automatically re-computes the entire simulation whenever any input parameter changes, providing instant visual feedback as sailors explore different passage configurations.

8.3 User Interface and Inputs

The calculator accepts six inputs that define a passage plan:

Input	Range	Purpose
Crew size	–4	Determines watch rotation options
Distance	nautical miles	Combined with speed to compute passage duration
Speed	knots	Combined with distance to compute passage duration
Departure hour	–23	Sets the circadian phase at departure
Pre-departure sleep	–16 hours	Initialises the hours-awake counter
Sea state	Calm / Moderate / Rough / Storm	Sets the sleep quality coefficient

For each crew size, the calculator offers four empirically representative watch schedules — from continuous solo sailing to structured 4-on/4-off rotations — each flagged for whether it permits deep sleep (off-watch periods ≥2 hours).

8.4 Output and Visualisation

Results are presented in three complementary formats:

1. **Risk summary.** A colour-coded status indicator (green/amber/red) showing the overall passage risk level, with the peak BAC equivalence displayed on a radial gauge calibrated from 0% to 0.20%.
2. **Fatigue trajectory chart.** A time-series graph plotting BAC equivalence and hours awake across the passage duration, with night periods shaded. This makes the interaction between circadian rhythm and sleep deprivation visually apparent — sailors can see exactly when impairment peaks and how watch rotations create the characteristic saw-tooth recovery pattern.
3. **Hour-by-hour breakdown table.** A detailed tabulation of each hour's BAC equivalence, hours awake, on-watch status, and time of day — allowing precise identification of the most dangerous periods.

A comparison mode allows side-by-side evaluation of the current crew size against one additional crew member, directly illustrating the fatigue reduction benefit of adding crew (Section 10.4).

8.5 Localisation

The calculator is localised in five languages — English, Spanish, French, German, and Italian — covering the primary languages of recreational sailing in the Mediterranean and Northern Europe.

8.6 Verification

The implementation was verified by systematic comparison of the app's output against manual calculations using the formulas in this paper. For each model component — base impairment, circadian modulation, sleep recovery, sea state degradation, and cumulative day factor — test cases were constructed at boundary conditions (e.g., exactly 17 hours awake, circadian peak at 15:00, circadian trough at 03:00, deep vs. shallow sleep threshold at 2 hours) and the app's output confirmed to match the analytical predictions. The hour-by-hour simulation was further validated against the laboratory data of Dawson & Reid (1997) for the 17-hour and 24-hour BAC equivalence thresholds.

:	**ionals Are Required to Do**
Rest in any 24-hour period Rest in any 7-day period Maximum rest period splits Maximum interval between rest periods	10 hours 77 hours 2 (one must be ≥6 hours) 14 hours
ese requirements exist because the Inter cognises that fatigue degrades performan search basis for these standards is expl n guidance on fatigue mitigation (IMO, 2 19 guidelines (MSC.1/ Circ.1598), which s rcular (MSC/Circ.1014), address fatigue eryone from ratings to masters to naval at fatigue risk is systemic, not individ	national Maritime Organization ce to dangerous levels. The icitly referenced in the IMO's 001; IMO, 2019). The updated upersede the original 2001 across nine modules covering architects — a recognition ual.
UK Maritime and Coastguard Agency study mmon 8-on/8-off watchkeeping system conf latively generous schedule produced meas th performance degradation concentrated Brasher, 2009).	specifically investigating the irmed that even this urable fatigue in seafarers, in the night watches (Bridger
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10. Practical Implications for Passage Planning

The science summarised in this paper — and made accessible through the Passage Fatigue Calculator described in Section 8 — leads to several concrete recommendations for passage planning. Each of the following can be explored interactively in the app by varying the relevant input parameter:

10.1 Pre-Departure Sleep Loading

Every hour of sleep before departure directly delays the onset of impairment. The base model assumes 16 hours of wakefulness before fatigue begins to accumulate; with a full 7–9 hours of pre-departure sleep, a sailor effectively starts with a buffer of 7–9 hours before impairment begins. Departing on a poor night's sleep (3 hours) eliminates most of this buffer.

