



The effects of fatigue on train handling during speed restrictions

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Abstract

Due to their schedules, train drivers are likely to experience elevated fatigue at work, which can have marked safety consequences. This study investigated the effects of fatigue on the ability to negotiate speed restrictions. Twenty male train drivers drove a realistic rail simulator and their performance was evaluated in three fatigue groups; low, moderate and high. Overall, fatigue had a marked effect on performance during speed restrictions. In general, drivers in the high fatigue group used the brake less and traveled at faster speeds. In addition, it appears that speed restrictions following moderate to heavy descending grades are more likely to be sensitive to fatigue. In contrast, performance was less affected during undulating territory, where a higher level of interaction was required to control the train. Overall, results suggested that there are certain types of track sections where fatigue is most likely to have serious effect.

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1. Introduction

Due to their schedules, train drivers often experience sleep of reduced duration and quality (Foret & Latin, 1972; Pilcher & Copen, 2000; Roach, Reid, & Dawson, 2003), and elevated fatigue levels (Härmä, Sallinen, Ranta, Mutanen, & Muller, 2002). Self-report (Åkerstedt, Torsvall, & Froberg, 1983) and objective polysomnographic (Caban, Coblentz, Mollard, & Fouillot, 1993; Torsvall & Åkerstedt, 1987) investigations have recorded incidences of drowsing and uncontrolled sleep attack while driving. Clearly, such research raises important questions about driver work scheduling, fatigue and safety.

In the last century, a significant body of research has established the potential occupational health and safety risks associated with sleep loss and fatigue. Fatigued individuals exhibit lapses in attention, longer response times and more frequent errors, and have increased difficulty identifying and processing salient environmental information (reviewed in Dinges & Kribbs, 1991; Harrison & Horne, 2000; Kleitman, 1963).

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Research has also indicated that sleep loss and fatigue can result in higher order cognitive deficits such as non-verbal planning (Horne, 1988) and memory (Harrison & Horne, 2000).

Train driving is a complex task, which relies heavily on numerous aspects of neurocognitive functioning including sustained attention, object detection and recognition, memory, planning, decision-making and workload management (Roth, 2000, in Reinach & Raslear, 2001). Thus, it is not surprising that fatigued train drivers display compromised driving performance. Negative outcomes associated with fatigue include increased fuel use, missed alerter signals and failures to sound the horn at grade crossings (Thomas & Raslear, 1997). Moreover, rail crash investigations have identified work-related fatigue (Pearce, 1999; Zhou, 1991), and the inability to maintain wakefulness (Kogi & Ohta, 1975; Lauber & Kayten, 1988) as contributing factors.

Laboratory studies have demonstrated that complexity and workload influence the extent to which a task is affected by sleep loss and fatigue. For example, Wilkinson (1964) found that augmenting the complexity of a card-sorting task, by increasing the number of sorting categories from 4 to 10, increased its sensitivity to the effects of sleep loss and fatigue. Williams and Lubin (1967) increased the workload of a mental addition task by decreasing the inter-sum interval from 2 to 1.25 s. This change rendered the previously unaffected test sensitive to the effects of 2 nights without sleep.

It can therefore be suggested that changes in the complexity and workload of the train driving task at any given point in time may influence the way in which fatigue effects are manifest. Within the train system, workload and task complexity are influenced by many factors. These can be conceptualised on four levels: (1) the engineer (individual characteristics and abilities), (2) the train (train consist, malfunctions, feedback mechanisms, dual engineer interaction), (3) the track (track characteristics), and (4) the environment (light, temperature, noise, weather) (Fig. 1).

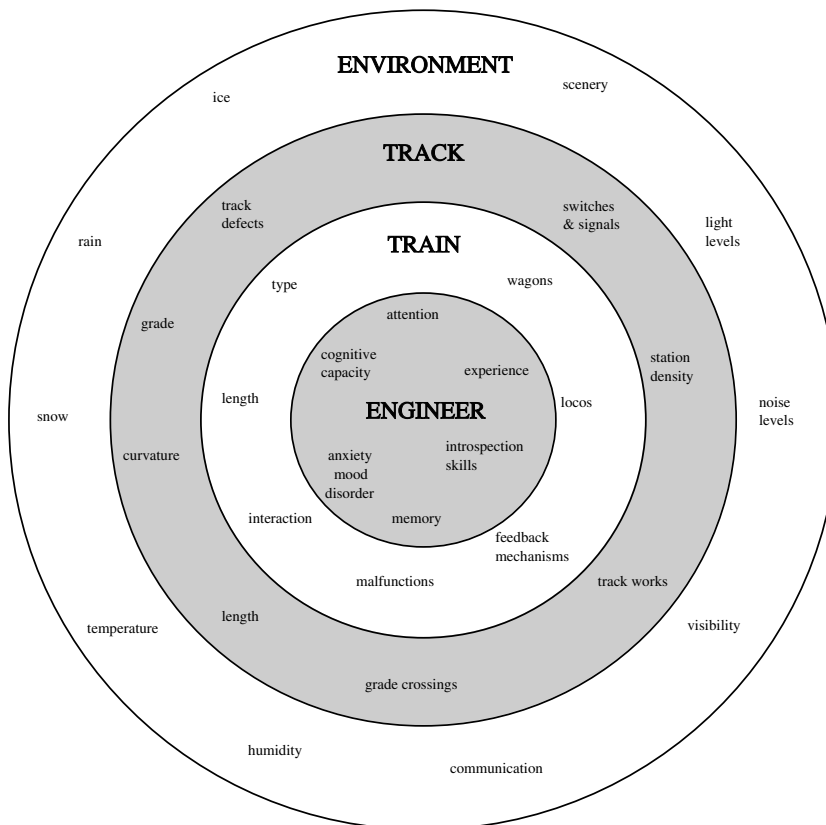


Fig. 1. Conceptual schematic of train system factors (from the inside out: engineer, train consist, track characteristics and environmental factors) that affect the task complexity and workload of the train driving task.

Perhaps the greatest proportion of workload and task complexity is determined by the track characteristics. The complexity of the track design (i.e. track length, placement and density of switches and signals, stations, track works, grade crossings speed restrictions) affects the degree of salient environmental information that must be identified, processed, committed to memory and used to develop an appropriate train control plan. In particular, the degree of interaction (i.e. brake and throttle manipulation) required to effectively control the train is directly dependent on changes in track grade, and upcoming track features such as speed restrictions.

For example, on an uphill grade, the force on the train due to gravity serves to decrease speed. The driver must use the brake and throttle to achieve a 'balance speed', where the train may ascend steadily in balance with the slowing force. Once this speed has been reached, further interaction with the train may not be required until the crest (top of the ascent). As such, long, uphill sections often require little from the driver in terms of train control. In contrast, when the train reaches the crest, the driving task demands are greatly augmented.

