Analysis of Braking Behavior of Train Drivers to Detect Unusual Driving

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Abstract

The safety devices for train systems are activated in emergency situations when a risk becomes obvious, and the emergency brake is applied. If such systems are faulty, the drivers’ operating errors may cause immediate accidents. So it is necessary to evaluate potential risks by detecting improper driving behavior before overt risks appear. This study analyzes the driving behavior of train drivers using a train-driving simulator. We focus on braking behavior when approaching a station. Two methods for detecting unusual braking operation are examined by giving drivers mental calculation problems as a mental workload. The first is a method monitoring the driver’s brake handle operation, and the second is a method measuring vehicle deceleration. These methods make it possible to detect unusual driving.

Key words: Train Driver, Braking Behavior, Driver Monitoring, Mental Workload, Safety

1. Introduction

Currently, the operation safety of railways is provided by sophisticated signaling equipment such as the Automatic Train Protection (ATP) systems. However, these signaling systems work only when the danger of an accident is apparent, and some danger may be undetectable in specific cases. Therefore, we consider that the train driver, who operates the train directly, has ultimate responsibility for ensuring safety. Accordingly, studies focusing on train driver and his/her condition have been conducted in recent years (1)-(3).

To develop more preventive safety measures, we consider it important to evaluate potential risks by detecting improper driving behavior, preliminarily through condition monitoring, before driving risks become obvious. In this study, we examined fault-detection methods that enable us to evaluate both actual and potential risks stemming from the train driver behavior by monitoring the condition of the train driver easily and without accompanying body restraints. We simulated abnormal conditions for the train driver by imposing secondary tasks and examined the possibility of judging unusual driving through driving tests using a train-driving simulator. Two detection methods of unusual braking operation are examined. One is a detection method by driver’s brake handle operation and the other is a method by vehicle deceleration.
2. Experiments using Train-Driving Simulator

2.1 Experimental Method

We conducted experiments using a train-driving simulator that was developed for studying human factors so that stimuli similar to those from an actual vehicle could be provided. Figure 1 presents the train-driving simulator, Fig. 1 (a) depicts the system configuration, Fig. 1 (b), an overview of the simulator (see reference 4 for details). This simulator calculates the vibration of the vehicle from the track irregularity and a vehicle dynamics model, and gives visual stimuli that make it feel as if the vehicle is vibrating without using a motion base by shaking the images on the simulator screen.

![Diagram of the train-driving simulator](image-url)

**Fig. 1** Train-driving simulator

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The test subjects consisted of four males; two of them had engine driver’s licenses and experience in driving actual vehicles. The other two subjects were students who were fully skilled in driving on the simulator but had no experience in driving actual vehicles.

2.1.1 Driving Task
The driving task consisted of driving on a simulated track with four stations, stopping at each station, as depicted in Fig. 2. The subject was required to start the train in response to the departure signal and stop the train at the prescribed stopping position at the next station.

2.1.2 Secondary Task
Mental calculation was used as a secondary task. The state of performing mental calculations concurrently with driving was assumed to be an unusual state for the train driver. For the mental calculation task, problems were presented by voice and spoken answers were required, in order to avoid direct interference with driving behavior.

The mental calculation task is as follows: A one-digit number is enunciated every 3s. The subject adds the present number to the last number presented 3s before and says the answer as shown in Fig. 3.

Mental calculation problems were imposed after completion of acceleration and continued until the vehicle was completely stopped. Furthermore, the subject was required to memorize the calculation result during the interval between solving the problem and the presentation of the next problem, in order to eliminate the no-load state.

The subjects are informed that train operation is the highest priority and the mental calculation is the second highest.

2.2 Experimental Results
Figure 4 shows an example result of vehicle speed when stopping at a station. From this figure, the vehicle was stopped without overrunning the stopping position when driving
both with and without mental calculation. In addition, it cannot be confirmed over speed that as ATP systems will be activated when driving both with and without mental calculation. Therefore overt risk does not exist.

![Graph showing vehicle speed against distance to desired position](image)

**Fig. 4** Vehicle speed

3. Fault Detection from Brake Handle Operation

3.1 Method of Fault Detection from Brake Handle Operation

The requirements for brake operation are to maintain riding comfort and to stop at the desired position with high accuracy. Although it is common for large movements of the brake handle to be avoided as far as possible in order to minimize shock, it can be expected the train driver will be unable to adjust the brake smoothly if he or she is experiencing abnormal conditions as illustrated in Fig. 5. Therefore, any unusual conditions for the train driver may appear in the measurements of brake-handle operation.

![Graph showing brake handle position over time](image)

**Fig. 5** Driver’s condition and operation behavior

The handle operation of railway vehicles is not continuous maneuver because the driver operates the handle to the notch which is the discrete command value. Here, the handle change is defined as the change value of the handle operation by the driver at one time. If the driver is under unusual condition, he or she cannot operate the handle smoothly. This behavior makes the handle change large value in comparison with the usual condition. Therefore, we evaluate the driver’s brake operation by analyzing the handle change. The handle change is described as \( u_k \) \((k = 1, 2, 3, \ldots, n)\). This variable is given until the vehicle stops as long as the handle is operated by the driver. Next, the average of the handle change \( \bar{u} \) is calculated by storing the date of the handle change \( u_k \). The handle operation is evaluated by the deviation of the handle change \( u_k \) from the average of the handle change \( \bar{u} \) as a standard operation.
Equation (1) expresses the mean squared error of the handle change to the average of the handle change, and corresponds to the variance of the handle change.

