Effect of Split Condition and Driving Duration on Fatigue Based on Changes in Brain Wave Signals when Driving a Train Simulator.

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Abstract. One of the causes of train accidents is driver fatigue. Train driver fatigue can be caused by sleep factors, known as split sleep. This study aims to assess the impact of split sleep on train driver fatigue. A total of 12 male participants were asked to drive a train simulator for 2.5 hours after facing two sleep conditions, namely split sleep and baseline. The split sleep condition required participants to sleep in two segments at 05.00-10.00 and 12.00-15.00, while the baseline condition was conducted in one segment at 21.00-05.00. Fatigue was measured based on changes in brain wave signals via electroencephalogram (EEG) and Swedish Occupational Fatigue Inventory (SOFI). Fatigue measurements with EEG were conducted at the 10-minute start and end of the simulation, while fatigue measurements with SOFI were conducted before and after the simulation. The results of this study showed a higher level of subjective fatigue in split sleep compared to the baseline. However, the EEG signal change data and other dimensions of SOFI dimensions showed no difference between the two sleep states. Another result was an increase in fatigue after simulation in all dimensions of the SOFI. Therefore, split sleep should not be applied by drivers because it can increase subjective fatigue. However, if split sleep needs to be applied, it is necessary to fulfill sleep quantity (7-9 hours) and improve sleep quality. In addition, the company also needs to ensure that the train driver are awake at least 15 minutes.

Keyword: electroencephalography (EEG), fatigue, train drivers, split sleep, SOFI, sleep time.

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1 Introduction

1.1 Background

Data from 2015 to 2021 shows that there were 143 train accidents in Indonesia [23]. Railway accidents causes are divided into categories: infrastructure, human factors, external factors, and natural factors. The human factor is the third highest factor causing railway accidents in Indonesia, with 10.07%. Fatigue and sleep is one of the factors causing accidents by humans [1]. Dawson et al. [2] stated that fatigue is a crucial issue in the transportation sector.

Fatigue based on its factors can be divided into several parts. May and Baldwin [3] divided fatigue into two factors, namely sleep-related fatigue and task-related fatigue. Sleep-related fatigue is related to circadian rhythms and sleep disorders, while task-related fatigue is related to cognitive load. Fatigue can result from sleep factors such as lack of sleep, sleep restriction, and untreated sleep disorders [4]. Fatigue due to drowsiness has become an issue in the railroad sector in Indonesia. Freight trains in Indonesia have a train travel time of 4-5 hours and can increase to 8 hours due to queues on the railroad. Iridiastadi [5] mentioned that train driver need to allocate their rest time for worship activities, family interests, and other social needs. Freight train drivers in Indonesia need to cut their rest time to support other activities and prepare for the work schedule at the next station. As a result, the driver's rest time is limited. To overcome this, the application of split sleep has become a common phenomenon among Indonesian train drivers.

Split sleep is an event where a person falls asleep two to three times in a 24-hour period [6]. Split sleep is common in various industries including transportation [7]. Riedy et al. [8] predicted that drivers tend to do split sleep rather than continuous or consolidated sleep. Research by Zhou et al. [9] showed that split sleep increases subjective sleepiness compared to continuous sleep. In contrast, Jackson et al. [7] found no difference in sleepiness between split sleep and continuous sleep when the amount of sleep time was met, but it can result in a poor mood.

Electroencephalogram (EEG) is one of the measurement tools that can be used to detect fatigue, such as increased sleepiness in split sleep conditions. Jap et al. [10] also suggested that EEG is an accurate indicator of fatigue, although it tends to be more suitable for use in simulators. EEG measurement tools review several brain waves, namely delta (δ), alpha (α), beta (β), teta (θ), and gamma (γ) waves. Koudelková, Strmiska, and Jašek (2018) divided delta waves at frequencies of 0.5-4 Hz, teta at frequencies of 4-8 Hz, alpha at frequencies of 8-13 Hz, beta at frequencies of 13-30 Hz, and gamma at frequencies greater than 30 Hz. Research related to fatigue in the context of driving by Lees et al. [11] showed an increase in wave activity at low frequencies, namely delta, teta, and alpha, and a decrease in waves at high frequencies, namely beta and gamma.