On a crest, the force on the train transitions from 'stretched' (wagons pulling apart) on the upgrade, to 'bunched' (wagons pushing together) on the downgrade. Cresting grades should be negotiated with care as the weight of the locomotive at the front and rear, and the changing forces on the train as it crests can result in severe forces. This issue is of particular importance when the brake must be applied during this time in order to slow the train for an upcoming track feature, such as a speed restriction. If not negotiated with care, the combination of the brake resistance, locomotive tractive effort and grade can increase the risk of train and cargo damage and wagon separation.

On a downhill grade gravity is always acting to increase speed. For this reason, braking effort must act to overcome this force or to 'balance the grade'. Several considerations are necessary on a downhill grade. Firstly, failure to make appropriate brake applications can rapidly result in loss of speed control. On the other hand, over use of the brake may lead to over heating of the wheels. Clearly, this is of particular importance when the downhill section occurs immediately prior to a speed restriction requiring further train slowing.

Undulating grade requires the greatest amount of interaction with the train. The driver should reduce train speed prior to entering an undulating section of track, allowing ample braking capacity to maintain constant speed through the undulations. On undulating territory, slack action is more severe, since wagons on descending grades tend to roll faster than those on ascending grades. As such, there is greater potential for dangerous forces on the train that can result in coupler damage and wagon separation. It is imperative that the driver remains conscious of the characteristics of the train such as length, number of wagons, weight loading in each wagon.

Thus, differences in grade shape both the complexity of the driving task and the amount of interaction with the train (i.e. the workload) required. In broad terms, track grades could be listed from least complex, lowest workload to most complex, highest workload: uphill, downhill, crest and undulating. Therefore, it is conceivable that speed restrictions occurring during sections of varying track grade may be affected differentially by sleep loss.

A broad aim of this study was to investigate the effects of fatigue on train handling during speed-restricted track sections. It was postulated that this relationship would be affected by track grade, and thus the complexity and workload of the task during each section.

2. Methods

2.1. Procedure

Ethics approval was granted by the North Western Allied Health Ethics of Human Research Committee and The University of South Australia Human Research Ethics Committee. Twenty male train drivers from four Queensland depots (24–56 y, mean = 39.4, SD = 9.4) volunteered to participate in the study. All testing was carried out at the Queensland Rail Driver Training Centre, Rockhampton. Each participant completed a general health questionnaire before commencing the study to screen for any sleep disorders, or medications known to affect sleep and alertness.

Participants attended the Driver Training Centre on two testing periods, designed to produce varying levels of fatigue. Each phase consisted of an eight-hour 'shift', which was incorporated into the participants' normal

work schedule. One period was conducted between 1000 and 1800 h (at the high point in the circadian cycle) following an adequate night's sleep. The other period was conducted between 2300 and 0700 h, after drivers had worked at least two consecutive night shifts. Each period consisted of four 2-h sessions that included 100-min of driving in a rail simulator and a 10-min psychomotor vigilance task (PVT) (Dinges & Powell, 1985). Therefore, participants drove the simulator (and completed the PVT) four times over two days, resulting in a total of 160 trips (20 participants \times 2 testing periods \times 4 sessions per testing period). For the purposes of this report, the PVT metric focused on in analyses was PVT lapses (i.e. reaction times greater than 500 ms in length). In accordance with award regulations, there was a 20-min meal break between sessions one and two, and a 10-min rest break between sessions three and four.

To minimise practice effects, participants attended a training session prior to the experimental phases. During training, participants observed at least one trip over the selected track section, and drove at least 2 complete trips. In addition, participants were encouraged to make track notes, as they would when learning any new piece of track, for reference during the experiment. Participants also completed at least three PVT trials, as research indicates that the PVT has a 1–3 trial learning curve (Dorrian, Rogers, & Dinges, 2004).

2.2. Rail simulator

Two rail simulators (housed in separate rooms) consisted of a realistic cabin with fully operational control panels and authentic sound. Cabins faced a 3 \times 3 m screen, onto which track footage was projected. Progress was monitored from an adjacent control room. The virtual train was a freight 2100 class diesel locomotive, measuring 432 m, weighing 1097 tonnes, with a single locomotive hauling 25 wagons. Participants drove a 62 km piece of track between Littabella and Netley Stations on the Bundaberg–Gladstone line (approximately 100-min of driving). The track contained 11 stations, 22 bridges, and 6 hills. Speed was restricted to 70 km/h in 2 areas, to 60 km/h in 14 areas, to 50 km/h in 6 areas and to 40 km/h in 8 areas, with a maximum track speed of 80 km/h for this type of train.

2.3. Fatigue level

During each session, participants rated their alertness level using 100 mm VAS, anchored with 'struggling to remain awake' on the left, and 'extremely alert and wide awake' on the right. In addition, participants average fatigue score for each session was calculated with Dawson and Fletcher's (2001) fatigue model. The basis of this model is the principle that fatigue can be produced by work, and reduced by rest or recovery. Importantly, the magnitude of fatigue production and recovery is dependent on the duration, circadian timing and recency of the work and rest periods. Using participants' 7-day work history, the model assigns values to work and recovery (non-work) periods and, using a fatigue algorithm, calculates an expected fatigue output (for further model information, the reader is directed to Dawson & Fletcher, 2001; Fletcher & Dawson, 2001; Roach, Fletcher, & Dawson, 2004).

2.4. Negotiating speed restrictions

Four speed-restricted sections were chosen for detailed analysis. They were selected to provide a range of track characteristics at different stages during the track. Each section was defined as the restricted area, the preceding and following 300 m of track. Fig. 2 illustrates the grade over the entire track, and the selected speed-restricted areas. The track grade for each section at a more detailed level can be seen in Figs. 4–7 in Section 3. For each section, brake use and train speed were assessed. Brake use is indicated by brake pipe pressure (BPP), which is reduced during a brake application to provide the stopping force on the train. That is, lower BPP represents greater brake use.

Restriction (a) is a 40 km/h speed restriction between 60 km/h and 80 km/h track sections. It is 15 km from the start of the track, and occurs after a long (approximately 10 km) uphill section (Fig. 2). At the beginning of this section there is a heavy descent (defined as a grade of $\geq 2\%$), followed by a cresting grade with heavy ascent and descent (grade is $\geq 2\%$). The restriction occurs in the trough after the crest.

