EYE-MOVEMENT ANALYSIS OF TRACK MONITORING PATTERNS OF NIGHT TRAIN OPERATORS: EFFECTS OF GEOGRAPHIC KNOWLEDGE AND FATIGUE

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Track maintenance is one of the most critical activities for railway safety, particularly for high-speed trains. In maintaining tracks, a number of special purpose trains are used for materials transportation, inspection of the track and rails, construction and other purposes. These track maintenance trains are operated under stressful and changing conditions such as the lack of traffic signals and low visibility. Therefore, it is of great importance to investigate train operators' human factors for enhancement of their operation quality and reliability. The present paper particularly focuses on their geographic knowledge on driving area and fatigue by time course as such factors. Through task analysis using eye-tracking data recorded during performance of track inspection task, several analytical diagrams were produced: transition network of attention allocation, distribution of eye-gaze duration at each location on the ground and tasks, and so forth. Based on these results, we examine the effects of the train operator's human factors on their cognitive and perceptual processes, and also discuss the operator's strategy for obstacle detection on the track.

INTRODUCTION

Human factors play a crucial role for railway safety as in other high-tech man-machine operations such as aviation, ship navigation and nuclear power plant control. It is well-known that human errors are the predominant cause of accidents and incidents in those areas (Margetta, 1976; and Miller and Swain, 1987), and their rate is largely affected by an individual operator's factors such as work experience, skills, knowledge, and workload and fatigue as well as working conditions. Train operations share many of these characteristics.

There are many types of trains operated in the railway: high-speed trains, commuter trains, subway trains, freight trains, track maintenance trains, and so on. In this study, we focus on the track maintenance trains operated to maintain tracks and rails for the high-speed train (Shinkansen) in Japan. The choice of focus was motivated by several reasons. The driving operations of this type of trains are performed under more changeable and stressful conditions than those of regular passenger trains. For example, the track maintenance train has no traffic signals available to it when it is operated in operation interval break during the night time after the last evening train and before the first bullet train the following morning. Its accident and incident rate is higher than that of passenger trains, though it is actually very low in terms of the absolute number and rate of accidents/incidents.

Driving operations in these trains are performed by a team of two operators, a driver and a supervisor, in a train cockpit according to a prescribed plan and directives and control by a station-based traffic controller. In this task, the driver controls the train within safety bounds, usually just manipulating acceleration and brake levers according to the time schedule and the supervisor's command. Besides supervision of the driver, the supervisor communicates with the traffic controller and other trains for safety. During most of the time, the driver and the supervisor monitor the tracks and their surroundings. This task relies heavily on their visual perception and attention allocation. For such task characteristics, it is very useful to employ the eye-tracking technique in analysis of operators' cognitive and perceptual performances (Itoh et al., 1998).

In the present paper, we use eye-tracking data to examine effects of night train operators' human factors as well as operating conditions on their cognitive and perceptual processes. Special concern is focused on geographic knowledge of the driving area as an operator's primary factor. Effects of fatigue, as well as driving conditions such as running speed, are also analyzed. Based on these analysis results, we conjecture on the operator's mental processes during track monitoring.

OBSERVATION OF TRACK INSPECTION TASK

There are several types of track maintenance trains, depending on their purposes. In this study, we focus on a special train called "Track-state Confirming Train" in which a supervisor performs a track inspection task while a driver is performing driving operations. The major purpose of this task is to ensure there are no obstacles on the track so that high-speed trains can run safely on the rail. When the supervisor finds something during his monitoring process, he orders the driver to stop the train and retrieves the object from the track. This train was chosen as our focus since the track monitoring activity exhibits the train operator's processing activities common to all the types of track maintenance trains.

In this study, we observed four track monitoring sessions, each of which was carried out in the same driving territory or inspection area on a different day using a different scenario. In each session, a supervisor performed the track inspection task while the train was running about 40 km distance on the outbound track and the same distance on the return track from approximately 3:00-5:20 am. His eye-movement data was recorded for approximately one hour using an ASL 4000 eye-tracking system.

In the first case (Session I), eye-movement recording (EMR) was performed with a supervisor who did not have geographic knowledge for this area, but who was an expert of this task in another area (the knowledge-less supervisor). In the other three cases, the same supervisor, who usually engaged in track inspection in the ten years, participated in the EMR sessions. In Session II, this supervisor's eye-movement data was recorded during the first half of the whole trip, i.e., outbound segment, immediately after starting the task. In Session III, the eye-movement recording was performed during the second half, i.e., return trip, about one hour and a half after starting the task when he seemed to be more tired than in the first half due to time course of the task. There are actually very few occasions that something is lying on the track. Therefore, in
the last case, Session IV, four boxes (15x25x8.5 cm) were put at different locations dispersed throughout the territory, and EMR data was obtained in the first half. The aim of this scenario is to observe the supervisor's actual monitoring process in detecting an obstacle.