3.2 Experimental Results of Brake Handle Operation

The brake handle operation of Subject A (a student) when stopping at a station is plotted in Fig. 6. The horizontal axis represents the distance from the desired position, which is denoted by 0. When driving with mental calculations, in contrast to driving without mental calculations, the driver performed a brake-force reinforcing operation immediately before stopping because the brake had been released too much. This demonstrates that the brake operation was not performed smoothly.

3.3 Fault Detection from Brake Handle Operation

3.3.1 Analysis of Brake Handle Operation using Histogram

A frequency distribution was obtained to determine values for the brake handle operation. The average of all trials of Subject A is given in Fig. 7. The horizontal axis represents the handle change value for a single operation, with negative values representing when the brake was released and positive values representing when the braking force was increased. The vertical axis represents the normalized frequency.
Without mental calculation, the frequency of operations with a brake handle change of -1 is high because the frequency of releasing the brake in one step is high. With mental calculation, however, the frequency of operations with a large brake handle change is higher than without mental calculation. Similar trends were also confirmed in the other subjects.

3.3.2 Fault Detection from Variance of Brake Handle Operation Value

Next, the variance of the brake handle change was obtained using Eq. (1). In Fig. 7, the variance without mental calculation was 0.820, and that with mental calculation was 2.85.

The variance $\varepsilon^2$ obtained for each trial of Subject A is shown in Fig. 8. The horizontal axis represents the variance of the brake handle change. As an overall trend, the variance exhibits higher values for driving with mental calculation. Therefore, it may be possible to detect the variance exhibits higher values for driving with faults by setting a threshold. Therefore, the threshold for each subject is defined by calculating the 95th percentile value of the variance of the handle change in the condition without mental calculation. This threshold is calculated by the average variance and the standard deviation in the all nine trials without mental calculation. The threshold for Subject A was 1.84.

When a judgment was made on the basis of Fig. 8 with this value as the threshold and assuming that a variance $\varepsilon^2$ above the threshold is abnormal and a variance $\varepsilon^2$ below the threshold is normal, “false detection” (i.e., judging a case with standard deviation below the threshold as abnormal) did not occur in the absence of mental calculation (i.e., 0% of the total), while “misdetection” (i.e., judging a case with a standard deviation above the threshold as normal) when performing mental calculation occurred once, 11.1% of the total.

The results obtained for all subjects in the same manner are given in Table 1. The rate of misdetection for the two licensed drivers (Subjects C and D) was higher than that in the student subjects (Subjects A and B), indicating a poor result for fault detection. The principal cause seems to be the difference in the average variance between the cases with and without mental calculation is relatively small for both Subjects C and D. In this case, there were no large changes in the values for brake operation because Subjects C and D performed brake operation while driving with mental calculation just as in the case of driving without mental calculation.
Table 1  Results of detection from break handle operation

<table>
<thead>
<tr>
<th>Subject</th>
<th>Average variance of handle change</th>
<th>Threshold</th>
<th>False detection</th>
<th>Misdetection</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W/O mental calculation W/ mental calculation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A (Student)</td>
<td>0.820 2.85</td>
<td>1.84</td>
<td>0%</td>
<td>11.1%</td>
</tr>
<tr>
<td>B (Student)</td>
<td>0.407 10.0</td>
<td>1.06</td>
<td>0%</td>
<td>12.5%</td>
</tr>
<tr>
<td>C (Licenced driver)</td>
<td>6.25 7.16</td>
<td>7.59</td>
<td>22.2%</td>
<td>77.8%</td>
</tr>
<tr>
<td>D (Licenced driver)</td>
<td>1.41 2.27</td>
<td>3.36</td>
<td>0%</td>
<td>88.9%</td>
</tr>
</tbody>
</table>

Here, Subject C exhibits a larger value of the variance than other subjects while driving without mental calculation. This indicates that Subject C performed brake operations with a larger value for the operation, regardless of the presence or absence of mental calculation tasks, possibly due to the influence of habitual practice on operations performed by the subject.

At the same time, Subject D exhibits a smaller value for the average of the variance when driving with mental calculation than other subjects, so it is possible that the braking operations of this subject were less influenced by the mental calculation tasks than other subjects.

In this experiment, we checked how braking operation is disturbed by mental calculation tasks. Because differences between individuals occur, however, we consider that an evaluation involving the reproduction of unusual conditions is necessary for examining the details of the detection accuracy.

4. Fault Detection from Deceleration

4.1 Method of Fault Detection from Deceleration

The method proposed in the previous section detected unusual driving after vehicle stopping. In this section, the real-time monitoring method to detect unusual driving earlier is examined.