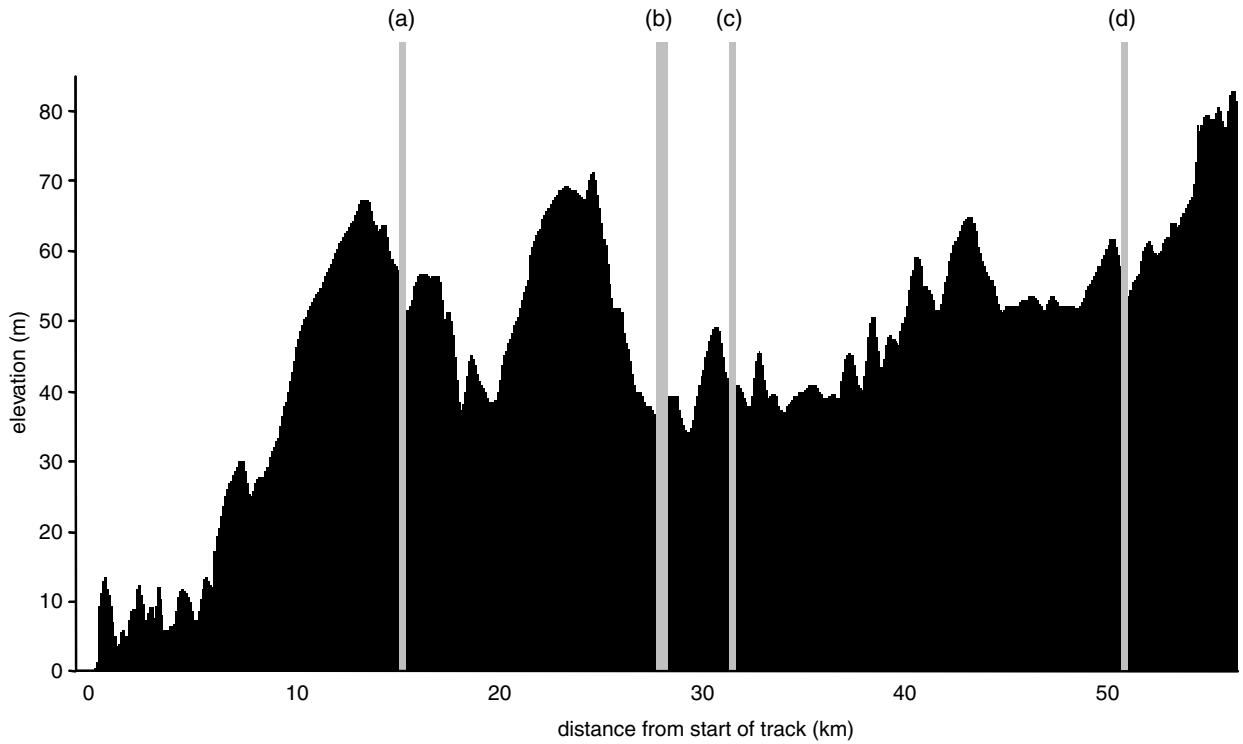


Fig. 2. Representation of the track elevation. Grey bars indicate the speed-restricted sections (a–d).

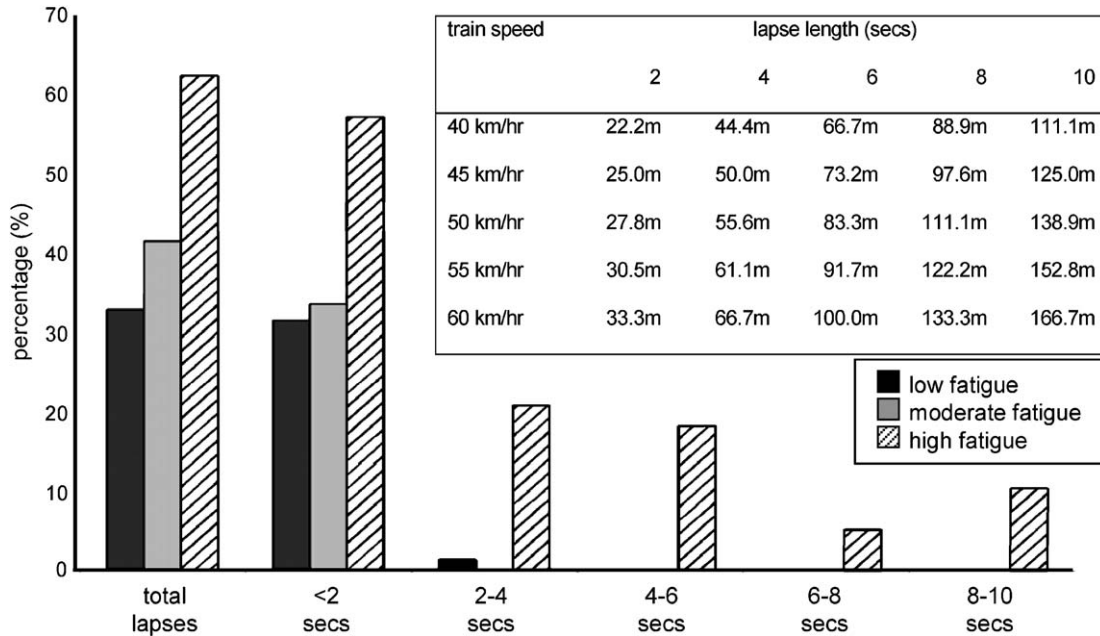


Fig. 3. Percentage of drivers who experienced at least one PVT lapse in each session. Column 1 indicates PVT lapses within the total lapse domain (>0.5 s). Columns 2–6 indicate percentage of PVT lapses lasting <2, 2–4, 4–6, 6–8 and 8–10 s. No driver exhibited PVT lapses greater than 10 s. The table inset details distance traveled (m) at a given train speed during lapses of varying lengths (s).

