Applied Ergonomics 39 (2008) 614–622
APPLIED ERGONOMICS
www.elsevier.com/locate/apergo

The sleep and performance of train drivers during an extended freight-haul operation ☆

David Darwent*, Nicole Lamond, Drew Dawson

Centre for Sleep Research, University of South Australia, Level 7, Playford Building, City East Campus, Frome Road, Adelaide, SA 5000, Australia

Received 31 October 2007; accepted 12 February 2008

Abstract

The sleep and performance of train drivers was monitored across a 106-h rail operation between the Australian cities of Adelaide and Perth. The drivers worked alternating 8-h shift rotations across the operation and rested in specially equipped, crew-van carriages during non-work periods. The crew-van rest opportunities were associated with shorter bedtime spans, less total sleep time, and poorer sleep efficiency than sleeps initiated at home. The duration of crew-van sleeps was primarily dependent on the time of day at which the rest opportunities occurred. Overall, drivers incurred a significant cumulative sleep loss across the duration of the operation. Despite the deficit, drivers were able to sustain vigilance performance across the operation.
Crown Copyright © 2008 Published by Elsevier Ltd. All rights reserved.

Keywords: Sleep; Performance; Rail

1. Introduction

In Australia, supply contracts often require rail companies to deliver goods and services across remote and sparsely populated regions of the country. Operations of this type have traditionally been staffed by train drivers living in rural towns and settlements. The notoriously complex task of scheduling trains and drivers in tandem was facilitated by establishing stations at strategic intervals of the rail line. Unfortunately, the costs associated with maintaining the network infrastructure were substantial, and far exceeded the collective revenues of the industry (Everett, 2006). In recent decades, policy makers have sought reform by promoting privatization, increased competition and economic rationalism (Everett, 2006; Wills-Johnson, 2007). One outcome of these efforts has been the introduction of a novel form of working-time arrangement termed ‘relay van work’.

Relay van work is a rotating shiftwork system that requires teams of drivers to work and sleep onboard a train travelling non-stop between an origin and destination city. In the typical scenario, two teams of two drivers work alternating 8-h shift rotations driving the train. Specially designed crew-van carriages, equipped with sleeping quarters and facilities for domestic activities, provide accommodation for drivers during non-work periods. Once having arrived at a destination terminal, drivers may be shuttled to a hotel room, or simply rest on-board the crew-van, while the train is unloaded and made ready for the return journey. While there are considerable economic and logistic benefits associated with relay van work, there are legitimate concerns about the occupational health and safety risks arising from it.

Circadian maladjustment and sleep loss have been widely reported in connection with rotating shiftwork systems (Akerstedt, 2003; Discoll et al., 2007). The physiological consequences of disruptions to the endogenous circadian and sleep homeostatic processes are well known. Symptoms include excessive sleepiness (Dinges et al., 1997; Rosenthal et al., 1993; Torsvall et al., 1989), neurobehavioural performance deficits (Belenky et al., 2003; Dinges et al., 1997; Van Dongen et al., 2003), and cognitive impairment (Harrison and Horne, 2000; Pilcher and Huffcutt, 1996). In industrial settings, these symptoms

☆Financial support provided by Freight Australia.
*Corresponding author. Tel.: +61 8 8302 6624; fax: +61 8 8302 6623.
E-mail address: david.darwent@unisa.edu.au (D. Darwent).

0003-6870/$ - see front matter Crown Copyright © 2008 Published by Elsevier Ltd. All rights reserved.
doi:10.1016/j.apergo.2008.02.012

manifest a heightened risk of accident (Akerstedt, 2000; Edkins and Pollock, 1997; Folkard, 1997).

Relay van work differs from common two- and three-shift rotating shiftwork systems in several respects. Shift changeovers are faster—the 8-h work–rest routine produces rapid counter-clockwise transitions between morning, afternoon, and night shifts. The rotation effectively imposes a 16-h sleep–wake cycle on drivers (instead of the customary 24-h cycle), and requires constant phase adjustments in the timing of sleep relative to the day–night cycle. Concomitantly, the relatively short duration of rest periods is counterbalanced, because rest periods occur more frequently (i.e. 1.5 rests/day). Thus, while drivers may have fewer hours for sleep in between successive work periods, they are likely to sleep more often in a single day and to be awake for correspondingly shorter periods. Relay van workers must also sleep in noisy crew-van carriages that shudder and vibrate along with the movement of the train. Living and recreation facilities inside crew-vans are generally sparse, while domestic and cleanliness routines must be performed in close proximity with other crew-members.

There is a paucity of empirical research investigating the distinct implications of relay van work for the sleep of train drivers. To our knowledge, only two such investigations have been reported—one in respect to a 40-h operation (Lamond et al., 2005a, b) and the other in respect to a 90-h operation (Jay et al., 2006). Sleep length was shown to vary according to expected circadian variation, but on average drivers obtained only 4.0 and 3.3 h of sleep in crew-van rests, respectively. In comparison to sleep obtained at home, this equated to a net sleep loss of approximately 2.0 h/day across both operations. Comparison of sleep quality measures across home and crew-van rest locations has yielded somewhat equivocal results. Longer sleep onset latency and poorer sleep efficiency were reported in connection with crew-van sleeps in the 40-h operation, but not for the 90-h operation.

The study by Lamond et al. (2005b) found that drivers were able to sustain vigilance performance across the 40-h relay van operation, despite the sleep loss incurred. Laboratory-based protocols indicate that performance deficits induced by partial sleep-deprivation (~5–6 h sleep/day) manifest in about two days (Belenky et al., 2003; Van Dongen et al., 2003). Taken in conjunction, these findings suggest that relay van operations longer than 40 h might compromise drivers' performance. To date, we are not aware of studies which have reported the impact of extended (i.e. >48 h) relay van operations on drivers' performance.

