Jillian Dorrian, Steven Hursh, Lauren Waggoner, Crystal Grant, Maja Pajcin, Charlotte Gupta, Alison Coates, David Kennaway, Gary Wittert, Leonie Heilbronn, Chris Della Vedova, Siobhan Banks

How much is left in your "sleep tank"? Proof of concept for a simple model for sleep history feedback

Accident Analysis and Prevention, 2018; 126:177-183

Published at: http://dx.doi.org/10.1016/j.aap.2018.01.007

Elsevier Editorial System(tm) for Accident Analysis & Prevention
Manuscript Draft

Manuscript Number:

Title: How much is left in your "sleep tank"? A simple model for sleep history feedback

Article Type: SI: MANAGING FATIGUE

Keywords: sleep, shiftwork, actigraphy, modelling, fitness for work

Corresponding Author: Dr. Jillian Dorrian, Ph.D., M.Biostat.

Corresponding Author's Institution: University of South Australia

First Author: Jillian Dorrian, Ph.D., M.Biostat.

Order of Authors: Jillian Dorrian, Ph.D., M.Biostat.; Steven Hursh, PhD; Lauren Waggoner, PhD; Crystal Grant, B Health Sci (Hons); Maja Pajcin, B Lab Med (Hons); Charlotte Gupta, B Psych (Hons); Alison Coates, PhD; David Kennaway, PhD; Gary Wittert, MD, PhD; Leonie Heilbronn, PhD; Chris Della Vedova, PhD; Siobhan Banks, PhD

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How much is left in your "sleep tank"? A simple model for sleep history feedback

Submitted for Consideration for the Tenth International Conference on Managing Fatigue Special Edition of Accident Analysis and Prevention

Jillian Dorrian[a], Steven Hursh[b], Lauren Waggoner[b], Crystal Grant[a], Maja Pajcin[a], Charlotte Gupta[a], Alison Coates[a], David Kennaway[c], Gary Wittert[d], Leonie Heilbronn[d], Chris Della Vedova[a], Siobhan Banks[a].

[a]University of South Australia, GPO Box 2471, Adelaide, South Australia 5001, Australia
jill.dorrian@unisa.edu.au; crystal.grant@mymail.unisa.edu.au; maja.pajcin@mymail.unisa.edu.au; charlotte.gupta@mymail.unisa.edu.au; alison.coates@unisa.edu.au; Chris.DellaVedova@unisa.edu.au; siobhan.banks@unisa.edu.au
[b]Institutes for Behavior Resources Inc., 2104 Maryland Avenue, Baltimore, MD 21218, USA
shursh@ibrinc.org; lwaggoner@ibrinc.org
[c]Robinson Research Institute and Adelaide School of Medicine, University of Adelaide, GPO Box 498 Adelaide, South Australia 5005, Australia
david.kennaway@adelaide.edu.au
[d]University of Adelaide, University of Adelaide, GPO Box 498, Adelaide, South Australia 5005, Australia
gary.wittert@adelaide.edu.au; leonie.heilbronn@adelaide.edu.au

Corresponding author:
Jillian Dorrian, MBiostat, PhD
Centre for Sleep Research
School of Psychology, Social Work and Social Policy
Division of Education, Arts and Social Sciences
University of South Australia
GPO Box 2471
Adelaide South Australia 5001
Ph: +61 88302 4484
Email: jill.dorrian@unisa.edu.au