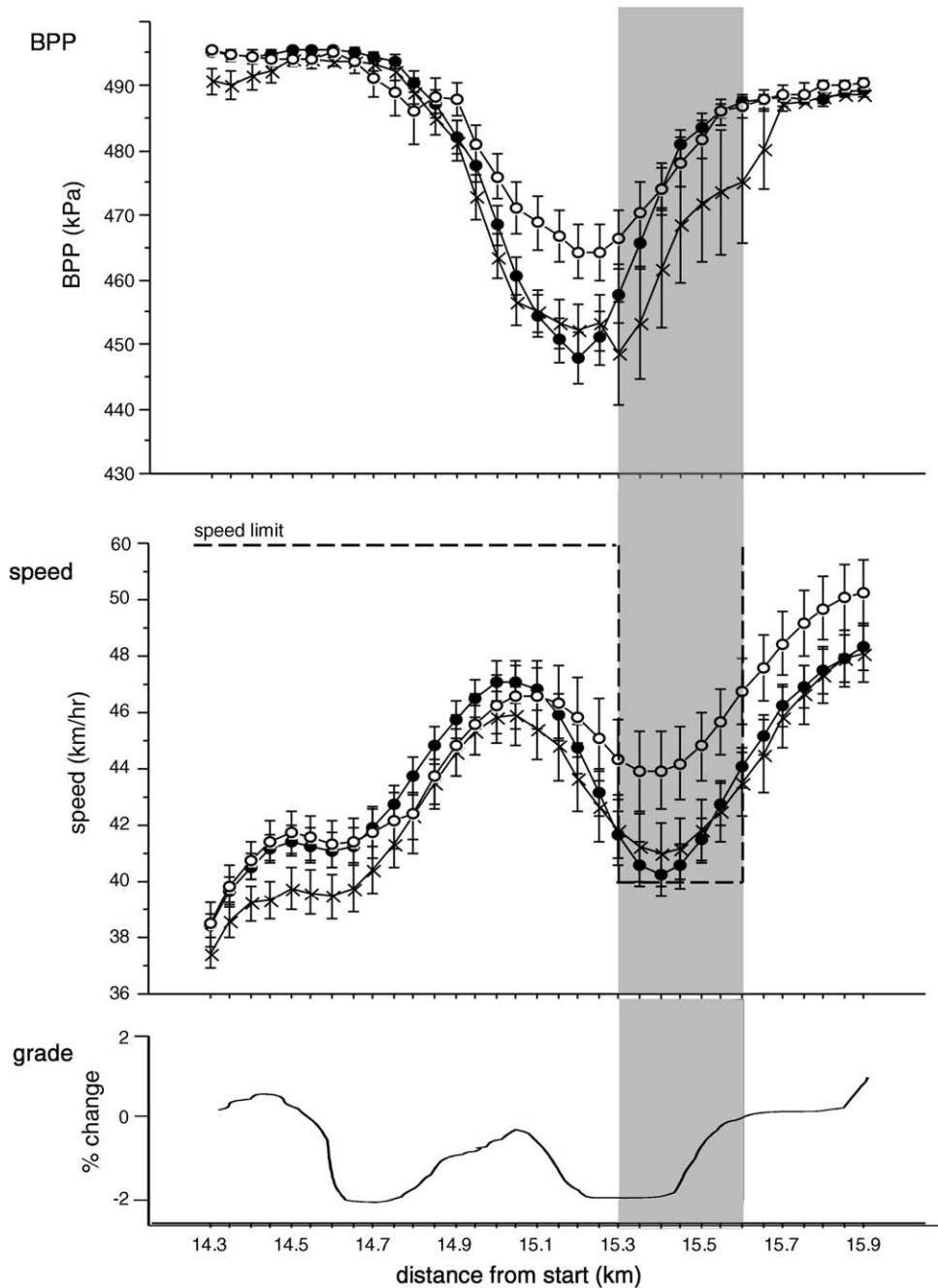


Fig. 4. Brake pipe pressure (BPP), train speed, speed limit (dotted line) and track grade in restricted section (a). Mean (with standard error bars) BPP and train speed are shown at low (closed circles), moderate (crosses) and high (open circles) levels of fatigue.

Restriction (b) is a 40 km/h speed restriction surrounded by an 80 km/h zone, 26 km from the start of the track. It occurs after the second large hill in the track (Fig. 2). The track grade during this section is undulating.

Restriction (c) is a 50 km/h speed restriction between surrounded by a 60 km/h zone. It is 30 km from the start of the track. The track grade during this section is predominantly downhill (Fig. 2). Before the restric-

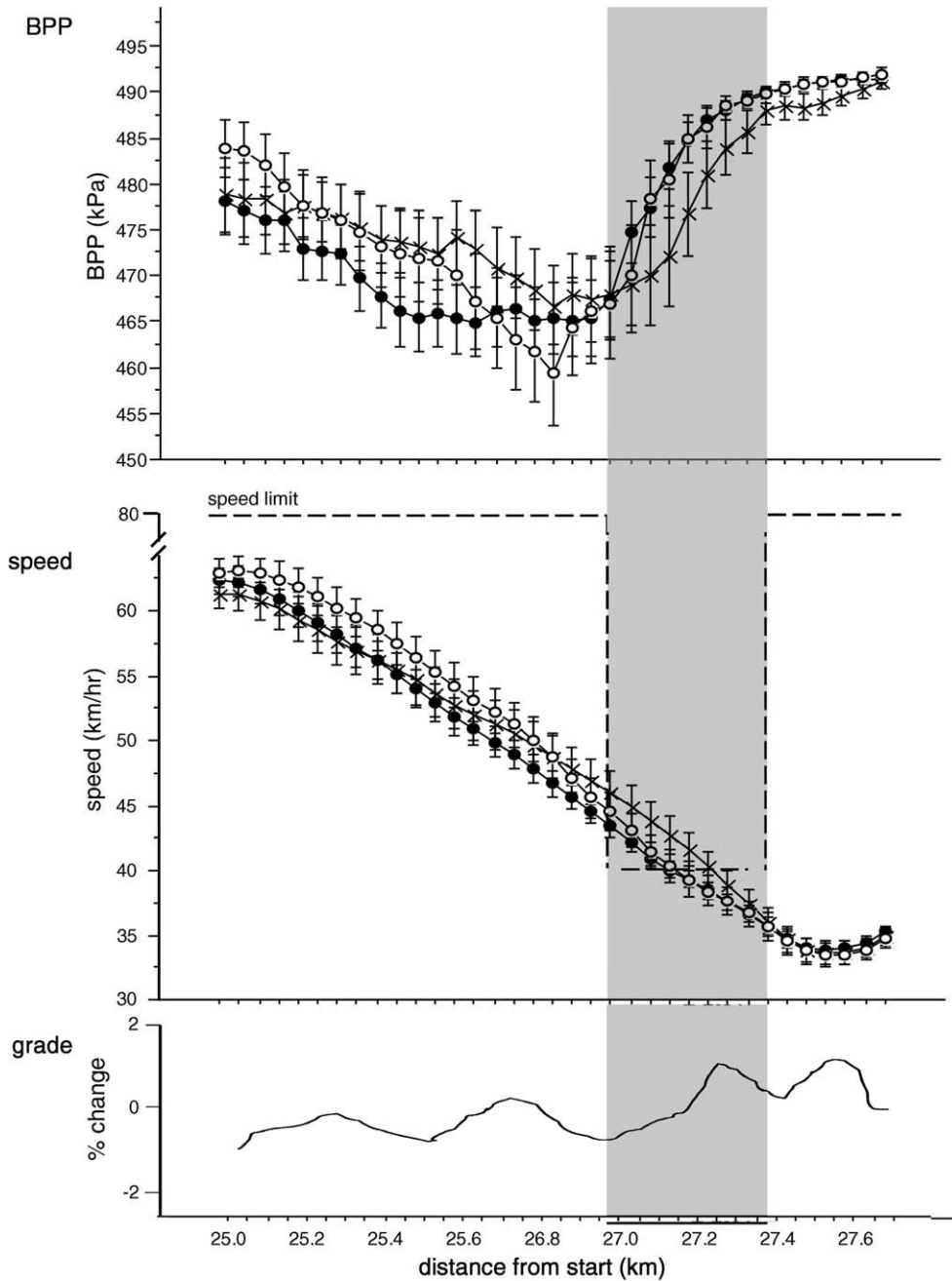


Fig. 5. Brake pipe pressure (BPP), train speed, speed limit (dotted line) and track grade in restricted section (b). Mean (with standard error bars) BPP and train speed are shown at low (closed circles), moderate (crosses) and high (open circles) levels of fatigue.

tion is a heavy descent (a grade of $\geq 2\%$), with the restriction occurring immediately after the trough in track grade.