Subjective measurements using the Swedish Occupational Fatigue Inventory (SOFI) questionnaire were also used in this study. Ahsberg et al. [12] developed the SOFI questionnaire to evaluate fatigue based on several dimensions consisting of lack of energy, physical exertion, physical discomfort, lack of motivation, and sleepiness. Each dimension was then measured using a Likert scale with a scale of 1 indicating that the dimension was not felt at all and a scale of 10 indicating that the dimension was very much in line with the feeling when filling out.
In the field of rail transportation, especially freight trains, increased fatigue and decreased work performance can lead to increased accident potential. This increase in fatigue can be caused by the application of split sleep. However, studies related to split sleep in Indonesia are still very limited. Thus, this study is intended to examine the effect of split sleep on fatigue in driving a train simulator based on the value of changes in brain wave signals based on EEG and SOFI. This research is expected to provide benefits for designing fatigue accident mitigation strategies.

1.2 Objectives

The aim of this study is to examine the impact of split sleep on the level of fatigue based on signal changes electroencephalogram (EEG) while driving a train simulator. The results of this study are expected to help Indonesian Railways Company in evaluating the impact of split sleep on fatigue and as a reference in the process of designing mitigation strategies in minimizing fatigue due to split sleep.

2 Literature Review

Williamson et al. [13] define fatigue as a condition when a person has a natural desire to rest. Fatigue can take many forms, including drowsiness, mental fatigue, and/or physical fatigue. Dawson et al. [2] define fatigue as a state that prompts a person to sleep. Fatigue is the result of a lack of rest from previous activities [14]. A person who is tired and sleepy will react more slowly and tend to find it more difficult to concentrate on driving, which increases the accident factor [15].

Williamson et al. [13] divided fatigue based on three causal factors, namely time of day, time/awake, and task-related factors. Similarly, May and Baldwin [3] divided fatigue based on two similar factors, including sleep-related fatigue and task-related fatigue. Time of day is a fatigue related to the pattern of waking and falling asleep [13]. Time/awake is a factor that is closely related to waking time, sleep quantity, and sleep quality. Task related factors are related to cognitive load, namely one’s work and environment. In the context of railways, Dorrian et al. [16] associate irregular scheduling to be the main factor that promotes fatigue, sleepiness, and unfitness of train driver in performing their work. Williamson et al. [13] state that sleepiness is part of fatigue. Research by Philip et al. [17, p. 20] concluded that fatigue at work is influenced by sleep duration and quality. In addition, Belenky et al. [7] stated that short-term sleep deprivation can reduce performance leading to errors and accidents.

Belenky et al. [6] divide sleep into three conditions, namely split sleep and consolidated sleep. Split sleep is a condition where a person falls asleep in a truncated manner, which is two to three times in a 24-hour period. Consolidated sleep is a condition in which a person falls asleep continuously in a 24-hour period without being cut. Research by Zhou et al. [9] showed that split sleep increases subjective sleepiness compared to consolidated sleep.

Electroencephalogram (EEG) is an electronic tool used to study human brain activity [10]. The human brain is divided into several lobes that have different functions. The frontal lobe plays a role in decision making, problem solving, planning, movement, and emotions. The temporal lobe has a role in memory processing, with the left part for verbal memory processing and the right part for non-verbal memory processing. The occipital lobe plays a role in visual processing. The parietal lobe plays a role in recognition, perceptual
determination of stimulus, orientation, and movement [18]. EEG recordings evaluate fatigue based on brain waves that are divided into delta (\( \delta \)), alpha (\( \alpha \)), beta (\( \beta \)), teta (\( \theta \)), and gamma (\( \gamma \)) waves [19]. Each brainwave consists of different frequencies and meanings, with frequencies ranging from 0.5 Hz to more than 30 Hz.