The purpose of this study was to assess the sleep and performance of train drivers during an extended 106-h relay van operation that also included a 16-h layover. The major aims were to: (i) compare sleeps across home, layover, and crew-van locations; (ii) identify patterns in drivers' decisions of when to attempt sleep (termed 'sleep behaviour'); (iii) determine whether drivers incurred an overall sleep loss; and (iv) assess whether drivers could sustain vigilance performance across the relay operation. Our expectations were that crew-van sleeps would be shorter and have poorer sleep efficiency and subjective quality than sleeps initiated at home or during layovers. During the trip, we expected that drivers would initiate a single sleep in each crew-van and layover rest period, and that sleep length in the crew-vans would be the longest for rest periods scheduled at night. We further expected that drivers would incur an overall sleep loss and suffer deficits in vigilance performance as the relay operation progressed.

2. Methodology

2.1. Participants

A sample of 13 male train drivers volunteered to take part in the study, representing approximately 90% of the driver population working the relay operation. Two participants subsequently withdrew from the study. Data from a third were not included in statistical analyses because of deviations from the planned work–rest schedule. The remaining 10 participants ranged in age from 32 to 53 years (mean ± standard deviation = 43.30 ± 7.42). A General Health Questionnaire was administered to screen for sleep disorders and assess general health. Participants had a mean (± standard deviation) body mass index of 30.69 (± 5.55), which is in the obese range. No relevant sleep or medical conditions were disclosed. Two of the drivers were smokers, and all reported consuming caffeine on a regular basis.

2.2. Materials

Sleep/wake states were assessed using Mini-Mitter Actigraph-L activity monitoring devices (Cambridge Neurotechnology Ltd.) in conjunction with sleep diaries. The devices were set to sample activity counts in 1 min epochs, and a medium sensitivity level (activity count per epoch <40) was used to classify sleep and wake states. The diary included sections for recording bed-times and subjective sleep quality ratings. Reported bed-times were cross-validated with activity data and adjusted where inaccuracies were obvious. Estimates of sleep were calculated for all sleep attempts using the algorithms provided by Mini-Mitter. This family of Actigraph devices and algorithms have been validated against polysomnography in applied shiftwork settings (Signal et al., 2005). Four dependent variables were derived from the Actigraph-L/sleep diary information, including

- *Time in bed*—the time difference between bed-time and get-up time.
- *Total sleep time*—the time between sleep onset and offset spent asleep.
- *Sleep efficiency*—total sleep time as a percentage of the sleep period.

- *Sleep quality*—subjective rating of sleep quality on a 5-point Likert scale.

Vigilance performance was measured using a hand-held psychomotor vigilance task (PVT) that measures reaction time (PVT-192, Ambulatory Monitoring Inc, New York). The PVT was configured in accordance with participant handedness and programmed to run for a period of 10 min. The PVT was selected because it is sensitive to neurobehavioural impairments incurred due to sleep loss and has a short learning curve of only 1–3 trials (Dinges et al., 1997). A set of three dependent variables were derived from the raw PVT data:

- *Reaction speed*—the mean inverse reaction time (RT) score ($1/\text{RT} \times 1000$).
- *Frequency of lapses*—the frequency of RT scores >500 ms.
- *Slowest* 10% *of RT scores*—the mean of the slowest 10% of RT scores.

2.3. Protocol

A schematic representation of the relay operation is presented in Fig. 1. The operation required two pairs of drivers to operate a laden freight train between the Australian cities of Adelaide (UTC +0930) and Perth (UTC +0800). All crewmembers reported for duty at 0800 h prior to departure. Drivers on the 'early' schedule commenced driving almost immediately, while drivers on the 'late' schedule rested in the crew-van. Shift changeovers were scheduled every 8 h until arrival in Perth, where a layover was scheduled. During the layover, all drivers were shuttled to a nearby hotel while the train was unloaded and then reloaded ready for the return journey. The duration of the layover was dependent on arrival and train preparation times at the Perth terminal, but lasted approximately 18 h. On the return trip, drivers worked alternating 8-h shift rotations until arrival back at the Adelaide rail terminal. Drivers were scheduled to have either five or six 8-h crew-van sleep opportunities across the relay operation (5×8 h for the early schedule and 6×8 for the late schedule). However, in most cases, delays across the rail line required a relatively short driving shift and rest period at the end of the operation.

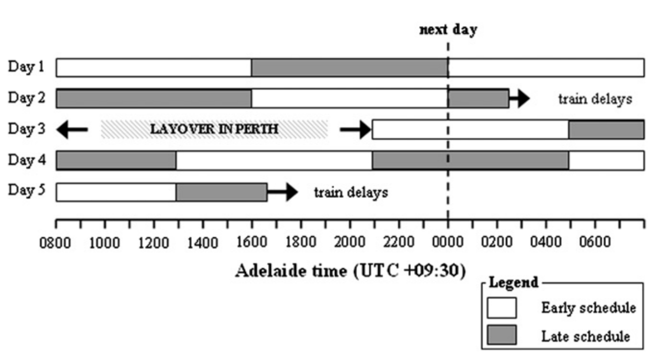

Fig. 1. A schematic representation of the 8-h rotating schedule worked during Adelaide to Perth relay operations.

The crew-van carriage was situated approximately 75 m anterior to the leading locomotive, behind two additional locomotives and the fuel tanks. Four crew-vans were dedicated to the Adelaide to Perth relay trip. Each was equipped with a kitchen and entertainment area, a bathroom and toilet, and sleeping quarters for each crewmember. The sleeping quarters were furnished with a single bed and an un-sprung mattress, an air-conditioning system to control room temperature, and black-out blinds to minimize light exposure. While resting in the crew-vans, the drivers engaged in normal domestic activities such as preparing meals, watching videos, hygienic care, and sleeping. Crews were responsible for providing their own food and beverages to last for the duration of the relay trip.

