

Eye-Tracking Applications to Design of New Train Interface for the Japanese High-speed Railway

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ABSTRACT

The present paper presents an eye-tracking project on new interface design of the bullet train cockpit that adapts to the improved train control system, ATC (Automatic Train Control). We specifically report an eye-tracking application to analysing train drivers' learning processes to a new bullet train interface. eye-tracking data were analysed applying a normative approach because of the task's well-defined property. In this approach, we introduced a principle of "*Gaze Relevance*" that is closely connected with the fundamental concept of safe and stable operations of the bullet train. The gaze relevance is involved by three metrics to uncover train drivers' information acquisition for a specific activity: *gaze economy*, *gaze redundancy* and *gaze robustness*. Based on application results of the proposed approach to train drivers' eye-tracking data in simulator experiments, we discuss their adaptation to a new train system and its interface.

1. INTRODUCTION: DRIVING TASK OF BULLET TRAIN

IT (information technology) applications enable train operators to perform more efficient and adaptive control in the high-speed railway ever than before. A Japanese high-speed train, "Tokaido Shinkansen", is running between Tokyo and Osaka (ca. 550 km distance) at the maximum speed of 270 km/h for two hours and a half. For the high-speed transportation, safe and highly reliable operations of the train are required, and the ATC (Automatic Train Control) system contributes to transportation these requirements as their technological background. In this control system, the upper speed boundary - which is primarily based on the radius of track and distance to a train running ahead or to the next station - is constantly displayed as a traffic signal in a speedometer. When the running speed exceeds the ATC signal, the train is automatically braked to reduce its speed to the upper limit.

In the current ATC system, the signal is changed in the discrete levels, e.g., 30, 70, 170, 220, 255 and 270 km/h. An advanced ATC system is planned to introduce in the next few years. In the new system, the ATC signal is adaptively changed continuously, not in the discrete level, by taking into account a train's braking performance. This allows a train driver to perform more flexible and effective control of the bullet train for the stable operation.

In the normal situation, a driver is required to operate a bullet train following the planned time schedule for all stations to be passed or stopped at. For this purpose, he sets several checkpoints between successive two stations and there he checks the current driving states in progress. Based on the states and much other information, he decides the running speed to the next station, and adjust it with the acceleration lever according to the current state of slope of the track and so forth. During this driving process he is continuously monitoring outside scene and various information sources such as the speed and the ATC signal indicators in the instrument console to maintain his situation awareness and anticipate events and states going on. As can be seen from this task description, under the normal condition, the driving task is performed in skill-based manner (Rasmussen, 1986) and its quality and efficiency highly depend on the driver's visual monitoring and attention allocation within relevant information sources in the train interface and outside environment. For such task characteristics, the eye-tracking technique is useful to analyse train drivers' cognitive processes toward various ergonomic purposes such as interface design, job redesign, and design of a training programme and of an operation procedure (Itoh et al., 1998; and 2000).

In this paper, we mention an eye-tracking application to cognitive task analysis of the train driver's learning with the new interface. As an analysis framework employing eye-tracking technique, we present a principle of "*Gaze Relevance*" that is involved drivers' information acquisition strategies from the aspect of efficient and reliable attention. Train drivers' learning processes are speculated based on the application results of this analysis framework to their eye-tracking data recorded in two-day experimental sessions.

2. ANALYSIS FRAMEWORK OF BULLET TRAIN OPERATIONS

2.1 Principle of Gaze Relevance

In the normal driving situation, a task structure can be described clearly in advance: task goal, constraints, working procedure and human mental processes. A *normative approach*, which prescribes how a system and/or an operator should behave, is suitable to employ for this category of well-defined task. As a process/activity-based analysis from a normative point of view, we propose a principle of "*gaze relevance*" as a framework for analysing eye-tracking data by comparing with an ideal eye-gaze sequence for each specific activity or process in the task.