Restriction (d) is a 40 km/h speed restriction between surrounded by a 60 km/h zone. It is 57 km from the start of the track. The track grade during this section is predominantly downhill (Fig. 2). The restriction occurs in a trough, which follows a medium grade ascent (a grade from 1% to 2%).

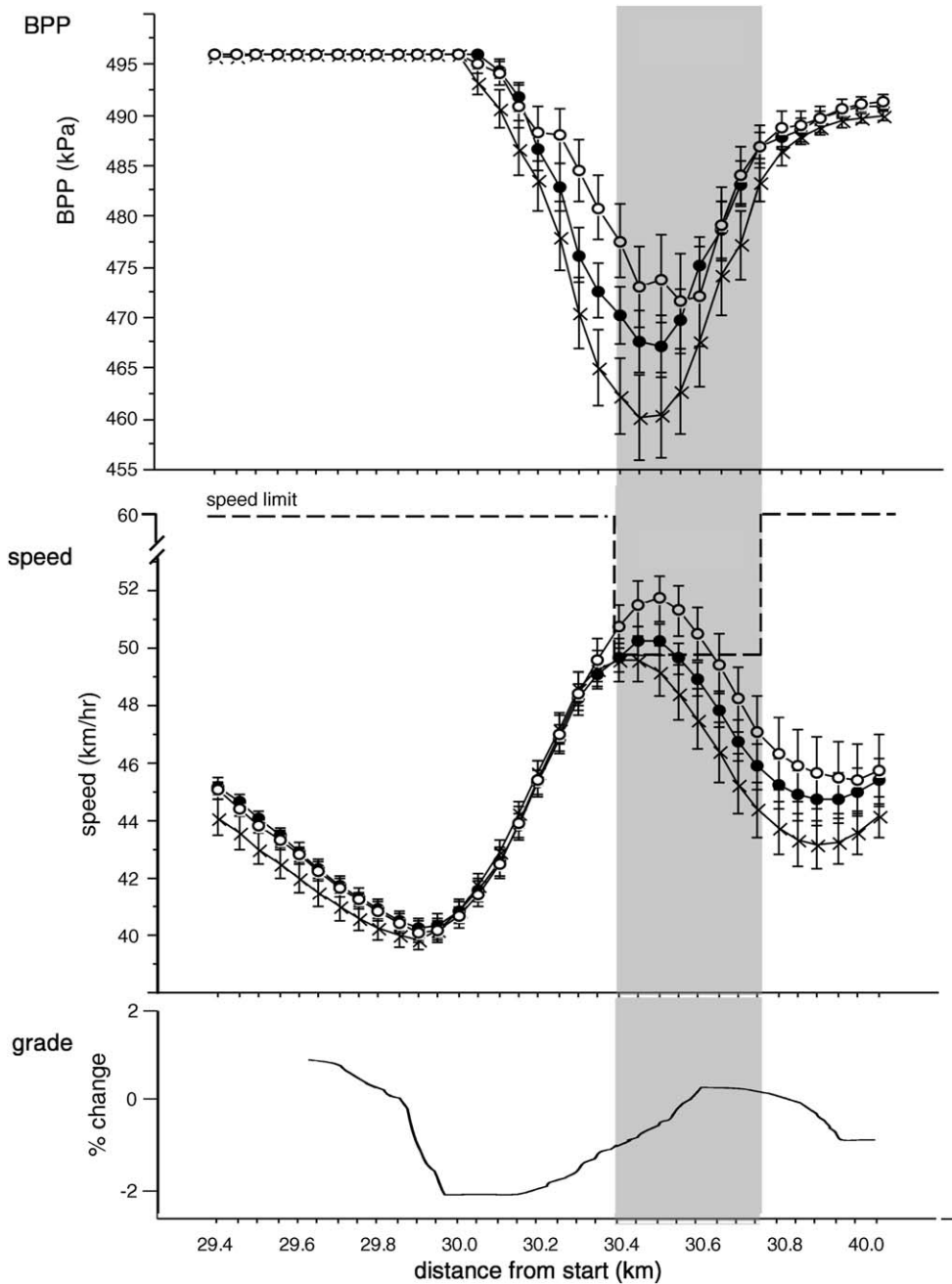


Fig. 6. Brake pipe pressure (BPP), train speed, speed limit (dotted line) and track grade in restricted section (c). Mean (with standard error bars) BPP and train speed are shown at low (closed circles), moderate (crosses) and high (open circles) levels of fatigue.

2.5. Statistical analysis

For the purposes of analysis, scores for each of the 160, 2-h sessions (100 min of driving plus 10 min PVT) were assigned to one of three groups according to the average of the two corresponding hourly fatigue scores: low, moderate and high. Low fatigue encompassed fatigue scores from 0 to 40, moderate fatigue included scores from 40 to 80, and high fatigue was designated as any score greater than 80. As previously described