Multiple data sets were collected for each participant. The drivers were initially asked to participate in the study on two occasions—once while working the early schedule and once while working the late schedule. Owing to considerable data loss (*see below*), participants were later asked to undertake the protocol for a third time. Participants met members of the research team three days prior to each field trial. They were provided with an Actigraph-L activity monitoring device and sleep/work diaries to record pre-trial information. In addition, the drivers completed three 5-min practice tests on the PVT. During field trials, drivers wore the wrist activity monitors on their non-dominant wrist and kept records of all sleep attempts, including naps, in the sleep diary. To assess vigilance performance, crewmembers completed a PVT test 30 min before and immediately following each duty period. A member of the research team accompanied the drivers during each field trial to assist with data collection.

2.4. Statistical analyses

A total of 32 data sets, each representing a single trial for a single driver, were collected during 13 Adelaide to Perth relay trips. Eleven data sets were excluded from statistical analyses owing to: (i) a structural failure leading to abandonment of the crew-van carriage during one trip (4 data sets); (ii) irregular scheduling factors (3 data sets); (iii) non-compliance with the study protocol (2 data sets); (iv) failure of the actigraphy devices to record activity (1 data set); and (v) crew illness (1 data set). The remaining 21 data sets included 11 in which drivers worked the early shift rotation, and 10 in which drivers worked the late shift rotation. Across these data sets, participants missed a total of three PVT tests owing to insufficient time in between wake-up and scheduled work periods.

To examine sleep behaviour, a plot representing the timing and length of all sleep periods was constructed. A visual analysis of the plot was undertaken to identify the basic characteristics of participants' sleep–wake patterns. To compare sleep location (home, crew-van, and layover), a one-way mixed-effects analysis of variance (ANOVA) was calculated with location as a repeated measure. The analysis was performed by averaging sleeps taken in each location for each participant. For crew-van sleeps, descriptive statistics were calculated for each crew-van rest period (ECR1, ECR2, ECR3, ECR4, ECR5, and ECR6 for the early schedule and LCR1, LCR2, LCR3, LCR4, LCR5, and LCR6 for the late schedule). Variation in the timing of rest periods meant that the shift rotation × rest timing relationship was not orthogonal. As such, sleep data from all participants were combined and categorized according to the start times of rest periods. One-way mixed-effects ANOVA was then calculated to compare sleep across time categories (20–02 h, 02–08 h, 08–14 h, and 14–20 h).

To assess sleep loss, cumulative distributions representing the amount of time in bed (TIB) and total sleep time (TST) lost across the relay operation were constructed. The loss values were calculated by comparing mean TIB and TST obtained during home-based nocturnal sleep with that obtained in the first four successive 24-h periods (0800 h–0759 h) of the relay operation. Mixed-effects ANOVA were performed to compare cumulative sleep loss across days (Day 1, Day 2, Day 3, and Day 4) and shift rotation (early and late), with repeated measures on day. The PVT data were analysed using two-way mixed ANOVA for trial number (E1, E2, E3, E4, E5, E6, E7, E8, E9, E10, E11, and E12 for the early schedule and L1, L2, L3, L4, L5, L6, L7, L8, L9, L11, and L12 for the late rotation, with repeated measures), and shift rotation (early and late).

Inferential analyses were performed using SPSS for Windows (version 12.0.1, SPSS Inc., USA). Mixed-effects ANOVA procedures were used to account for systematic inter-individual variation attributable to repeated sampling of participants between relay trips and repeated measurements within relay trips. Analyses were restricted to main effects for each factor, interaction effects were not considered owing to sample size restrictions. All distributions of dependent variables met the basic assumptions of the respective statistical tests. Where applicable, post hoc comparisons, weighted using Bonferroni procedures, were calculated to identify within factor differences. A significance level of $P \leqslant 0.05$ was used for all statistical analyses. Corrected Satterthwaite (1946) degrees of freedom (DF) are reported. Descriptive statistics are reported as mean (± standard deviation).

3. Results

3.1. Relay trips

A pictograph representing the work and rest periods for each driver is shown in Fig. 2. Since multiple participants were sampled during each trip, work and rest periods are sometimes duplicated. The relay trips had a mean duration of 105.81 (±4.57) h and encompassed 4 nights and 5 days.

On average, the trips departed from Adelaide at 0800 h and arrived in Perth 45.11 (±1.54) h later at 0506 h. The timing of work–rest rotations were homogenous across the Adelaide-to-Perth portion of the relay trip, but arrival times in Perth varied according to delays across the rail line. The layover period had a mean duration of 18.08 (±2.03) h and ended at 2311 h. Variability in layover lengths occurred because of varied arrival and train loading times at the Perth terminal. As a consequence, the timing of subsequent shift rotations was not homogenous across the sampled relay trips. The return driving segment extended for 42.61 (±3.48) h and terminated in Adelaide at 1614 h, subject to train delays. During the driving segments, the majority of crews worked the planned alternating 8-h shift rotations until arrival in the respective destination cities. However, the length of the shifts immediately prior to arrival in Perth and Adelaide varied depending on travel times. These shifts had mean durations of 5.45 (±1.56) and 3.94 (±1.51) h, respectively.