Abstract

Technology-supported methods for sleep recording are becoming increasingly affordable. Sleep history feedback may help with fatigue-related decision making – Should I drive? Am I fit for work? This study examines a "sleep tank" model (SleepTank™), which is analogous to the fuel tank in a car, refilled by sleep, and depleted during wake. Required inputs are sleep period time and sleep efficiency (provided by many consumer-grade actigraphs). Outputs include suggested hours remaining to "get sleep" and percentage remaining in tank (Tank%). Initial validation was conducted using data from a laboratory-based simulated nightshift study. Ten, healthy males (18-35y) undertook an 8h baseline sleep opportunity and daytime performance testing (BL), followed by four simulated nightshifts (2000h-0600h), with daytime sleep opportunities (1000h-1600h), then an 8h night-time sleep opportunity to return to daytime schedule (RTDS), followed by daytime performance testing. Psychomotor Vigilance Task (PVT) and Karolinska Sleepiness Scale were performed at 1200h on BL and RTDS, and at 1830h, 2130h 0000h and 0400h each nightshift. A 40-minute York Driving Simulation was performed at 1730h, 2030h and 0300h on each nightshift. Model outputs were calculated using sleep period timing and sleep efficiency (from polysomnography) for each participant. Tank% was a significant predictor of PVT lapses ($p<0.001$), and KSS ($p<0.001$), such that every 5% reduction resulted in an increase of one lapse, or one point on the KSS. Tank% was also a significant predictor of %time in the Safe Zone from the driving simulator ($p=0.001$), such that every 1% increase in the tank resulted in a 0.75% increase in time spent in the Safe Zone. Initial examination of the correspondence between model predictions and performance and sleepiness measures indicated relatively good predictive value. Results provide tentative evidence that this "sleep tank" model may be an informative tool to aid in individual decision-making based on sleep history.

key words: sleep, shiftwork, actigraphy, modelling, fitness for work

1. Introduction

Sleep loss results in increased likelihood of error and accident, in the workplace and on the roads (Rajaratnam and Arendt 2001, Rogers, Hwang et al. 2004, Dorrian, Tolley et al. 2008). In Australia, in any workplace covered by the Work Health and Safety Act (SafeWorkAustralia 2011), fatigue management is a reciprocal responsibility for employers and employees, whereby the employers have a duty of care to provide a safe workplace, and the employees have a responsibility to be fit for work. Decisions about whether an employee is safe to start or to continue work are frequently self-reported, and in some circumstances (e.g. truck cab, driver-only train cab) solo operators may only have their own insight to rely on (Dorrian, Lamond et al. 2003). This leads us to consider the information that people use to make decisions about whether they are sufficiently fit to start, or to continue work.

Sleepiness is often used as an indicator of fatigue-related impairment, and in many circumstances, it tracks performance measures (Kaida, Takahashi et al. 2006). However, this is not always the case (Van Dongen, Maislin et al. 2003). Further, measuring sleepiness is not necessarily measuring awareness of risk. Performance ratings often track sleepiness more closely than they track performance (Dorrian, Lamond et al. 2000, Dorrian, Lamond et al. 2003, Dorrian, Roach et al. 2007; Paech, Banks et al. 2016). Given these inconsistencies, an alternative to solely relying on self-assessment could involve integration of technology-supported methods for sleep recording. Indeed, consumer-grade sleep technologies (CST) are becoming increasingly affordable (Ko, Kientz et al. 2015) and may provide data that can scaffold personal monitoring systems to inform decisions relating to fitness for work. While the proliferation of such devices supports their potential, current barriers to effective use of CST include a lack of validation against research-grade actigraphy and polysomnography, which is the gold-standard for sleep measurement.

Current international best practice in workplace fatigue management involves a Fatigue Risk Management System (FRMS) (Dawson and McCulloch 2005, Gander, Hartley et al. 2011, Cabon, Deharvengt et al. 2012, Gander, Mangie et al. 2014), which includes specific policy, education and awareness training, fatigue monitoring systems with feedback, procedures for reporting, investigating and recording fatigue-related incidents and accidents, and evaluation processes and mechanisms for testing the impact of any fatigue-interventions (Gander, Hartley et al. 2011). In this context, validated CSTs may assist with fatigue monitoring, however, it is critical to consider the form of the feedback. At present, CSTs provide information such as prior sleep duration, timing, and sometimes an indicator of sleep quality or efficiency. In operational settings, a worker needs to be able to use sleep history information to assess what this may mean for their fatigue level when starting work. Further, it is often necessary to project fatigue assessments into the future – towards the end of my shift, will I still be fit for work, or for my commute?

Techniques to transform sleep history to indicate fatigue likelihood are already in use as part of FRMS in a number of industries including, for example, rail (TransportCanada 2011) and healthcare (SA_Ambulance 2008). These incorporate a simple calculation based on the allocation of "fatigue likelihood points" according to the amount of sleep in the prior 24 and 48h, and the number of hours that the employee has been awake (Dawson and McCulloch 2005). The calculation may be performed by the worker (TransportCanada 2011), or may be automated based on simple inputs (SA_Ambulance 2008), and is followed by a series of actions to take should the employee reach critical thresholds indicating that fatigue, at levels of operational concern, is likely.