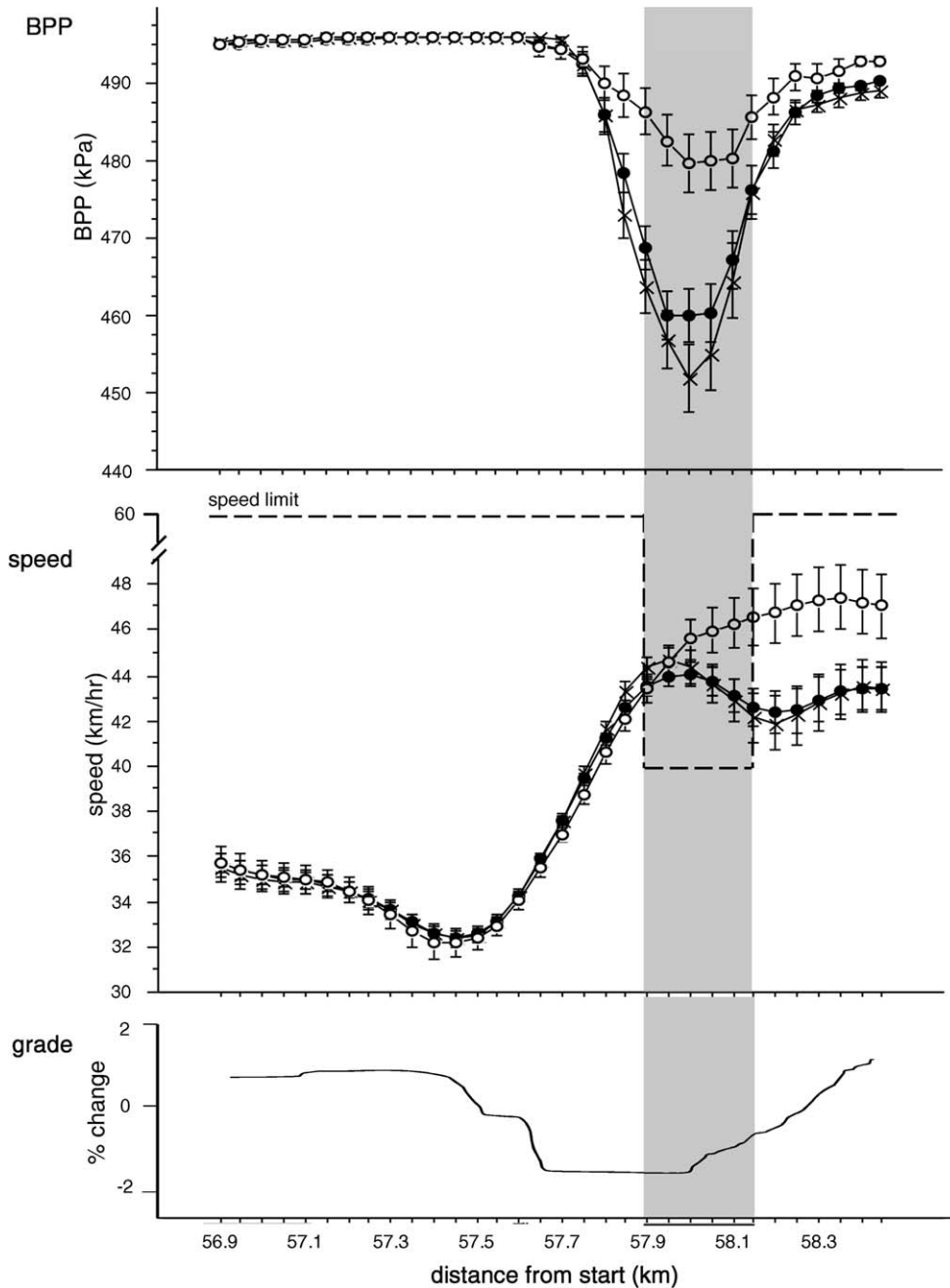


Fig. 7. Brake pipe pressure (BPP), train speed, speed limit (dotted line) and track grade in restricted section (d). Mean (with standard error bars) BPP and train speed are shown at low (closed circles), moderate (crosses) and high (open circles) levels of fatigue.

by Fletcher and Dawson (2001), ‘high fatigue’ was determined using data from Dawson and Reid (1997) who found that a fatigue score of 80 was produced after 21–22 h of sustained wakefulness, with performance impairment equivalent to that produced at a blood alcohol concentration (BAC) of greater than 0.05% (the legal driving limit in many countries). As a relative comparison, low fatigue scores (0–40) are produced by the fatigue model for a standard 0900–1700 h, Monday to Friday roster.

The fatigue score group cut-off values were specifically chosen for conceptual reasons (as outlined above). This method of splitting the data resulted in groups of uneven size (low fatigue, $n = 72$; moderate fatigue, $n = 50$; high fatigue, $n = 38$), and thus potential arises for violation of the assumption of homogeneity of variance (and therefore inflated risk of a Type 1 error). Group numbers could have been equalized by randomly excluding cases in low and moderate groups. However, the following checks were conducted to ensure robustness: (1) the ratio of largest to smallest group size was less than 4:1, and (2) the ratio of variances in each cell was less than 10:1 (Tabachnick & Fidell, 1996). Since these conditions were met, cases were not excluded to avoid unnecessary data loss.

Importantly however, this method of splitting the data also resulted in repeated measurements for individual drivers within each fatigue group. To account for this, linear mixed effects models were used. Drivers were specified as a random effect in order to control for intercorrelated observations within drivers across the track. Evaluation of systematic differences in speed and BPP between fatigue groups were assessed for the section of track 300 m before the restriction (BEFORE), the actual restricted section (DURING) and the 300 m section immediately following the restriction (AFTER). Post-hoc contrasts were specified between levels of the fixed effect factor (fatigue level). Uncorrected degrees of freedom are reported. In addition, the number of sessions in which drivers experienced lapses (>500 m s) on the PVT was calculated, in order to compare frequency at different levels of fatigue.

3. Results

3.1. PVT lapses

The percentage of drivers who exhibited at least one lapse on the PVT for each fatigue level is illustrated in Fig. 3. In the high fatigue group, 63.1% of drivers experienced lapses compared to 42.0% in the moderate group, and 33.3% in the low group. Most of these lapses were less than 2 s in duration. In general, only the high fatigue group experienced lapses greater than 2 s long. Of note, 21.1% of highly fatigued drivers experienced lapse durations between 2 and 4 s, 18.4% between 4 and 6 s, 5.3% between 6 and 8 s, and 10.5% between 8 and 10 s. No lapse durations exceeded 10 s. The table inset of Fig. 3 displays the distance the train would travel during lapses of these durations if this were to occur on the track. For example, if the train was traveling at 50 km/h and the driver experienced a lapse of 10 s, the train would travel 138.9 m in this time.

3.2. Restriction (a)

Means and confidence intervals (CIs) for brake use and speed during all track sections are displayed in Table 1. Mixed effects analysis revealed a significant main effect of fatigue for brake use before the restriction ($F_{2,957} = 6.2$, $p < 0.01$), with factor-level contrasts indicating that brake use at a high fatigue level was significantly less than at either a moderate or low fatigue level ($p < 0.05$). There was a significant effect of fatigue during the restriction ($F_{2,1117} = 5.3$, $p < 0.01$), with moderate brake use significantly higher than at either a low or a moderate fatigue level ($p < 0.05$). After the restriction, there was also a significant effect of fatigue ($F_{2,957} = 11.0$, $p < 0.01$), with brake use at a high fatigue level significantly less than at either a moderate or low fatigue level ($p < 0.01$) (Fig. 4).

There was a significant main effect of fatigue for train speed before ($F_{2,957} = 24.9$, $p < 0.01$), during ($F_{2,1117} = 38.0$, $p < 0.01$) and after ($F_{2,957} = 20.0$, $p < 0.01$) the restriction, with speed at a high fatigue level significantly above speed at either a moderate or low fatigue level ($p < 0.01$). Train speed in the low and moderate fatigue groups was maintained within 10% of the speed limit during the 40 km/h restriction (i.e. <44 km/h). This was exceeded by drivers in the high fatigue group (Fig. 4).