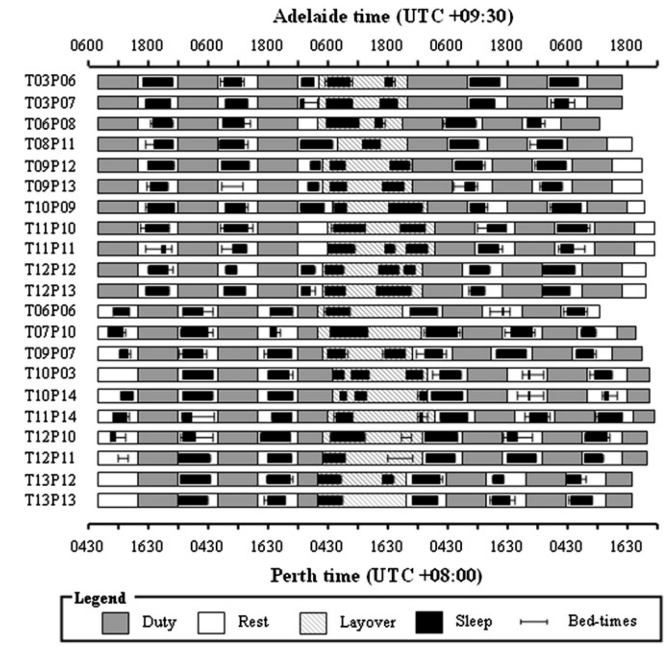

Fig. 2. A pictograph of the work–rest schedule and bed-time spans and sleep periods for individual participants. Labels on the left-hand side denote the trip participant number. The top 11 records correspond to participants who worked the early schedule; the lower 10 to participants who worked the late schedule.

3.2. Sleep location

A total of 76 home, 109 crew-van, and 42 layover sleep periods were presented for analysis. For comparison of sleep locations, data for each participant were collapsed to derive mean values for each location. Table 1 presents the means ± standard deviations for attempted sleeps in each location. The results of mixed-effects ANOVA comparing the home, crew-van, and layover sleep periods are also reported. Significant differences were found for all dependent variables except subjective sleep quality. Post hoc comparisons indicated that home sleeps were associated with longer TIB and greater TST than either crew-van or

Table 1
Mixed-effects ANOVA results comparing sleep location[a] (home, crew-van, and layover) for time in bed, total sleep time, sleep efficiency, and subjective sleep quality

	Home ($n=10$)		Crew-van ($n=10$)		Layover ($n=10$)		ANOVA		
	M	SD	*M*	SD	*M*	SD	*F*	DF	*P*
Time in bed (h)	7.82	0.47	4.89[b]	0.35	4.03[b]	0.96	166.66	14.70	0.000
Total sleep time (h)	6.84	0.70	3.06[b]	0.39	3.17[b]	0.81	139.72	17.59	0.000
Sleep efficiency (%)	91.01	4.32	80.59[b,c]	7.14	90.40	5.89	8.59	15.71	0.003
Subj. quality[d]	2.22	0.76	2.68	0.41	2.49	0.41	1.78	20.67	0.193

[a]For each participant, sleep attempts were collapsed to derive mean values for each sleep location.
[b]Indicates significant post hoc differences from home sleeps for crew-van and layover sleeps.
[c]Indicates significant post hoc differences from layover sleeps for crew-van sleeps.
[d]The subjective sleep quality measure is negatively coded; lower scores indicate greater subjective sleep quality.

layover sleeps. Similarly, sleep efficiency was poorer for sleeps initiated in the crew-van carriages than at home or during layovers.

3.3. Sleep behaviour

Fig. 2 shows the TIB (horizontal lines with error bars) and sleep periods (black boxes) for each participant across the relay trips. When working the early shift rotation, all participants attempted a single sleep during ECR1 and ECR2. Most participants (73% of data sets) attempted to sleep during the shorter ECR3 prior to arrival in Perth. During the layover, participants initiated one (1 data set), two (8 data sets), or three (2 data sets) sleep periods. The predominant strategy was to initiate sleep shortly after arrival in Perth (approximately 0415 h Perth time), to remain awake during the local afternoon, and then to sleep in the evening prior to departure (approximately 2100 h Perth time). On the return portion of the trip, all participants initiated a single sleep during ECR4 and ECR5 while no one attempted to sleep during the shorter ECR6.

When working the late shift rotation, most participants (70% of data sets) attempted to sleep during LCR1 while all participants took a single sleep during LCR2 and LCR3. During the Perth layover, participants initiated one (3 data sets), two (5 data sets), or three (2 data sets) sleep periods. As when working the early shift rotation, the majority of participants initiated sleep shortly after arriving in Perth, remained awake during the local afternoon, and then attempted to sleep in the evening prior to departure. Visual inspection of the plot shows this strategy was more prevalent when drivers worked the early shift rotation than when drivers worked the late shift rotation. On the return trip, all participants initiated a single sleep in LCR4, LCR5, and LCR6.

3.4. Sleep quantity

Means and standard deviations for sleeps attempted within each crew-van rest period are reported in Table 2. Overall, participants spent 31.87 ($\pm$ 2.44) h in bed and obtained 21.68 ($\pm$4.69) h of sleep across the relay trips when working the early rotation. This equated to 7.16 ($\pm$0.51) h in bed and 4.86 ($\pm$1.02) h of sleep/24-h period. In contrast, when working the late rotation participants spent 35.27 ($\pm$3.67) h in bed and obtained a total of 22.84 ($\pm$1.91) h of sleep. This equated to 7.94 ($\pm$0.82) h in bed and 5.14 ($\pm$0.40) h of sleep/24-h period.

3.5. Sleep timing

Fig. 3 shows the TIB, TST, sleep efficiency, and subjective sleep quality associated with crew-van rests beginning in particular time intervals (i.e. 2000–0200 h, 0200–0800 h, 0800–1400 h, and 1400–2000 h). Mixed-effects ANOVA indicated significant time-of-day effects for TIB, $F_{3,60.92} = 15.94$, $P = 0.000$, and TST, $F_{3,75.03} = 6.85$, $P = 0.000$. Pairwise comparison of the estimated marginal means, weighted using Bonferroni procedures, indicated shorter TIB spans for the 08–14 h category. For TST, significant differences were found between the 0200–0800 h category, the 0800–1400 h and 1400–2000 h categories. No other differences were found.