The Swedish Occupational Fatigue Inventory (SOFI) questionnaire is a questionnaire used as a subjective test of fatigue. Developed by Ahsberg et al. [12], this questionnaire is used to evaluate fatigue in several dimensions, namely lack of energy, physical exertion, physical discomfort, lack of motivation, and drowsiness. Each dimension is measured using a Likert scale with a scale of 0 indicating that the dimension is not felt at all, and a scale of 10 indicating that the dimension is very much in line with feelings.

3 Methodology

The objective of this study is to investigate the impact of split sleep on fatigue levels based on brainwave signal changes EEG when driving a train simulator. An experimental study was conducted using a train simulator. Fatigue was identified using objective and subjective instruments. The objective measuring instrument used is an electroencephalogram (EEG) that can measure brainwave signal changes. Meanwhile, the subjective measuring instrument used was the Swedish Occupational Fatigue Inventory (SOFI). Prior to data collection, an additional questionnaire in the form of Morning-Eveningness Questionnaire (MEQ) was also used to determine the participants' circadian rhythm type.

The participants of this study were 12 non-train driver, but had similar characteristics to train driver. The participants were male, aged 20-30 years old, with a minimum education history of high school graduates majoring in science or vocational high school with electricity, machinery, or automotive vocations. Participants also have a minimum height of 165 cm and an ideal body mass index (BMI) in the range of 18-25. Participants must also be physically and mentally healthy, have no history of chronic illness, and not color blind. In addition, participants were prohibited from consuming caffeine, alcohol, and cigarettes during the experiment. Dunn and Williamson [20] stated that in train driving activities, there is no difference in performance results between train driver and non-train driver.

This study was conducted with an experimental method in the form of within-subject design using a train simulator. Each participant got the same two treatment factors: sleep conditions and driving duration. The controlled variables in this study include gender, age, BMI, circadian type, intake of caffeine, alcohol, and cigarettes, participants' sleep time, driving duration, lighting, temperature, noise level, train travel route, and number of cars on the train simulator. The dependent variable of this study was fatigue based on EEG signal change parameters and SOFI values. Finally, the independent variables that were intentionally changed in this study were sleep condition and driving duration.

This study set up participants' sleep schedules, namely split sleep (SS) and baseline (BL) as shown in Fig 1. Participants' activities at the inn were monitored through Xiaomi Mi 360° Home Security Camera CCTV and Redmi Watch 2 Lite smartwatch. CCTV is used to monitor participants to sleep and wake up according to the specified schedule. The smartwatch was used to record sleep duration data through accelerometer, gyroscope (body movement sensor), and photoplethysmography (heart sensor) sensors. Prior to running the series of experiments, the experimental participants were asked to undergo 30 minutes of training. In this study, the driving duration of the train simulator used was 2.5 hours. This
design is based on Iridiastadi's [5] research where driving activities for 2 hours can have an effect on driver fatigue.

![Split Sleep Table]

**Fig 1.** Sleep condition

The train simulator used in the laboratory is Railworks Trains Simulator 2015 software (PI Engineering Software Inc, USA) produced by Dovetail Games. The instruments used in this study, namely EEG as an objective measurement tool and SOFI as a subjective measurement tool. The EEG used in this study was the EPOC+ EEG (Emotiv Inc., USA), which uses the standard 10-20 electrode pairing. The lobes reviewed in this study were the frontal and occipital lobes, which according to various studies can detect fatigue well [11].