Another approach that has received much attention in the literature for transforming sleep history into estimation of fatigue likelihood (or performance impairment, alertness, or effectiveness) involves biomathematical modelling (Dinges 2004, Hursh, Redmond et al. 2004, Mallis, Mejdal et al. 2004, Van Dongen, Mott et al. 2007, Dawson, Noy et al. 2011). Frequently, the input is simply work hours, from which sleep (and then the outcomes) are estimated (Kandelaars, Fletcher et al. 2006). Sleep estimation is primarily based on the two-process model (Borbély 1982), which includes a circadian oscillator, representing the sinusoidal 24h rhythm, and a homeostatic function, which increases with wake, and decreases during sleep. These models are used as part of FRMS in industry at an aggregate level to predict fatigue hotspots across rosters, target roster areas for countermeasure application, and to compare potential rosters (Mallis, Banks et al. 2017).

A current area of development for biomathematical models is their application in the context of predicting individual fatigue likelihood (Van Dongen, Mott et al. 2007, Dorrian, Darwent et al. 2012). One challenge for individual modelling is the estimation of the circadian component, especially in the context of irregular work hours and/or time zone changes, as are frequent in 24h industries including aviation. The circadian system adapts slowly to sleep in new time zones, and is influenced strongly by differences in light exposure (Mallis, Banks et al. 2017). In contrast, the homeostatic function is relatively simple to model if sleep history is known. Further, since there is a circadian rhythm to sleep length and quality (Van Dongen and Dinges 2005), measures of sleep timing, length, and efficiency (as can be estimated from CSTs), these measures, to some extent, have an implicit circadian signal. This study examines a model that mathematically transforms sleep history (timing, length, efficiency), using our understanding of homeostatic component only of the two-process model, that could be built-in to CSTs to provide useful feedback to aid in fatigue-related decision-making and forward planning. This "sleep tank" model (SleepTank™[1]) was invented by the second author and enhances the homeostatic component of the two-process model with factors to account for the effects of prolonged sleep restriction (Belenky, Wesensten et al. 2003, Van Dongen, Maislin et al. 2003, Hursh, Redmond et al. 2004) and individual differences in sleep requirement. For this study, the sleep tank was calibrated to an average sleep requirement of 8 hrs of sleep per day.

[1] SleepTank™ is a trademark of the Institutes for Behavior Resources, Inc.

2.0 Method

Initial validation of the "sleep tank" model (SleepTank™) was conducted using data from a simulated nightshift study. This study was approved by the University of South Australia Human Research Ethics Committee (0000033621) and was conducted in accordance with the Declaration of Helsinki.

2.1 Participants

Ten, healthy males (18-35y) were recruited using flyers and social media. Interested participants underwent screening. Inclusion criteria included good physical (confirmed by a general health questionnaire and fasting blood screen) and mental health (assessed by clinical history and Beck Depression Inventory) (Beck, Steer et al. 1996), a score between 22-43 on the Composite Morningness Questionnaire (Horne and Ostberg 1976), and habitual nightly sleep time between 7 and 9 h (confirmed by sleep diaries and wrist actigraphs, Actiwatch 2, Philips Respironics, Bend, OR). Exclusion criteria included reported: (a) sleep disorder (general health questionnaire) or sleep disturbance (>6 on the Pittsburgh Sleep Quality Index) (Buysse, Barzansky et al. 2003); (b) food allergy/ intolerance; (c) restrained eaters; (d) BMI >30 kg/m^2; (e) use of prescription or over-the-counter medications known to affect glucose metabolism (Grant, Coates et al. 2017) or sleep; or (f) engagement in night shift work, trans-meridian travel, smoking, illicit drug use, excessive alcohol consumption (>2 standard drinks/day) or caffeine consumption (>2 cups/day) in the three months prior to the study. Participants were instructed to abstain from alcohol and caffeine in the week prior to the study (with compliance checked using a 3-day food diary completed on non-consecutive days).