3.6. Sleep loss

Fig. 4 shows cumulative TIB and sleep (TST) loss distributions calculated across the first four successive days of the relay trip. The TIB plot suggests that TIB loss was initially high and then either remained steady (early schedule) or declined (late schedule) across subsequent days. These trends were not significant differences across trip day or shift rotation. In contrast, the cumulative sleep loss plot revealed that cumulative sleep loss increased across subsequent trip days for both rotations. Mixed-effects ANOVA indicated significant differences in cumulative sleep loss across days, $F_{3,36.71} = 7.92$, $P = 0.000$, but not between shift rotations. Pairwise comparisons revealed that cumulative sleep loss was greater on days 2 and 4 than on day 1.

3.7. Performance

Fig. 5 presents line graphs showing the mean ($\pm$S.E.M.) for reaction speed ($1/\text{RT} \times 1000$), the slowest 10% of RT, and frequency of lapses organized by PVT trial and shift

Table 2
Number of sleeps, time in bed, total sleep time, sleep efficiency, and subjective sleep quality for sleeps attempted during crew-van rest periods

	Adelaide–Perth						Perth–Adelaide					
Early schedule	ECR1		ECR2		ECR3[a]		ECR4		ECR5		ECR6[a]	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
N sleeps	11		11		8		11		11		0	
Time in bed (h)	5.2	0.6	4.8	1.1	3.4	1.6	5.0	1.1	5.6	1.0	–	–
Total sleep time (h)	3.0	1.2	2.7	1.1	2.3	1.5	3.4	1.2	3.8	1.4	–	–
Sleep efficiency (%)	74.9	14.9	76.2	14.5	89.2	12.8	80.8	11.2	80.1	11.2	–	–
Subj. quality	3.0	0.6	2.5	0.9	2.1	0.6	2.6	1.0	2.5	0.8	–	–
Late schedule	LCR1		LCR2		LCR3		LCR4		LCR5		LCR6	
	M	SD	M	SD	M	SD	M	SD	M	SD	M	SD
N sleeps	7		10		10		10		10		10	
Time in bed (h)	2.9	0.6	6.1	0.3	4.7	1.1	6.2	1.1	5.0	1.2	4.2	0.8
Total sleep time (h)	1.8	0.7	3.6	1.4	3.3	0.9	4.7	1.0	1.8	1.6	2.7	1.0
Sleep efficiency (%)	83.1	13.7	76.0	13.2	82.1	13.8	88.1	8.7	76.2	23.8	83.4	12.6
Subj. quality	3.1	0.8	2.7	0.9	3.0	0.6	2.5	0.7	2.7	0.9	2.4	0.9

[a]Indicates crew-van rest periods with mean durations shorter than 8 h.

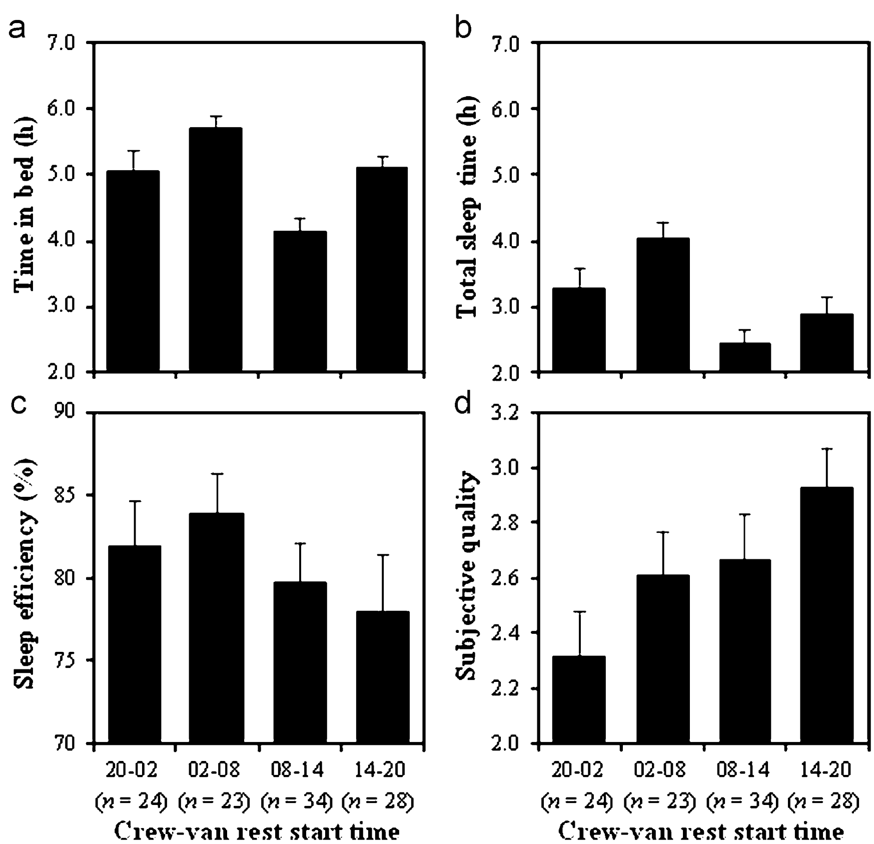

Fig. 3. Bar charts showing mean (+S.E.M.) time in bed, total sleep time, sleep efficiency, and subjective sleep quality organized by start time of crew-van rests. Values for subjective sleep quality are negatively coded; lower scores indicate greater subjective sleep quality.

rotation. Mixed-effects ANOVA indicated significant differences between the early and late schedule for reaction speed, $F_{1,205.78} = 25.47$, $P = 0.000$, the slowest 10% of RT, $F_{1,167.12} = 25.35$, $P = 0.000$, and the frequency of lapses, $F_{1,100.16} = 23.00$, $P = 0.000$. As indicated in the figure, participants performed poorer on these measures when working the late schedule. No significant differences were obtained for trial number.