After the participants came to the laboratory, they were asked to fill in participant data, sleep duration, temperature and blood pressure measurements, and the SOFI questionnaire (15 minutes). Then, the EEG was installed and calibrated through EmotivPro software until all channel quality indicators were green with a value of 100%. After the EEG was installed properly, the participants will perform a 150-minute train simulation, where the EEG is only installed in the first and last 10 minutes of the entire driving duration. The experiment was then closed by filling out the SOFI questionnaire (15 minutes), followed by the measurement of tension and body temperature. Visualization of simulation time can be seen in figure Fig 2.

![Baseline Table]

**Fig 2.** Details of the simulation

The collection data in this study are changes in EEG signal waveforms and SOFI values at the beginning and end of the simulation. EEG signal waveform recording data needs to be processed through filtration and transformation first [11]. The results of pre-processing EEG data will then be further transformed into power spectral density (PSD), which is the average value of each brain wave. The PSD value is then converted into relative power for each brainwave by calculating the area under the curve at alpha (α), beta (β), and teta (θ) frequencies. In addition, the ratio (θ+α)/β will be used as an indicator of fatigue [10]. After that, statistical tests such as normality test, t-test, and correlation test were conducted using IBM SPSS Statistics 25 software.
4 Results

In this study, there were no participants who were in the extreme morning or extreme evening type and all participants were able to participate in the experiment. Based on the paired t test, it is known that sleep duration for both conditions is not significantly different ($p = 0.449$). Then the Wilcoxon test, it can be seen that the quality of sleep for both conditions is not significantly different ($p = 0.138$).

In the frontal lobe, there are 4 indicators, namely the change value of alpha ($\alpha$), beta ($\beta$), and theta ($\theta$) waves, followed by the ratio ($\theta+\alpha)/\beta$. Each indicator was tested for normality using Shapiro-Wilk. Overall, all data on changes in frontal lobe EEG signals were normally distributed, except for changes in beta wave relative power. The change value of relative power alpha in SS condition showed a smaller decrease (-0.16%) compared to BL (-2.91%). The results of paired t test on frontal alpha relative power showed that the two sleep conditions were not significantly different ($p = 0.621$). The change value of relative power beta in the frontal lobe decreased for both conditions, with the change value in the SS condition tending to be greater (-5.24%) compared to the change in the BL condition (-1.20%). Based on the Wilcoxon test, the relative power beta data for both SS and BL conditions showed no significant difference ($p = 0.480$). The change value of relative power theta in the SS condition showed a greater increase (6.28%) compared to BL (4.04%) at the beginning and end of the simulation. Based on the paired t-test, both SS and BL sleep conditions did not have a significant difference ($p = 0.544$). The last indicator reviewed in this study is the change in the ratio ($\theta+\alpha)/\beta$, in the SS sleep condition has a higher increase (11.24%) compared to the BL condition (4.46%). The results of the paired t-test on the data of the change in the ratio ($\theta+\alpha)/\beta$ showed that the two sleep conditions, SS and BL, did not show any significant difference ($p = 0.108$).
In the occipital lobe, there are 4 indicators, namely the change value of alpha (α), beta (β), and theta (θ) waves, followed by the ratio (θ+α)/β. Each indicator was tested for normality using Shapiro-Wilk. The results of normality testing showed that the data on changes in EEG signals in the occipital lobe were mostly normally distributed, but there were groups of data that were not normally distributed, namely data on changes in the ratio (θ+α)/β. On average, the value of changes in relative power alpha in SS decreased by -5.04%, while for BL conditions it increased by 1.87%. Paired t test on the data of changes in relative power alpha in the occipital lobe showed that the two sleep conditions were not significantly different (p = 0.212). After that, in the beta indicator there was a smaller decrease in the SS condition (-2.00%) compared to the BL condition (10.24%). The results of the paired t test show that the data of relative power beta in the occipital lobe is not significantly different (p = 0.174). Changes in the value of relative power theta in SS showed a smaller increase (5.51%) compared to BL (11.31%). The paired T-test results of these two sleep conditions showed no significant difference (p = 0.544). Based on the average, the change in the ratio value (θ+α)/β in the SS sleep condition (7.47%) tends to be smaller than in the BL condition (26.73%). Based on the Wilcoxon test, the results showed that the data of the ratio change in both sleep conditions did not have a significant difference (p = 0.308).