2.2 Procedure

Participants (in groups of three or four) stayed in the Centre for Sleep Research laboratory at the University of South Australia for 7 days. This period included an 8 h baseline sleep opportunity (2200h-0600h) and daytime performance testing (BL), followed by four simulated nightshifts (2000h-0600h), with daytime sleep opportunities (1000h-1600h), then an 8h night-time sleep opportunity (2200h-0600h) to return to daytime schedule (RTDS), before a final period of daytime performance testing. Psychomotor Vigilance Task (PVT) and Karolinska Sleepiness Scale (KSS) were performed at 1200h on BL and RTDS, and at 1830h, 2130h 0000h and 0400h each simulated nightshift. A 40-minute York Driving Simulation was performed at 1730h, 2030h and 0300h on each simulated nightshift (Figure 1). On BL, Day4 and RTDS, sleep was monitored using polysomnography.

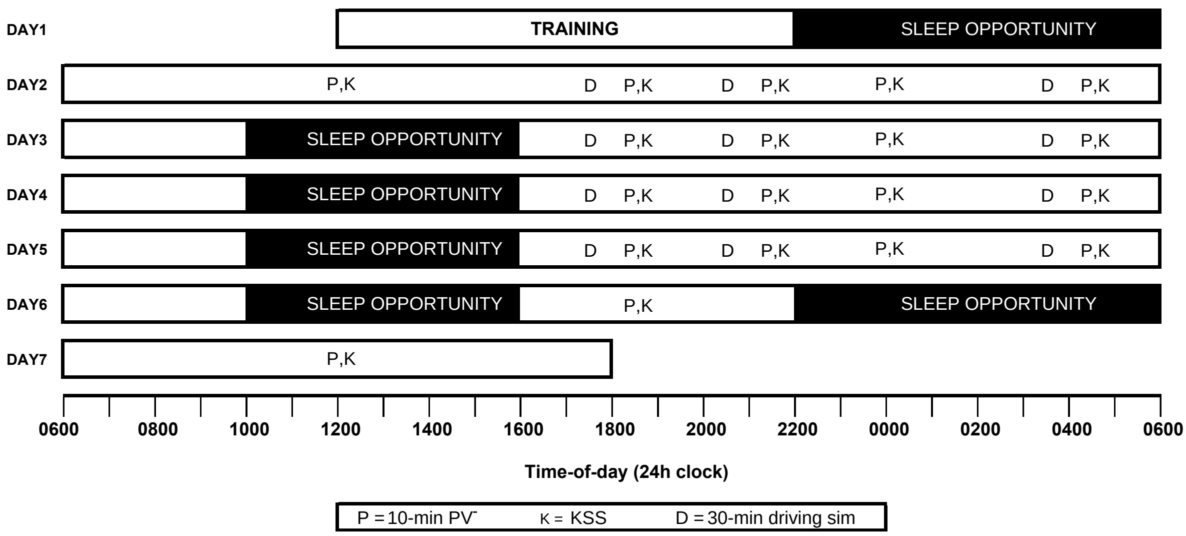

Figure 1. ***Protocol Diagram –*** Time-of-day (24h clock) is on the x-axis, with day of study on the y-axis. Black bars indicate sleep opportunities and grey bars indicate simulated night shifts. BL=Baseline, Shift1-4=simulated night shifts, RTDS=return to daytime schedule. PVT=Psychomotor Vigilance Task, KSS=Karolinska Sleepiness Scale.

The laboratory was sound-attenuated. Light levels were maintained at <50 lux during wake periods and <0.03 lux during sleep opportunities. Temperature was kept constant at 23 ± 1°C. No access to time cues was permitted throughout the protocol (i.e. clocks, mobile phones, television, internet). When not completing study tasks, participants were allowed to watch DVDs, play board games, or listen to music. Meals were controlled according to estimated energy requirement, calculated for each participant given the sedentary laboratory protocol (Harris and Benedict 1918). Participants were on one of two eating schedules (Grant, Coates et al. 2017). In one, participants had a meal during their simulated night shifts, and in the other, energy was redistributed to times outside of 1900 to 0700h. Importantly, for all participants, 24h energy consumption was kept constant. Since this was a proof-of-concept analysis to investigate whether the model would track average performance and sleepiness across this schedule, eating groups were not looked at separately. Moreover, differences in eating patterns are consistent with the workplace, where employees differentially distribute their food consumption around the clock (Banks, Dorrian et al. 2014).