3.3. Restriction (b)

Mixed effects analysis revealed a significant main effect of fatigue for brake use before the restriction ($F_{2,957} = 4.9$, $p < 0.01$), with factor-level contrasts indicating that brake use at a moderate fatigue level was

Table 1
Mean and 95% confidence intervals (CI) for brake use and speeding before, during and after speed restrictions (a)–(d)

Restriction	Fatigue group	BEFORE		DURING		AFTER		
		Mean	CI (95%)	Mean	CI (95%)	Mean	CI (95%)	
(a)	<i>Brake</i>	Low	463.0	459.7–466.2	487.1	486.3–487.9	489.6	489.3–490.0
		Mod	456.3	450.2–462.4	480.7	475.7–485.7	489.3	488.9–489.6
		High	469.6	466.2–473.1	487.2	485.8–488.6	490.6	490.1–491.1
	<i>Speed</i>	Low	41.8	41.2–42.5	44.9	44.3–45.5	47.5	46.8–48.2
		Mod	41.9	41.0–42.9	44.6	43.8–45.5	47.4	46.6–48.2
		High	44.5	43.4–45.6	47.5	46.6–48.3	49.5	48.6–50.4
(b)	<i>Brake</i>	Low	465.5	462.5–468.5	479.5	477.6–481.4	490.9	490.5–491.2
		Mod	469.5	466.0–472.9	474.9	471.9–477.9	489.9	487.8–490.0
		High	463.5	459.1–468.0	479.0	476.2–481.7	490.8	490.3–491.4
	<i>Speed</i>	Low	47.0	46.0–48.0	39.9	39.4–40.4	34.4	33.9–34.9
		Mod	47.5	46.0–49.1	41.1	40.2–42.1	34.1	33.4–34.8
		High	48.7	47.2–50.3	39.9	39.1–40.8	33.9	33.2–34.6
(c)	<i>Brake</i>	Low	480.4	478.4–482.5	477.3	475.3–479.4	490.4	489.9–491.0
		Mod	473.8	471.0–476.6	471.0	468.5–473.5	488.8	488.2–489.4
		High	485.0	482.6–487.4	479.0	476.1–481.4	490.5	489.7–491.3
	<i>Speed</i>	Low	47.2	46.8–47.6	48.1	47.6–48.6	45.1	44.5–45.8
		Mod	47.4	46.9–47.9	46.8	46.1–47.5	43.7	43.1–44.3
		High	47.5	46.9–48.2	49.5	48.8–50.2	45.8	44.8–46.7
(d)	<i>Brake</i>	Low	490.3	489.0–491.7	465.5	462.7–468.2	487.5	486.5–488.6
		Mod	489.8	488.2–491.4	461.3	457.9–464.8	487.1	486.1–488.1
		High	492.8	491.3–494.3	482.4	479.6–485.1	491.2	489.9–492.4
	<i>Speed</i>	Low	38.5	38.2–38.9	43.5	43.0–44.0	43.0	42.2–43.8
		Mod	38.7	38.3–39.2	43.7	43.0–44.3	42.9	41.9–43.8
		High	38.0	37.5–38.6^a	45.4	44.6–46.2	47.1	46.1–48.2

Bolded numbers indicate fatigue groups significantly different from the others (from factor-level contrasts).

^a Indicates different to low fatigue group only.

significantly less than at either a low or high fatigue level ($p < 0.05$). There was no significant effect of fatigue during the restriction. After the restriction, there was a significant effect of fatigue ($F_{2,957} = 5.4$, $p < 0.01$), with brake use at a moderate fatigue level significantly greater than at either a low or high fatigue level ($p < 0.05$) (Fig. 5).

No significant main effect of fatigue level was found for speed (see Table 1 for means and CIs). With the exception of the moderate fatigue group immediately on entering this restriction, speed in all three fatigue groups was maintained within 10% of the speed limit (<44 km/h, Fig. 5).

3.4. Restriction (c)

Mixed effects analysis revealed a significant main effect of fatigue for brake use before the restriction ($F_{2,957} = 22.5$, $p < 0.01$), with factor-level contrasts indicating significant differences in brake use between all fatigue levels ($p < 0.01$). There was a significant effect of fatigue during ($F_{2,1277} = 10.7$, $p < 0.01$), and after ($F_{2,957} = 7.3$, $p < 0.01$) the restriction, with moderate brake use significantly higher than at either a low or a moderate fatigue level ($p < 0.01$) (Table 1, Fig. 6).

There were significant differences between groups in terms of speed during ($F_{2,1277} = 27.5$, $p < 0.01$) and after ($F_{2,957} = 12.6$, $p < 0.01$) the restriction, with significant differences between all fatigue groups ($p < 0.05$). Drivers in the high fatigue group were traveling fastest, followed by those in the low group.

3.5. Restriction (d)

There was a significant effect of fatigue on brake use before ($F_{2,957} = 3.1$, $p < 0.05$), during ($F_{2,957} = 38.2$, $p < 0.01$), and after ($F_{2,957} = 13.2$, $p < 0.01$) the restriction. Visual inspection of Fig. 7 clearly reveals reduced brake use in the high fatigue group compared to the other two groups. Indeed, this difference was significant ($p < 0.05$). Again, those in the moderate fatigue group appear to be using slightly more brake than the low fatigue group (Table 1).

There was also a significant effect of fatigue on speed before ($F_{2,957} = 4.1$, $p < 0.05$), during ($F_{2,957} = 18.3$, $p < 0.01$), and after ($F_{2,957} = 39.0$, $p < 0.01$) the restriction. Before the restriction, drivers in the high fatigue group were traveling significantly slower ($p < 0.01$) than those in the low fatigue group. In contrast, during and after the restriction, high fatigue drivers were significantly ($p < 0.01$) faster than drivers in the low or moderate groups. Furthermore, while the low and moderate groups remained within 10% of the speed limit during the restriction, this was exceeded by drivers in the high fatigue group.

4. Discussion

The aim of the current study was to examine the relationship between fatigue, braking behaviour and speeding during four speed-restricted areas on a simulated train track. PVT performance, considered to be a sensitive indicator of fatigue (Dorrian et al., 2004), revealed a concomitant increase in fatigue level and PVT lapses, particularly for those at the higher end of the lapse domain (i.e. 2–10 s long). Thus, as expected, increases in fatigue produced increases in frequency and duration of attentional lapses. Translating PVT lapse durations into operational terms, a train driver who experiences a lapse of between 2 and 10 s, in a train traveling at a speed of 45 km/h (the approximate speed of high fatigue drivers in the study entering the 40 km/h zones), will have traveled between 25 m and 125 m during the lapse period. Clearly, this could have a significant effect on the ability to plan and negotiate a speed restriction adequately, and as a consequence, pose a serious safety risk.

In general, examination of speed-restricted sections (a), (c) and (d) yielded similar results. All three of these sections were predominantly downhill, with restrictions occurring in, or immediately after a trough in track grade. As such, gravity was acting to increase speed on the approach to these restrictions. Throughout restriction (a), those in the high fatigue group used less brake, and as a consequence, exceeded the speed limit by greater than 10%. Drivers at a moderate fatigue level released the brake later than those in the low or high groups. Similarly, in restriction (c), drivers in the high fatigue group used less brake and traveled at a faster speed. Indeed, the high fatigue group were the only drivers to exceed the speed limit. In addition, moderately fatigued drivers used the brake more heavily and for a longer period than those in the low or high groups. In restriction (d), the high fatigued drivers used clearly less brake, and exceeded the speed limit by greater than 10%. Brake use among the moderate fatigue group was a little heavier.