The SOFI score data is the participant's subjective fatigue and sleepiness score. It consists of 5 components and is a Likert scale from 0-10. The higher the number selected by the participant, the higher the level of fatigue. SOFI data was tested based on two variables, namely sleep condition (SS and BL) and time condition (before and after). The normality test
results showed that there were abnormal data, namely the SOFI of SS physical discomfort before, BL energy deficiency before, BL physical exertion before, and BL physical discomfort before.

The SOFI value in the energy deficiency dimension increased from before and after the simulation for both SS and BL conditions. In addition, the BL condition has a value that tends to be lower than the SS condition. Wilcoxon test results showed that the sleep conditions for SOFI lack of energy before for both sleep conditions had a significant difference (p = 0.031). The results of the paired t-test showed that the sleeping conditions for SOFI energy deficiency after were not significantly different (p = 0.552). The t-test results for energy deficiency SOFI in the SS sleep condition indicated that there was no significant difference (p = 0.054). In contrast, in the BL sleep condition, the t-test results indicated a significant difference (p < 0.05).

The SOFI value in the physical exertion dimension, there was an increase in the SOFI value at the time before and after for the BL condition, but a decrease in the SS condition. In addition, it can be seen that in the BL condition, the SOFI value tends to be lower than the SS condition. Wilcoxon test results, SOFI of physical labor based on sleep condition indicated rejection of H0 in the before condition (p = 0.018). Other indications include the results of the paired t-test of SOFI of physical labor that showed rejection of H0 in the after condition (p = 0.761). The t-test results of the SOFI of physical exertion in the SS sleep condition indicated that there was no significant difference (p = 0.559). In contrast, in the BL sleep condition, the t-test results showed a significant difference (p < 0.05).

The SOFI value of physical discomfort showed an increase at the time before and after for both SS and BL conditions. In addition, it can be seen that in the SS condition, the SOFI value tends to be higher than the BL condition. Based on sleep conditions, for the pre-simulation condition, there was no significant difference between the two sleep conditions (p = 0.107). The after condition also showed no significant difference between the two sleep conditions (p = 0.509). The Wilcoxon SOFI test results for before and after in the SS condition showed no significant difference (p = 0.075). In contrast, in the BL condition there was a significant difference for the before and after time conditions (p = 0.008).

The SOFI scores on the lack of motivation dimension showed an increase in SOFI scores in the after time condition. In addition, it can be seen that on average, the SOFI value of lack of motivation in the SS condition is higher than that in the BL condition. Based on the paired t-test, the before time condition did not show a significant difference (p = 0.385). In addition, the SOFI value in the time after condition also showed no significant difference (p = 0.745). In the SS sleep condition, the results of the SOFI t-test for lack of motivation showed no significant difference (p = 0.056). In the BL condition, the difference in time conditions was significant (p = 0.005).

The SOFI value on the sleepiness dimension showed an increase from before and after. In addition, the SOFI value of sleepiness in the SS condition was on average higher than that in the BL condition. Based on the paired t-test, the before time condition showed that there was no significant difference between the SS and BL conditions (p = 0.065). The results of the next t-test, namely the time after condition, also showed no significant difference between the two sleep conditions (p = 0.777). In the SS sleep condition, the before and after time conditions showed a significant difference (p = 0.010). The drowsiness SOFI data in the BL sleep condition also showed a significant difference (p = 0.000).
The subjective indicators in this study show that in the SS condition, participants tend to have higher fatigue, which is shown by higher SOFI values in all dimensions. Thus, there are indications that the SS sleep condition provides higher subjective fatigue, especially in the dimensions of lack of energy and physical exertion. This study showed an increase in the average SOFI value in all dimensions before and after simulation, except for the physical energy dimension in the SS condition. Based on these results, it can be shown that driving a simulator for 2.5 hours can increase subjective fatigue.