2.3 Psychomotor Vigilance Task (PVT)

The PVT was delivered via a hand-held response box. Participants were required to respond as quickly as possible to a stimulus in the form of a red millisecond counter by pressing a response button with the thumb of their dominant hand. When the button is pressed the millisecond counter stops, the number representing the response time in milliseconds. The stimulus was displayed at random intervals between 2 and 10 milliseconds, across the 10-minute task duration. This task is sensitive to the effects of sleep loss and has a 1-3 trial learning curve (Dorrian, Rogers et al. 2005). The variable for analysis in this manuscript was the average number of PVT lapses, defined as response times greater than 500 msec.

2.4 Karolinska Sleepiness Scale (KSS)

Sleepiness was measured using the KSS, which is a 9-point scale ranging from 1=extremely alert to 9=extremely sleepy-fighting sleep. This scale has been used extensively and has been validated against polysomnography and performance measures (Kaida, Takahashi et al. 2006).

2.5 Driving Simulator

Driving performance was measured using the York highway driving simulator (York Computer Technologies, Kingston, ON). The simulator was run on a computer with a steering wheel and accelerator and brake pedals. The simulated drive was a two-lane country road with road markings, signs, and oncoming cars. Speed was displayed at the bottom of the screen and participants were instructed to follow the road rules including a maximum speed limit of 100 km/h. This simulator has demonstrated sensitivity in studies of sleep restriction (Arnedt, Wilde et al. 2000), with minimal practice effects (De Valck, De Groot et al. 2003). The variable for analysis was the percentage of time spent in safe zone, which was defined as within 10km/h of the speed limit and within 0.8m of the centre of the lane.

2.6 Polysomnography (PSG)

Sleep period time and efficiency were measured using PSG with standard electrode placements (C3/A2, C4/A1) during the baseline sleep, one of the 6 h daytime sleep opportunities, and during the RTDS sleep.

2.7 The "Sleep Tank"

The "sleep tank" (SleepTank™), analogous to the fuel tank in a car, is refilled by sleep, and depletes during wake. Required inputs are sleep period time and efficiency. Maximum tank size represents the sleep-fuel required to remain awake for four days. The model focuses on the homeostatic process of the two-process model. It does not include a circadian factor (i.e. it will have a known residual error due to this rhythmic component). This "simplification" is deliberate to enable immediate and continuous feedback from basic sleep inputs.

2.8 Statistical Analyses

In order to investigate changes in performance and sleepiness metrics across the simulated nightshift protocol. Mixed effects ANOVA specified dependent variables of PVT Lapses, KSS, and driving simulator %time in safe zone with fixed effects of shift (1-4), trial (PVT, KSS = 1830h/ 2130h /0000h /0400h; %safe zone = 1730h/ 2030h/ 0300h) and shift* trial with a random effect of subjectID on the intercept. In order to investigate the relationship between model predictions and performance and sleepiness metrics, mixed effects regression specified dependent variables of PVT Lapses, KSS, and driving simulator %time in safe zone with a fixed effect of the percentage left in the "sleep tank" (Tank%) with a random effect of subjectID on the intercept. In order to estimate an effect size for correlations between Tank% and performance and sleepiness metrics, time series correlations were conducted for each individual. Since distributions of *r*-values are skewed, they were transformed using Fisher's *r-z* transformation, the average and standard error (sterr) across participants was calculated, and then values were converted back to *r*-values using the inverse Fisher function.

3.0 Results

Performance and sleepiness were significantly worse during the last test session of the shift compared to earlier trials, and sleepiness was significantly worse during the first shift compared to shifts 2-4 (*p*<0.01, Table 1).

Table 1. ***Performance Changes During Simulated Night Work –*** Mixed effects ANOVA for PVT Lapses, KSS and driving simulator %time in safe zone with fixed effects of shift (1-4), trial (PVT, KSS = 1830h/ 2130h /0000h /0400h; %safe zone = 1730h/ 2030h/ 0300h) and shift* trial with a random effect of subjectID.