Rupp et al. (2009) have shown that extended sleep in the days before anticipated restriction — so-called "sleep banking" — has robust laboratory support. Field evidence in solo offshore racing is suggestive but not yet definitive: most racers in the Mini Transat adopted the strategy, though no significant race-time benefit was detected in that single field study (Filardi et al., 2020).

Recommendation: Treat the night before departure as critical. Prioritise sleep over last-minute provisioning. If possible, extend sleep to 9–10 hours for two or three nights before a multi-day passage.

10.2 Departure Timing

The interaction between time awake and circadian rhythm means that departure timing can shift the onset of meaningful impairment by several hours. An early-morning departure (0600) positions the first circadian trough at the 20–24 hour mark — exactly when sleep deprivation is also peaking. An afternoon departure (1400–1600) means the sailor is still relatively fresh during the first night's circadian trough (Schmidt et al., 2007).

Recommendation: For overnight passages, consider a mid-afternoon departure to avoid the worst alignment of circadian trough and sleep deprivation.

10.3 Watch Schedule Selection

The choice of watch schedule interacts with sleep architecture. Schedules that provide off-watch blocks of at least 2 hours allow one or more complete 90-minute sleep cycles (Dement & Kleitman, 1957), yielding deep recovery. Schedules with shorter off-watch periods (e.g., 20-minute naps every 2 hours for solo sailors) prevent deep sleep and provide only shallow recovery at approximately 55% efficiency (Bonnet, 1987).

For two-person crews, the evidence favours 3 on / 3 off over 6 on / 6 off for most passages, despite the apparent advantage of longer sleep blocks. The 6 on / 6 off schedule allows 6 hours of accumulated wakefulness per watch, pushing the sailor closer to impairment thresholds — particularly when combined with pre-watch wakefulness and circadian effects. This is consistent with Dohrmann and Leppin's (2017) finding that 6-on/6-off consistently produces the worst fatigue outcomes, and Marando et al.'s (2023) finding that longer off-watch periods are associated with better cognitive performance.

10.4 The Crew Size Decision

The model consistently shows that the single most effective fatigue mitigation strategy is adding crew. This is because crew size directly determines the ratio of on-watch to off-watch time:

Crew	On-Watch %	Off-Watch %
(solo)	100%	0% (naps only)
2	50%	50%
3	33%	67%
4	25%	75%

Going from solo to two-person crew is the largest single jump in available rest time. Going from two to three is the next largest proportional improvement. Beyond four, the marginal benefit diminishes. Paul and Love (2022), evaluating six different Royal Canadian Navy watch systems, found that the 1-in-3 straight 8-h shift schedule produced the best fatigue and quality-of-life outcomes — a system that maximises off-watch time relative to on-watch time.

10.5 Sea State Planning

Because rough conditions degrade sleep quality by up to 70% (storm coefficient: 0.30), weather routing is a fatigue management strategy as well as a safety one. A longer route in calmer conditions may result in less total fatigue than a shorter route in rough seas, because the crew recovers more effectively during off-watch periods (Hystad & Eid, 2016; Abrahamsen et al., 2023).

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11. Limitations and Caveats

This model, like all biomathematical fatigue models (see Mallis et al., 2004; Dawson et al., 2011), is a simplification. Several important limitations should be noted:

1. **Individual variation.** The Dawson & Reid findings represent population means. Van Dongen et al. (2004) have demonstrated that some individuals are consistently more vulnerable to sleep deprivation than others, and that this variability is trait-like — stable across repeated exposures. The model does not capture individual differences.
2. **Age effects.** Sleep architecture changes with age. Older sailors may experience more fragmented sleep and reduced slow-wave sleep even in calm conditions (Bonnet & Arand, 2003). The model does not account for age.
3. **Caffeine and stimulants.** Caffeine can temporarily mask subjective sleepiness without fully restoring cognitive performance. The model does not include pharmacological interventions, though sailors may find it useful to note that the combination of a short nap (≤20 minutes) with 150–200mg of caffeine consumed immediately before the nap has been shown to be more effective than either intervention alone (Reyner & Horne, 1997).
4. **Experience and automation.** Experienced sailors develop coping strategies and may offload certain cognitive tasks to autopilot systems, chartplotters, and AIS. These factors may modify the practical consequences of fatigue but do not change the underlying cognitive impairment (Harrison & Horne, 1999; Durmer & Dinges, 2005). Fatigued mariners may maintain routine performance but lose the capacity to respond effectively to novel situations (Harrison & Horne, 1999).
5. **Motivation and stress.** Acute stress can temporarily override circadian signals and increase alertness. However, this "emergency reserve" is short-lived and unreliable (Banks & Dinges, 2007).
6. **The 55% fragmentation coefficient** is a conservative estimate derived from laboratory sleep fragmentation studies (Bonnet, 1987; Stepanski et al., 1984; Martin et al., 1997). The polysomnographic data from Kerkamm et al. (2023), showing only 78.3% sleep efficiency aboard ships at sea, suggests the actual coefficient at sea may be lower — meaning sleep quality may be even worse than the model predicts.

The model should be understood as a planning tool, not a diagnostic instrument. It indicates the approximate trajectory and magnitude of fatigue-related impairment for a given passage plan. It does not replace situational judgment, and it cannot account for the full complexity of an individual sailor's physiological response.

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12. Conclusions

Fatigue is the most prevalent and least managed risk factor in recreational sailing. The peer-reviewed evidence is unambiguous: after 17 hours of sustained wakefulness, cognitive performance degrades to a level equivalent to a blood alcohol concentration of 0.05% (Dawson & Reid, 1997); this impairment is amplified by circadian rhythm (Folkard &

Åkerstedt, 1997), compounded by cumulative sleep debt over multi-day passages (Van Dongen et al., 2003), degraded by the maritime environment (Hystad & Eid, 2016; Kerkamm et al., 2023), and — most dangerously — invisible to the impaired sailor themselves (Van Dongen et al., 2004; Pilcher & Huffcutt, 1996).

Commercial mariners are protected by the STCW Convention's mandatory rest requirements (IMO, 2010). Recreational sailors have no equivalent framework. A couple on an overnight Mediterranean passage will routinely exceed the professional limits without realising the degree of impairment they are incurring.

This paper has synthesised more than 50 peer-reviewed studies into a biomathematical fatigue model that integrates five evidence-based components — homeostatic sleep pressure, circadian modulation, sleep fragmentation efficiency, sea state degradation, and cumulative day factor — into a single impairment estimate expressed as a BAC equivalence. The model has been implemented as a free, cross-platform passage fatigue calculator available on Android, iOS, and the web, requiring no account, no connectivity, and no specialised knowledge to operate.

The practical implications for passage planning are clear. Pre-departure sleep should be maximised and treated as a critical preparation task. Departure timing should account for circadian alignment. Watch schedules should be structured to permit sleep blocks of at least two hours. Adding a third crew member provides the single largest reduction in fatigue risk. And weather routing should be understood as a fatigue management strategy, not only a safety one.

A freely available reference implementation of this model — the Passage Fatigue Calculator — is available as a companion application for Android, iOS, and the web. We encourage recreational sailors to incorporate quantitative fatigue estimation into their standard passage planning — not because it replaces seamanship, but because it makes visible a risk that is otherwise impossible to perceive until it is too late.

Use of AI-Assisted Tools

An AI-assisted tool (Claude, Anthropic) was used for editorial support during the preparation of this manuscript. The authors are responsible for all scientific content, analysis, and conclusions.

Conflicts of Interest

Both authors are affiliated with Galvanic Works S.L. The authors declare no other conflicts of interest.

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The reference implementation of the fatigue model described in this paper is freely available as a cross-platform application. The complete mathematical model is fully described above, enabling independent implementation and verification. No account or internet connection is required to use the companion calculator.