**TRAIN OPERATOR’S ATTENTION ALLOCATION**

**General Pattern of Track Monitoring**

A general pattern of a supervisor's track inspection process is generated, using eye-movement data from all three sessions (II-IV) involving the knowledge-holding supervisor. Figure 1 indicates the transition network of the supervisor's attention allocation during the track inspection task. In this figure, the size of each circle represents the percentage of total gaze time at each location on the tracks and surrounding environment. The bigger a circle is, the more attention was paid to that location during the task. The thickness of the arced arc between two locations indicates the frequency of transition in terms of the relative percentage over the total number of eye-movements. The thickest lines in this figure, i.e., lines between the distant position on the (currently) running track and the side of the running track, and between the distant position and the parallel track, represent 5-10% of transition over all the attention shift. The thinnest lines mean 0.5-1.0% of transition. No line is provided for a smaller percentage of transition than 0.5% in the network.

![Figure 1: Transition pattern of operator's attention during track monitoring](image)

The most frequently attended location was a distant region on the running track (about 200 meter ahead), on which a head light of the train focused. The supervisor gazed at this location for about 30% of time during the task. From this fact, this location seems to be the home-base of his attention for track monitoring. Besides this location, he also frequently looked at the side of the running track for about 20% of total duration. In this location, markers indicating distance from Tokyo and a telephone box are placed at regular intervals and due to the reflection of the train's light, shining spots sometimes appeared. Therefore, it is natural to deduce that his fixation shifted automatically to this location, rather than that he paid critical attention to this region. His attention was also shifted frequently to the area between the two tracks (9.3%), the parallel track (8.9%) and a near-point (about 50 meter ahead) on his own running track (7.1%). Attention in the direction of the other parallel track was relatively infrequent, totaling less than 20%.

The frequency distributions of gaze times are shown in Figure 2 for some locations at which the supervisor looked relatively frequently. As can be seen in this figure, the distribution of gaze time is found to be highly skewed and biased towards the side of short duration for each location. The mean gaze time is approximately one second for every location, and its standard deviation is also about one second. This tendency of gaze time is almost identical to those of other locations at which were not gazed frequently.

![Figure 2: Histogram of gaze duration at each information source](image)

From these results, the supervisor's track inspection process can be conjectured to be a home-base monitoring strategy for inspecting the states on the tracks and surroundings. In this strategy, his home-base of attention is the distant region of the present running track approximately 200 meters ahead. He monitors the states on his tracks around his home-base by a short look at each gazed location (taking less than a few seconds). That is, his attention shifts from the home-base to another location such as the side of his own track, the parallel track, etc. and then returns to the home-base of monitoring.

**Effect of Geographic Knowledge**

A schematic representation identical to Figure 1 is employed to indicate the transition of attention allocation in each EMR session. Figure 3 shows a transition network of the supervisor having the geographic knowledge for the first half of the trip (Session II). His attention was distributed unevenly among various locations, including other regions with the home-base accounting for about a quarter of total duration. He also frequently monitored the states in the side of the running track and the area between two tracks.

![Figure 3: Attention transition pattern of operator having geographic knowledge](image)

The eye-movement pattern of the supervisor having no geographic knowledge (Session I) is depicted in Figure 4. It is easily seen that his attention was more concentrated on the running track. About half of time (46%), he gazed at the home-base of attention, i.e., the distant region on the running track. In addition, this supervisor's mean time for a single gaze at this region was twice as long (2.1 sec., SD=2.3 sec.), compared with the knowledge-holding supervisor. This
suggests that the knowledge-less supervisor performed cautious inspection of the tracks. Regarding attention allocation at the near region on the running track, his percentage of gaze time was much larger (16.2%) than that of the knowledge-holding supervisor (7.0%). In addition, the knowledge-less supervisor seldom looked at the places outside of the running track (only for 4.4% of total gaze time) which the other supervisor paid attention to these places for about 20%.

Effect of Time Course

The transition of attention allocation is depicted in Figure 5 for the knowledge-holding supervisor's second half trip (Session III). Comparing this figure with Figure 3, it is seen that the supervisor was monitoring the states less diversified for the second half than for the first half. As can be seen in Figure 5, his attention allocation was much more concentrated on the home-base of monitoring (32.9%) in particular, he looked less frequently (8.9%) at the other direction of his running track, i.e., the parallel track, the side of the parallel track, and its outside (17% for the first half).