	Shift			Trial			Shift*Trial			*Post-hoc*
	F	df	*p*	*F*	df	*p*	*F*	df	*p*	*p*<0.01
PVT	0.09	3,134.0	0.966	23.96	3,134.0	<0.001	0.25	9,134.0	0.985	1830h, 2130h, 0000h < 0300h
KSS	6.63	3,134.0	<0.001	62.02	3,134.0	<0.001	1.42	9,134.0	0.183	1830h < 0000h, 0300h Shift1 > Shifts2-4
%Safe Zone	2.04	3,99.0	0.113	10.24	2,99	<0.001	0.87	6,99.0	0.518	1730h, 2030h > 0300h

Average total sleep time during the baseline night was 7.11 h (SEM=0.05 h), during daytime sleep opportunities was 5.51 h (SEM=0.06), and during the return to daytime schedule night was 6.79 h (SEM=0.05 h). Average sleep efficiency was 89.5 % (SEM=0.6), 92.4% (SEM=1.1), and 84.9% (SEM=0.7) for each of these sleep opportunities respectively. Figure 2 illustrates the suggested hours left to "get sleep" for the laboratory study protocol. Model outputs were calculated using sleep period timing and sleep efficiency (for BL, day sleeps and RTDS using polysomnographic recordings) for each participant. These were then compared to study metrics of performance and sleepiness. On waking at BL, there is >20h "in the tank," with a latest advisable bedtime of 5:45am. After waking from subsequent daytime sleep periods, the starting value "in the tank" is lower, with latest advisable bedtimes moving earlier in the shift across multiple nights.

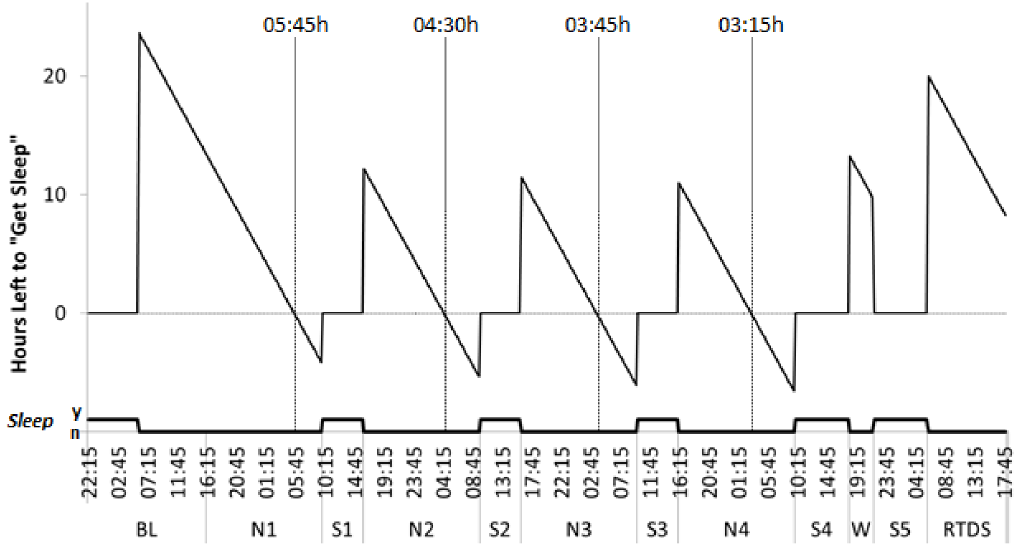

Figure 2. ***Model Hours Left to "Get Sleep" Metric –*** Time-of-day (24h clock) is on the x-axis, hours left to "get sleep" (an estimate of the latest advisable bedtime given what remains in the "Sleep Tank") on the y-axis. Sleep opportunities are shown along the x-axis. BL=Baseline, N1-4=nightshifts, S1-4=Sleep opportunities, RTDS=return to daytime schedule. Times for y=0 (latest advisable bedtimes) are indicated.

Figure 3 displays the percentage remaining in the tank (Tank%), which is highest on waking, with longer, more efficient sleep periods filling the tank to a greater level. Tank% was a significant predictor of PVT lapses (β=-0.44, sterr=0.06, t=-6.87, p<0.001), and KSS (β=-0.20, sterr=0.03, t=-7.68, p<0.001), such that every 5% reduction resulted in an increase of one lapse, or one point on the KSS. Tank% was also a significant predictor of %time in the Safe Zone (β=0.75, sterr=0.22, t=3.40, p=0.001), such that every 1% increase in the tank resulted in a 0.75% increase in time spent in the Safe Zone.