Thus, overall, drivers in the low and moderate fatigue groups negotiated these speed-restricted areas successfully with a cost in terms of brake efficiency for the moderate group. The high fatigued drivers were less successful, the elevated speed reflecting an increased risk to safety. This safety risk resulted from exceeding the track limit, which is specifically calculated for typical trains crossing the corridor in order to prevent wheel lift and rail rollover, which can result in train derailment. Drivers are trained and supervised to run to speed limits exactly, particularly during curved terrain.

It could therefore be argued that in general terms, fatigue affects drivers' speed control, particularly during restrictions on downhill terrain. At moderate levels of fatigue, drivers appear to compensate for this by over-braking. While this can reduce driving efficiency by increasing fuel use and brake wear and tear, safety is conserved by adhering to track speed limits. Interestingly however, it appears that highly fatigued drivers no longer engage in this compensatory braking behaviour. The end result is an apparent (and somewhat misleading) conservation of efficiency at the expense of safety. There could be several suggestions for this effect. For example, highly fatigued drivers may lose their ability to introspect, and accurately assess their performance. This has been suggested as a trigger for compensatory behaviour (Fairclough & Graham, 1999). On the other hand, drivers at high levels of fatigue may be more likely to engage in risky behaviour, as there is evidence to suggest that sleepiness affects decision-making and risk-taking (reviewed in MacLean, Davies, & Thiele, 2003).

Finally, drivers may reach threshold level where they disengage from the driving task, simply letting the train run itself. This may be a specific cognitive effect or a result of general environmental disengagement due to sleep onset (e.g. during microsleeps or sleep attack).

In contrast to the other track sections studied, restriction (b) was negotiated reasonably well by drivers in all groups. There was no significant effect of fatigue on speed. In terms of brake use, drivers in the moderate group used slightly less brake before, and slightly more following the restriction. The reason why brake use and speeding during restricted section (b) was not comparable to that during the other restrictions could be explained by the track grade. Firstly, section (b) was a predominantly uphill section. As such, there was a natural slowing of the train due to the climb, which would have occurred in the absence of braking. Indeed, the train continued to slow down after the release of the brakes (during the restriction). It should be noted that the brakes were already applied more than 1 km before the restriction. This is in compliance with train operating guidelines, which dictate that the driver reduce train speed prior to entering an undulating track section (Shellman et al., 1980). Brake application in this section was used not only for control during the speed-restricted area. Rather, it was primarily directed at managing the train over the highly undulating track grade. The combination of overall uphill slope and brake use to manage frequent undulations resulted in a linear decline in speed before and during the restriction. Speed in all drivers was maintained within 10% of the track limit.

Further, it could be argued that the need for increased braking in order to accurately negotiate the constantly changing grade required drivers to interact with the train to a greater degree, rendering the section less monotonous and more interesting. The absence of an effect of fatigue level could have been due to this increased level of interest. Indeed, laboratory studies have found that tasks that are more monotonous and lacking in interest may be more sensitive to sleep deprivation (Bohlin, 1971; Johnson, 1982; Wilkinson, 1964), and crash investigations have identified an association between monotony and increased crash risk (Horne & Reyner, 1995).

Interestingly, the drivers appear to apply the brake at the same distance before each restriction regardless of fatigue level. This finding is surprising given that it could be expected that with increasing fatigue, and the observed impairment in sustained attention, drivers would apply the brake progressively later. However, due to the way in which the simulator program collected and outputted the data, the highest resolution that could be achieved was 50 m increments. As such, fatigued drivers could apply the brake up to 50 m later, without a visible change to the results. Looking at PVT lapse lengths may provide an explanation. In terms of lapsing, in a train traveling at 45 km/h, a driver could experience a lapse of up to 4 s duration and still manage to apply the brake no more than 50 m later. A higher level of data resolution would be a great advantage in future studies.

A further limitation of the current study is the potential contribution of motivation, which cannot easily be isolated from the effects of fatigue. Indeed, the observed performance impairment could conceivably result from (a) fatigue-related lapses in attention, poor information processing, reduced memory capacity and/or decision-making decrements, or (b) decreased motivation due to increased fatigue and thus a lack of incentive to maintain driving standards. Motivation issues have been a primary source of criticism in studies of sleep loss and performance, particularly since such studies have typically involved repeated testing over time. It has been suggested that not only does repeated testing reduce motivation, but that traditional performance indicators (i.e. computer or paper-and-pencil based laboratory measures) are so unrealistic that people are less motivated to perform optimally. These criticisms must also be taken into account with simulator investigations, such as the current study.

In the context of the current study, it could be expected that the constant conditions would minimise the likelihood of any systematic effect of motivation on performance (i.e. it should be constant across fatigue groups). However, the potential interaction effect between fatigue and motivation cannot be discounted. Importantly, it was impossible to “derail” our virtual train. As such, the drivers may have felt reduced motivation to drive in a safe manner due to a perceived lack of consequences for their performance impairment. This could conceivably affect the specific way in which performance impairment was manifest. For example, as previously mentioned, drivers at a moderate level of fatigue engaged in compensatory “heavy-handed” braking behaviour to maintain safety-critical speed control. However, highly fatigued drivers failed to do this and exceeded the speed limit. In the real world, perceived consequences may mediate this relationship, such that even at high levels of fatigue, drivers may engage in compensatory braking (which may become concomitantly more “heavy-handed”) in order to maintain safety.

While there are many factors that affect the complexity and workload of the train driving task over time, the current study aimed to examine one factor—track grade. Given the complex nature of the train system environment, one specific aspect of train control was chosen for analysis—the ability to accurately negotiate speed restrictions. Overall, results suggest that differences in track grade may influence the effects of fatigue on driving performance. Specifically, it appears that speed restrictions following moderate to heavy descending grades are likely to be sensitive to fatigue, particularly those which occur later during a trip. During these sections, drivers at a high level of fatigue may use less brake, and fail to slow the train adequately. The result is a serious increase in crash risk for these drivers. In contrast, restrictions during sections requiring a higher level of interaction, as is the case during undulating territory, appear to be less affected. Unfortunately, from results of this study, it is impossible to tease apart effects of track grade (i.e. slope, degree of track undulation) and time-on-task. However, it can be concluded that these factors have an important effect. In operational settings, track “hotspots” could be identified and highlighted to drivers during training in order to increase awareness of likely areas of increased crash risk, and implement extra precautions. Future research should be conducted to identify the differences in fatigue-related sensitivity of particular track specifications in more detail.

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