The average deceleration $\alpha_r(t)$ required by a vehicle at position $x(t)$ moving at a speed of $v(t)$ to stop at the desired position $x_d$ is defined by the following equation.

$$\alpha_r(t) = \frac{v(t)^2}{2(x(t) - x_d)}$$  (2)

This $\alpha_r(t)$ is hereinafter called the required deceleration. When the actual deceleration of the vehicle $\alpha(t)$ exceeds the required deceleration $\alpha_r(t)$, i.e. $\alpha(t) > \alpha_r(t)$, the vehicle stops before reaching the desired position $x_d$ if the actual deceleration is kept constant, and when $\alpha(t) < \alpha_r(t)$, the vehicle overruns the desired position $x_d$ if the actual deceleration is kept constant. The train driver operates the brake to adjust the braking force so that the actual deceleration $\alpha(t)$ approaches the required deceleration $\alpha_r(t)$.

The actual deceleration $\alpha(t)$ may not converge to the required deceleration $\alpha_r(t)$ in special cases, such as delays in adjusting the braking force due to some abnormality involving the train driver.
Therefore, we consider that a trajectory plotted on a plane with the horizontal axis representing the required deceleration $\alpha_r(t)$ and the vertical axis representing the actual deceleration $\alpha(t)$ will clearly indicate the characteristics of changes in the actual deceleration $\alpha(t)$ with respect to the required deceleration $\alpha_r(t)$, i.e., the brake adjustments. An example of a deceleration trajectory is given in Fig. 9.

### 4.2 Experimental Results of Deceleration

The required and actual decelerations are examined by comparing with and without mental calculation. Figure 10 illustrates the transition of the required and actual decelerations to the distance in the same trial as shown in Fig. 4. Without mental calculation as shown in Fig. 10 (a), the actual deceleration follows the required deceleration when the actual deceleration deviates from the required deceleration. This means the subject modifies the brake operation to generate the appropriate deceleration to compensate the deviation of the actual deceleration from the required deceleration.

![Deceleration Trajectory](image)

**Fig. 10** Required and actual decelerations
With mental calculation as shown in Fig. 10 (b), on the other hand, the deviation of the actual deceleration from the required deceleration becomes large value. This is because the subject did not modify the brake operation in spite of the large deviation. In addition, when the distance to the desired stopping position remains under 20m, the actual deceleration lowers the required deceleration and it shows the negative value of the deviation. This is because the subject decreases the brake force and it is not enough to make the vehicle stop at the desired position. Finally, the subject strengthens the brake again in front of the desired stopping position.

From these behaviors of both the actual and the required decelerations, we can evaluate the braking operation.

4.3 Results of Fault Detection from Deceleration

4.3.1 Analysis of Deceleration Trajectory

Figure 11 plots the deceleration trajectories. Arrows in the figure denote movement of the trajectory with time. Because the sensitivity of the required deceleration \( \alpha_r(t) \) increases and approaches 0 or \( \infty \) as the vehicle approaches the stopping position, only the trajectory up to 5m before the stopping position is graphed, in order to remove such effects from evaluation.

Without mental calculation, the trajectory goes to the datum after the actual deceleration \( \alpha(t) \) rises because the brake is released by stages after being applied. With mental calculation, however, the trajectory draws a counterclockwise circle because the brake correction is larger than necessary. It may be possible to identify unusual driving by evaluating these characteristic trajectories.

![Fig. 11  Relation between required and actual decelerations](image)

Fig. 11  Relation between required and actual decelerations
4.3.2 Fault Detection by Area Setup on Deceleration Trajectories

Figure 12 depicts the trajectories of all trials of Subject A with no mental calculation. It can be seen that the trajectories form a somewhat fixed pattern. From this result, it would be possible to identify an area on the deceleration trajectory where the trajectory does not normally transit as an abnormal area (1), as seen in Fig. 12, and to then identify any intrusion from the normal area into the abnormal area as a fault as a method for identifying any unusual driving in real-time. Abnormal area (2) represents the area where overrun is determined when the maximum deceleration of the vehicle is set to 4km/h/s. This area represents overt risks. The result indicates that this method enables detecting both potential and overt risks.

![Fig. 12 Example of abnormal area set up](image)

5. Conclusions

We examined methods for detecting any unusual conditions affecting a driver, based on driving behavior. We focused on braking operation when stopping at a station and proposed two methods for detecting unusual driving at an early stage based on a brake-handle operation value and deceleration. Furthermore, by conducting experiments using a train-driving simulator, we compared cases with secondary tasks consisting of mental calculation to cases without such tasks.

The variance of the brake handle operation was significantly larger when secondary tasks were imposed, indicating the possibility of determining the driving characteristics of individuals.

Characteristic deceleration trajectories were observed in cases with secondary tasks imposed. We examined the possibility of detecting unusual driving by evaluating such trajectories with abnormal areas established on the deceleration trajectory.

In the future, we need to examine common trends by increasing the number of subjects who have a driver's license. Furthermore, the train-driving simulator used for the experiments in this study is not equipped with a motion base to shake the vehicle, so it could not provide the physical sense of acceleration (deceleration), an important element of the feedback experienced during braking. Therefore, we consider that on-track tests will be necessary for a detailed examination of the validity of these methods.
References