On average, time series correlations between Tank% and performance and sleepiness were moderate (PVT lapses r_{Lag0}=-0.50, sterr=0.08, R^2=0.25; KSS r_{Lag0}=-0.54, sterr=0.08, R^2=0.30; %Time in Safe Zone r_{Lag0}=0.45, sterr=0.17, R^2=0.20).

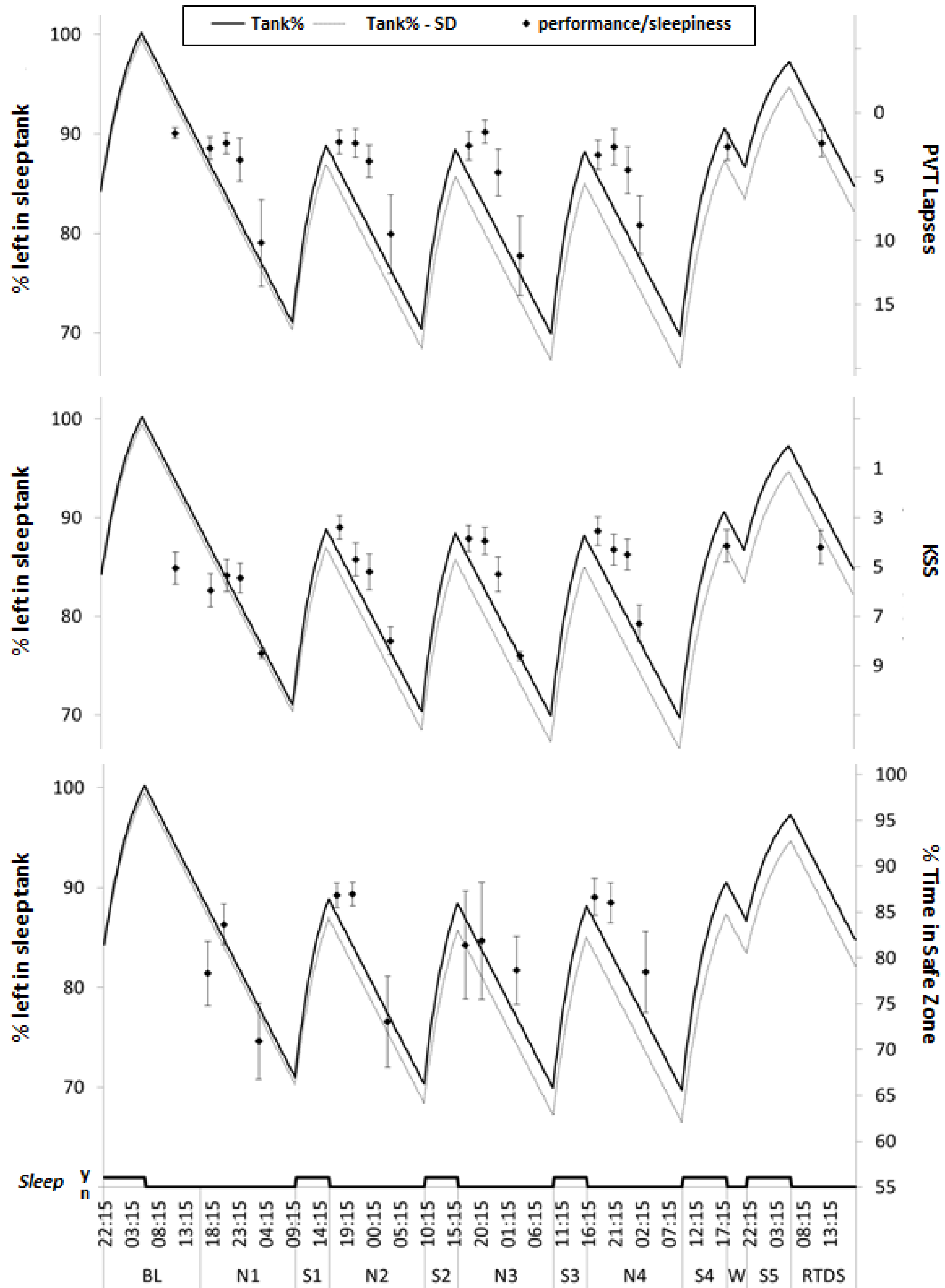

Figure 3. ***"Sleep Tank", Performance and Sleepiness*** **–** Time-of-day (24h clock) is on the x-axis, with % left in the sleep tank on the y-axis. Sleep opportunities are shown along the x-axis. BL=Baseline, N1-4=nightshifts, S1-4=Sleep opportunities, RTDS=return to daytime schedule. PVT Lapses (upper), KSS (middle) and %Time in the Safe Zone from the driving simulator (lower) are superimposed over model output.