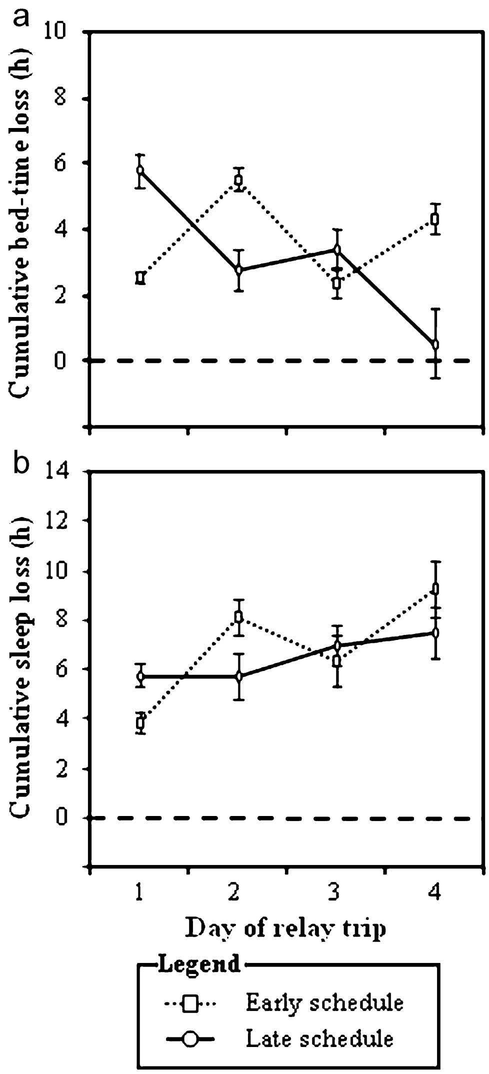

Fig. 4. Mean (±standard error) cumulative bed-time and sleep loss distributions across the first successive four days of the relay operation.

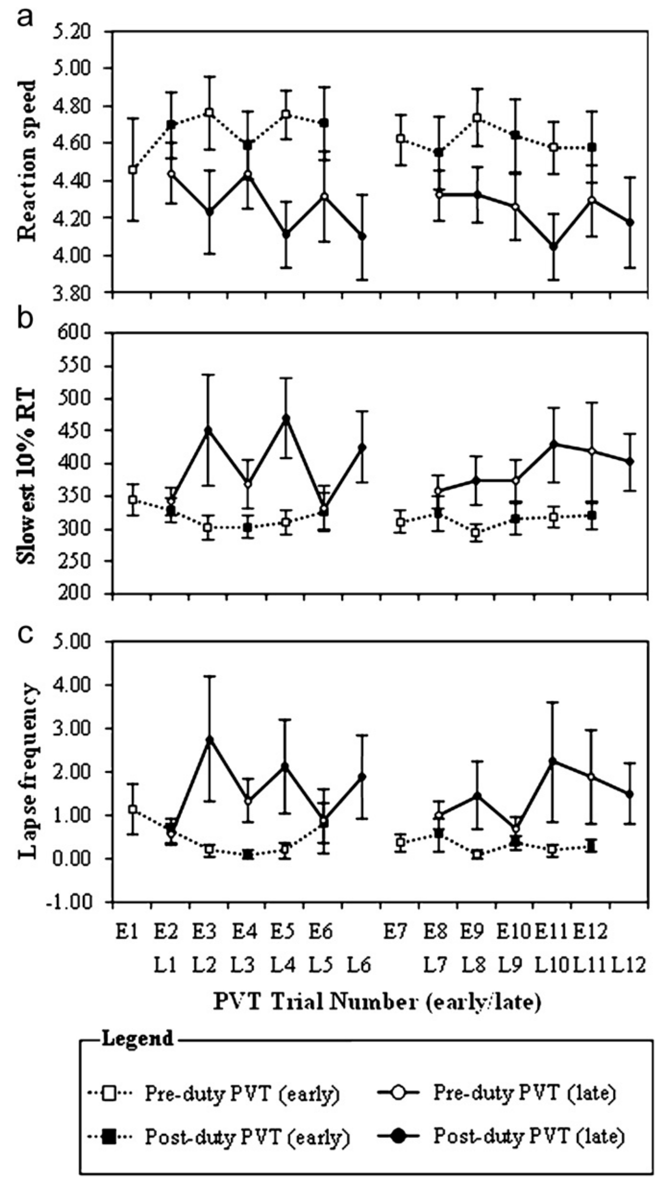

Fig. 5. Line graphs showing mean (±S.E.M.) PVT reaction speed (1/RT × 1000), the slowest 10% of RT (milliseconds), and lapse frequency for tests conducted 30 min before and immediately after scheduled work periods.

4. Discussion

The results indicate significant differences in the quantity of sleep obtained by drivers at home and in crew-van carriages. Sleeps onboard the train were associated with less TIB and less TST than sleeps at home. This was expected given that home sleeps were sampled during unimpeded rest opportunities (i.e. longer than 24-h), while crew-van sleeps had a maximum length of only 8 h. The rotating work–rest schedule meant that crew-van rests were scheduled at intermittent phases of the day–night cycle. In line with expectations, the longest sleeps occurred when rests began in the late evening/early morning period. Sleeps initiated in the late morning/early afternoon rests had the shortest durations. Overall, these findings are consistent with that expected on the basis of circadian physiology (Dijk and von Schantz, 2005) and coroborate that reported in previous investigations of relay van work (Jay et al., 2006; Lamond et al., 2005a, b).