This study tested the correlation between the parameters of the research instruments using the Spearman test. In this study, there was a positive correlation between fellow EEG brain wave parameters, both in the frontal and temporal lobes. All SOFI indicators also had positive correlations between parameters on the SOFI.

![Graphs showing SOFI scores before and after simulation](image1)

**Fig 5.** (a) Average of lack of energy component, (b) Average of physical exertion component, (c) Average of physical discomfort component, (d) Average of lack of motivation component, (e) Average of sleepiness component

5 Discussion
Fatigue can be evaluated through various indicators, including brain wave signals [10]. Among these indicators, EEG indicators are referred to as the "gold-standard" in detecting fatigue [21], [22]. In addition, the use of EEG measurement tools has been widely carried out in detecting fatigue in the transportation field, especially in monotonous driving (Jap et al., 2009; Ma et al., 2018; Lees et al., 2018) [11], [22].

Based on the recording results in the frontal lobe at the beginning and end of the simulation, this study showed a decrease in the relative power of alpha (-0.16% SS and -2.91% BL) and beta (-2.01% SS and -10.42% BL) waves, as well as an increase in the relative power of teta (+5.52% SS and +11.32% BL) and ratio (+7.47% SS and +26.74% BL) waves. This pattern of wave activity is consistent with the study of Jap et al. [10], in which fatigue is indicated by a decrease in alpha and beta waves, and an increase in teta and ratio waves. Based on these findings, it is known that a driving duration of 2.5 hours can provide an indication of increased fatigue. Slightly different from the results on the frontal lobe, the results on the occipital lobe showed a difference in the BL condition, where the alpha relative power value increased (+1.88%) while using the train simulator. The EEG signal changes in the occipital lobe did not indicate higher fatigue in the SS condition, but rather the opposite in the BL condition. This difference may be due to the different functions of the two lobes of the brain, with the frontal lobe involved in decision making, problem solving, planning, movement, and emotion, and the occipital lobe involved in visual processing.

In the subjective parameter, SOFI, there were differences in fatigue levels based on sleep condition, namely in the dimensions of lack of energy and physical exertion before simulation. In addition, this study showed a higher indication of sleepiness between the two sleep conditions, although, the sleepiness dimension did not have a significant difference between the two conditions. In this study, objective fatigue measurements, namely EEG in the frontal lobe and occipital lobe had a positive correlation in the same wave parameters. In addition, the beta wave parameter has an almost perfect negative correlation with the teta wave parameter, with a value of -0.890 in the frontal lobe and -0.970 in the occipital lobe. Similarly to the subjective measurements, the dimensional measurements on the SOFI have a positive correlation with each other. However, the correlation between objective measures and subjective measures was only found in frontal alpha wave EEG compared to all SOFI dimensions. This appears to be due to the different levels of fatigue that participants felt subjectively compared to objective measures.

6 Conclusion

Based on the results of this study, it can be concluded that split sleep can affect fatigue higher than the baseline. Significant fatigue was found based on participants' subjective fatigue, namely on the SOFI dimension of lack of energy and physical strength before performing the simulation. However, no significant differences were found based on changes in EEG wave signals. Nonetheless, the implementation of split sleep tends to be discouraged. If split sleep conditions must be applied, mitigation strategies need to be implemented to overcome the fatigue that can be caused, including fulfilling the driver's sleep duration of 7-9 hours in a 24-hour period, supported by adequate sleeping facilities. Comfortable sleeping facilities include cool conditions, dim lighting, and low noise. Other strategies that need to be implemented include ensuring the driver wakes up at least 15 minutes before the start time to avoid the effects of sleep inertia. In overcoming fatigue due to long driving duration, it is
necessary to ensure that the driver has sufficient rest time between shifts, which is at least 30 minutes every 4 hours of driving time.

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