4.0 Discussion

Initial examination of the correspondence between model predictions and performance and sleepiness measures from a four-night simulated nightshift protocol indicated relatively good predictive value, with percentage left in the "Sleep Tank" significantly predicting performance lapses, subjective sleepiness and safe driving during a 40-minute driving simulation. The model explained an average of 20-30% of the variance across participants. Performance and sleepiness were worst at the trials closest to model-indicated latest advisable bedtimes. Not only did this simple model map onto the performance and sleepiness low points during the night shifts, but also onto the recovery points after the final daytime sleep and return to daytime schedule.

As expected, during the study, performance and sleepiness were significantly impaired towards the circadian low on each night shift (Dorrian, Lamond et al. 2000, Lamond, Dorrian et al. 2001). Interestingly, there was no significant cumulative impairment across nights, which may be expected across multiple nightshifts (Folkard and Tucker 2003). Sleepiness was worse on the first night in the series, which likely reflects the extended wakefulness that often accompanies transition to night shift (Tepas, Walsh et al. 1981). The relative stability in performance, and improvement in sleepiness across consecutive nights is consistent with previous laboratory studies (Dorrian, Lamond et al. 2003) and may reflect the ideal sleeping conditions in the laboratory, since sleep length and quality are likely to be lower in sleeping environments where light, temperature, and noise frequently cause sleep disturbance (Åkerstedt and Gillberg 1981b, Åkerstedt 1991).

Indeed, this study was a first-step proof-of-concept in a controlled laboratory environment, with young, healthy males on basic performance tests. This clearly limits generalisability to the workplace where employees include females, as well as people who are older, people who are experiencing health complaints, such as gastrointestinal and cardiovascular disease, which are higher amongst shiftworkers (Knutsson 1989, Costa 1997, Lowden, Moreno et al. 2010), and where countermeasure use (e.g. caffeine) is common. The controlled light exposure during the study is also different to the variable light exposure often experienced by nightshift workers, which often includes a bright pulse of morning light during the commute home (Eastman, Stewart et al. 1994). This is a particularly important reason for trialling this work in the field, since the "sleep tank" model only picks up circadian changes implicitly via changes in sleep, and it is necessary to investigate how model predictions map onto performance in the more chaotic workplace environment.

Therefore, critical next steps include examining the model with different shift schedules in the laboratory and the field, and using polysomnographic sleep recording to estimate sleep period time and sleep efficiency (as in the current study) as well as actigraphic estimates of these measures. Results provide tentative evidence that this "sleep tank" model may be an informative tool to aid in individual decision-making based on sleep history. Field validation will allow us to be ready to pair the model with CSTs as they are validated against research-grade sleep measurement tools.

4.1 Summary

Increasingly, people are gaining access to information about their sleep. Using this information to make evidence-based decisions relating to fatigue safety is not always straightforward. Arithmetic transformation of sleep duration and quality into an intuitive "sleep tank" (SleepTank™), which includes suggestions such as the number of hours until more sleep is critical, may assist individual deliberation about fitness for work at that moment, and across a coming shift. Further validation is necessary, however initial findings are promising. Following validation of the model (and the devices) "sleep tank" calculations could be added to consumer-grade actigraphs and/or sleep monitoring apps to help people to map the performance and safety implications of their recent sleep history. Such a device could display time left in the tank (hours), the latest advisable sleep time and a sleep tank gauge, along with advice on how naps might refill the "tank".

5.0 Acknowledgments

The authors would like to thank the research staff and students for their contributions. In particular; Stephanie Centofanti, Emily Watson, Cassie Hilditch, Alex Agostini, Alex Chatburn, Katja Morsky, Kenji Sison, students and volunteers. Thank you also to all the participants. Funding for this study was obtained through internal competitive university grant schemes. The PhD students (Crystal Grant, Maja Pajcin) working on this study were funded through the Australian Government Research Training Program scholarship.

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