The reduced frequency of sleep attempts observed in some crew-van rests suggests that sleep was moderated by rational decision-making processes. For instance, drivers sometimes elected (27% of cases) not to sleep in the night-time crew-van rest period scheduled immediately prior to arrival in Perth. Presumably, this behaviour prevented the release of homeostatic sleep pressure and helped drivers to sustain sleep during the subsequent hotel-based layover. Nonetheless, sleeps initiated during the layover were surprisingly short. Instead of taking a single long sleep as hypothesized, most drivers exhibited a split-sleep strategy in which sleeps were timed to coincide with the start and end times of the layover. This strategy was particularly evident when drivers worked the early rotation; most likely because this required them to work the initial driving segment after the layover.

The foregoing rationalization implies that drivers' sleep–wake cycles were moderated by anticipatory behaviours in consideration of physiological sleep drives. Thus, we speculate that drivers chose to forgo sleep on some occasions in order to maximize sleep quantity and quality on others. Managing sleep behaviour has the potential to give drivers a measure of control over how much sleep they obtain in the hours leading up to work. Further analyses of shiftworkers' sleep behaviour are needed to identify the factors which may prompt drivers to adopt particular sleep strategies in response to given work schedules. Educational programs designed to facilitate safety-oriented sleep behaviours could well prove beneficial for drivers engaged in relay van work, especially for novice drivers.

The sleeping conditions available to drivers in crew-van carriages and layovers are a salient concern for rail safety advocates. Unsuitable conditions have the potential to mitigate the quality and quantity of sleep obtained by drivers, irrespective of the timing or length of rest periods. Sleep efficiency and subjective sleep quality ratings were similar in the home and layover locations. In contrast, sleep efficiency in the crew-van carriages was relatively poor. Drivers were awake for approximately 10% more time in crew-van sleeps than in either home or layover sleeps. This difference was not reflected in correspondingly poorer sleep quality ratings, suggesting that drivers may have been unaware of the sleep disturbances.

The results of the sleep efficiency analysis were consistent with that of Lamond et al. (2005a), who also used wrist actigraphy to assess sleep. Similar distributions of sleep efficiency were observed at home and in crew-vans during the 40-h relay operation examined in their study. The 90-h relay van study reported by Jay et al. (2006), in which sleep was measured using polysomnography, gave contradictory results. This later study found no differences in sleep efficiency among home, layover, and crew-van locations. Of particular note, however, estimates of sleep efficiency in the crew-vans were nearly the same in all three studies (~80%). The discrepancy with Jay et al. (2006) resides in the fact that the home and layover sleep efficiency values were just as poor as that in the crew-vans.

Unlike the physiological processes that govern sleep–wake regulation, crew-vans may be reengineered to provide facilities that are more conducive to sleep. The findings of this and previous investigations of relay van work indicate that the sleeping conditions currently available to drivers in crew-vans are less than ideal. However, it has yet to be conclusively established whether drivers would obtain better sleep quality while resting in alternative accommodation. Given the importance of obtaining good sleep in crew-vans, a more definitive answer to this question should be sought using a controlled experimental protocol.

Merely comparing the duration and quality of sleep periods does not adequately address whether drivers obtain sufficient sleep to maintain safety across the course of relay operations. While TIB, TST, and sleep efficiency were reduced in comparison to home, sleeps were initiated more frequently due the fast rotating work–rest schedule. The cumulative sleep loss distribution was calculated to allow a comparison of sleep amounts across standard 24-h periods. The results showed that drivers incurred a significant sleep debt across the first four days of the relay operation. However, the sleep loss was not accompanied by significant reduction in TIB. Drivers spent an average of about 7.5 h/24-h period attempting to sleep. In comparison, drivers only managed to obtain about 5.0 h/24-h period of TST. This finding confirms that drivers had considerable difficulty initiating and maintaining sleep in the crew-van carriages and layovers.

Drivers were able to sustain vigilance performance for the duration of the relay van operation despite having incurred a significant sleep debt. These findings are consistent with those reported by Lamond et al. (2005b) in connection with a 40-h operation, but contrary to expectations. The findings of laboratory-based studies suggest that performance deficits should have been manifested after approximately two days (Belenky et al., 2003; Van Dongen et al., 2003). The failure to find a significant effect may be related to the reduced wake times engendered by the 16-h work–rest cycles. Performance tests were administered 30 min prior to the start of driving shifts, when drivers had been awake for only a short time. Performance tests were also administered at the end of driving shifts, but only once drivers had returned to the crew-van carriage. The change in context, and the walk back to the crew-van carriage (~75 m), may have had an alerting influence on drivers. If so, the research protocol may not have been sensitive to possible performance deficits occurring within driving shifts.

The extent to which sleep loss correlates with train driving performance has been examined in only a few studies (e.g. Dorrian et al., 2007; Roach et al., 2001). Most pertinent in the current context is the study by Thomas et al. (1997), in which train handling performance was measured across fast (mean work-to-rest ratio = 10.0:9.3 h) and slow (mean work-to-rest ratio = 10.0:12.0 h) rotating schedules. A cumulative sleep loss occurred in connection with both schedules. Average daily sleep quantity was less in the fast rotating schedule ($M = 4.6$ h) than in the slow rotating schedule ($M = 6.1$ h). Of particular relevance, the cumulative sleep loss was similar to that experienced by drivers in the relay operation and occurred across a similar time span. The sleep loss correlated with decreased subjective alertness, increased fuel use, missed alerter signals, and failures to sound the horn at grade-crossings.