We assumed higher level of the supervisor's fatigue with time course of task performance, and it is reasonable to infer that his vigilance, assumed to be closely related to ability to detect an obstacle on the track, is decreasing due to higher level of fatigue for the second half. To compensate for decreased vigilance, he seemed to concentrate more on the running track for the same reason as the monitoring strategy of the knowledge-less supervisor so as to eliminate the risk of high-speed train derailment due to an obstacle. However, it is difficult to exactly identify the actual causes leading to different attention allocation patterns between the first and second halves of the time course since several factors are confounded in these two scenarios (Sessions II and III). It should be recognized, for example, that the parallel track for the return trip is the track which was checked while running the outbound segment an hour earlier. Therefore, it may be true that the supervisor need not have monitored that track again.

Effect of Driving Speed

As an example of operating condition, the driving speed was analyzed in this study. According to operating rules, the upper speed limit of track maintenance trains is 60km/h. However, their operating diagrams are scheduled, supposing that trains are running at the speed of 40km/h on average. Therefore, we examine effects of the driving speed by comparing results of the supervisor's attention allocation patterns at 40km/h and 60km/h. Transition networks of the supervisor's attention allocation at these two levels of are shown in Figures 6 and 7.

As can be seen from these figures, the most remarkable difference between the two levels of driving speed is that of his attention allocation pattern to the near-point of the running track. That is, the supervisor hardly looked at this region when driving at the speed of 40km/h (0.8%), while he often shifted his attention to this region at 60km/h (8.9%). Instead, the rate of his attention allocation to the home-base was decreased with the driving speed: 46.4% at 40km/h and 32.7% at 60km/h. The increase of attention to the near region at higher speed may be because the supervisor's visual image of the outside scene passed quickly in running at higher speed, and therefore he needed to see the scene longer to
catch its clear image. Regarding other characteristics on the monitoring process, e.g., percentage of attention allocation to other locations, and gaze time distribution to each location, there are almost identical tendencies between these two levels of driving speed. From these results, it is found that there may exist no big difference in track monitoring processes for the range of driving speed between 40km/h and 60km/h. However, if the speed is increased much further, for example, to 100km/h, the supervisor would be expected to employ another attention allocation strategy like that of the knowledge-less supervisor's to compensate for the difficulty of acquiring clear visual image from outside.

**OBSTACLE DETECTION PROCESS**

Using EMR data of Session IV, the supervisor's actual detection processes of obstacles were analyzed. Transition of fixation points is shown in Figure 8 for one of the four boxes left on the track. This is the case where a box was put at the most difficult place to detect, i.e., on the center-pathway between two tracks (one meter below the track level).

Up until about 10 seconds before his report of the obstacle detection, the supervisor was inspecting the states in his track and its surroundings in a usual home-base monitoring as shown in Figure 1. About 5 seconds before detection, he got a sense of something left on the center-pathway when he attended to the parallel track. He later described this situation as follows: When he gazed at the parallel track he obtained a visual image of its surrounding in his peripheral vision. He performed a pattern matching of his acquired visual image with the visual template stored in his memory as geographic knowledge. As a result of the pattern matching, he supposed there be a discrepancy between his visual acquisition and his geographic knowledge. Then, he shifted his attention to the place he sensed the discrepancy, i.e., on the center-pathway, to test his hypothesis about the obstacle. After fixing properly at the box, he reported its detection approximately 150 meter before the obstacle. The other three boxes examined in Session IV were all detected by him by this same process.

**CONCLUSION**

In the present paper, track maintenance train operators' monitoring processes were analyzed by use of EMR data for the track inspection task. We also examined effects of their human factors and operating conditions to their perceptual and cognitive performance. Major findings in this study are as follows. Train operators employ a home-base monitoring strategy. The home-base of attention is a distant region on their running track about 200 meters ahead. The operator's attention shifts very quickly from the home-base to another location, and then go back to the home-base, repeatedly. Operator's geographic knowledge is of critical importance for driving operations of the track maintenance train. An operator who has no geographic knowledge must concentrate more intensively on the running track which is the critical region for safe driving of the high-speed train. Therefore, it seems to be very stressful for train operators to drive inexperienced area. As an effect of time, more attention is paid to the running track for the later half of working hours probably due to fatigue. More frequently attention is paid to the home-base, and longer gaze duration on the near-point of the track is increased with increased speed. However, there is a slight difference in attention allocation between 40km/h and 60km/h driving.

As a future project, we plan to build a cognitive-perceptual model of a train operator's track monitoring process, applying basic data sources obtained in this study: operator's attention allocation patterns, eye-gaze distribution for each location, etc. This model will allow us to simulate train operator's behaviour as well as to track driving states during train operations. It will also enable us to estimate an accident/incident risk under a specific condition based on the simulation result. Additional data sources on human aspects, e.g., detection rate with eccentricity of visual field and with size of object, are required to develop a complete model.

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