Like all research, this study had a number of methodological weaknesses that merit consideration. One obvious limitation was the relatively small number of drivers ($N = 10$) sampled. To some extent, the sample size restriction was offset by asking drivers to participate in the study on more than one occasion. However, the extent to which this sample of drivers can be considered representative of the population of relay van workers in Australia is probably limited. Another weakness of the study was the absence of an experimental design and rigorous control procedures. The major independent variables (i.e. rest location, rest duration, and rest timing) were not orthogonal, and hence their independent contribution to drivers' sleep could not be ascertained. Given these limitations, the generalizability of the study findings to other relay van operations may be regarded with some uncertainty. However, the major findings of this study were in accordance with those found in other similar investigations conducted so far.

5. Conclusion

The present study has addressed a number of issues pertinent to the conduct of relay van work in the Australian rail industry. The findings were based on observations of train drivers' sleep behaviours in 'real-world' industrial settings. Despite the methodological weaknesses, the findings have an ecological authenticity that could not easily be replicated in an experimental protocol. On the basis of the evidence amassed thus far, there is no direct evidence that the sleep loss is sufficient to induce performance deficits across relay operations; at least not in respect to relatively short operations (~42 h) or longer operations (~106 h) punctuated by hotel layovers. Nonetheless, it is doubtful whether vigilance performance could be maintained indefinitely on relay-type schedules in view of ever-increasing levels of sleep debt. Additional research is needed to ascertain the length of time that operations could feasibly be sustained before performance deficits become manifested.

References

Akerstedt, T., 2000. Consensus statement: fatigue and accidents in transport operations. J. Sleep Res. 9 (4), 395.

Akerstedt, T., 2003. Shift work and disturbed sleep/wakefulness. Soc. Occup. Med. 53, 89–94.

Belenky, G., Wesensten, N.J., Thorne, D.R., Thomas, M.L., Sing, H.C., Redmond, D.P., Russo, B.M., Balkin, T., 2003. Patterns of performance degradation and restoration during sleep restriction and subsequent recovery: a sleep dose–response study. J. Sleep Res. 12 (1), 1–12.

Dijk, D.J., von Schantz, M., 2005. Timing and consolidation of human sleep, wakefulness, and performance by a symphony of oscillators. J. Biol. Rhythms 20 (4), 279–290.

Dinges, D.F., Pack, F., Williams, K., Gillen, K.A., Powell, J.W., Ott, G.E., Aptowicz, C., Pack, A.I., 1997. Cumulative sleepiness, mood disturbance, and psychomotor vigilance performance decrements during a week of sleep restricted to 4–5 h per night. Sleep 20 (4), 267–277.

Discoll, T.R., Grunstein, R.R., Rogers, N., 2007. A systematic review of the neurobehavioural and physiological effects of shiftwork systems. Sleep Med. Rev. 11 (3), 179–194.

Dorrian, J., Roach, G.D., Fletcher, A., Dawson, D., 2007. Simulated train driving: fatigue, self-awareness and cognitive disengagement. Appl. Ergon. 38, 155–166.

Edkins, G.D., Pollock, C.M., 1997. The influence of sustained attention on railway accidents. Accid. Anal. Prev. 29 (4), 533–539.

Everett, S., 2006. Deregulation and reform of rail in Australia: some emerging constraints. Transp. Policy 13 (1), 74–84.

Folkard, S., 1997. Black times: temporal determinants of transport safety. Accid. Anal. Prev. 29 (4), 417–430.

Harrison, Y., Horne, J.A., 2000. The impact of sleep deprivation on decision making: a review. J. Exp. Psychol. Appl. 6 (3), 236–249.

Jay, S.M., Dawson, D., Lamond, N., 2006. Train drivers' sleep quality and quantity during extended relay operations. Chronobiol. Int. 23 (6), 1241–1252.

Lamond, N., Darwent, D., Dawson, D., 2005a. How well do train driver's sleep in relay vans? Ind. Health 43 (1), 98–104.

Lamond, N., Darwent, D., Dawson, D., 2005b. Train drivers' sleep and alertness during short relay operations. Appl. Ergon. 36 (3), 313–318.

Pilcher, J.J., Huffcutt, A.I., 1996. Effects of sleep deprivation on performance: a meta-analysis. Sleep 19 (4), 318–326.

Roach, G.D., Dorrian, J., Fletcher, A., Dawson, D., 2001. Comparing the effects of fatigue and alcohol consumption on locomotive engineers' performance in a rail simulator. J. Hum. Ergology (Tokyo) 30 (1–2), 125–130.

Rosenthal, L., Roehrs, T.A., Rosen, A., Roth, T., 1993. Level of sleepiness and total sleep time following various time in bed conditions. Sleep 16 (3), 226–232.

Satterthwaite, F.E., 1946. An approximate distribution of estimates of variance components. Biom. Bull. 2, 110–114.

Signal, T.L., Gale, J., Gander, P.H., 2005. Sleep measurement in flight crew: comparing actigraphic and subjective estimates to polysomnography. Aviat. Space Environ. Med. 76 (11), 1058–1063.

Thomas, G.R., Raslear, T.G., Kuehn, G.I., 1997. The Effects of Work Schedule on Train Handling Performance and Sleep of Locomotive Engineers: A Simulator Study (No. DOT/FRA/ORD-97-09). US Department of Transportation, Federal Railroad Administration and IIT Research Institute, Washington, DC.

Torsvall, L., Akerstedt, T., Gillander, K., Knutsson, A., 1989. Sleep on the night shift: 24-h EEG monitoring of spontaneous sleep/wake behavior. Psychophysiology 26 (3), 352–358.

Van Dongen, H.P., Maislin, G., Mullington, J.M., Dinges, D.F., 2003. The cumulative cost of additional wakefulness: dose–response effects on neurobehavioral functions and sleep physiology from chronic sleep restriction and total sleep deprivation. Sleep 26 (2), 117–126.

Wills-Johnson, N., 2007. Competition policy and railway investment—project summary. Planning and Transport Research Centre Working Paper no 12.