The concept of gaze relevance comprises three subordinate metrics: gaze economy, gaze redundancy and gaze robustness. The *gaze economy* is referred to as a metric of how economically an operator acquires information required for a specific activity. This can be paraphrased as how promptly the required information acquisition is completed after an activity cue is provided to an operator. The other two metrics are relating to reliable activity ensured by multiple or redundant inspections, not only a single input of the required information. The *gaze redundancy* is a metric on which the information relevant to an activity is examined multiple times not only from different information sources but also from the same information sources. This metric can be evaluated by the number of fixations or fixation duration at

relevant information within a certain time interval after an activity cue is provided. Relevant information pieces only from different information sources are counted as robust information pieces to ensure more reliable activities for the *gaze robustness*. This metric is particularly important to perform reliable operations even with a uncertain system environment by malfunction or faulty system components.

2.2 Operation Model and Hierarchical Information Description

With the introduction of the new ATC system, there exists a major change in the driver's operations when the bullet train is under control of the ATC system and immediately before this situation. A cognitive model for the changed operation is depicted in Figure 1, applying the scheme of ITM (Information Transition Modelling) (Itoh, 1998). As can be seen in this figure, the driving operations consist of the following seven activities: (1) anticipation of the forthcoming ATC-control area, in which the ATC signal is reducing continuously, (2) confirmation of entering the ATC control area, (3) anticipation of the forthcoming ATC braking area, in which the train speed reducing with the ATC brake control, (4) confirmation of applying the ATC brake, (5) anticipation of making free from the ATC brake, (6) confirmation of non-ATC brake control, and (7) confirmation of change to a higher ATC signal.

A driver is required to acquire corresponding information piece(s) to each activity in. For example, for Activity 3, he judges whether an ATC brake will be soon applied based on the information on estimated time or distance to the ATC braking area. This information can be directly acquired or generated alternatively by one or more information pieces displayed in the instrumental console. Such a relation between information pieces on the interface and the required information for each activity is represented hierarchically as shown in Figure 2. In this figure, information pieces laid at Level 0 are the ones directly required to perform the activity. Some of Level 0 information pieces are

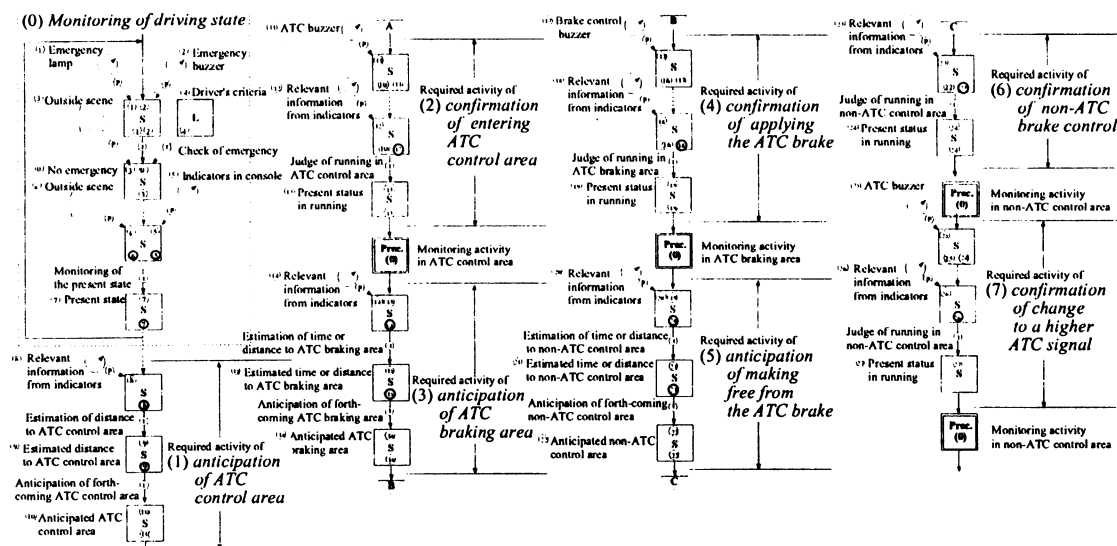


Figure 1 Operation model of the bullet train under control of the ATC system

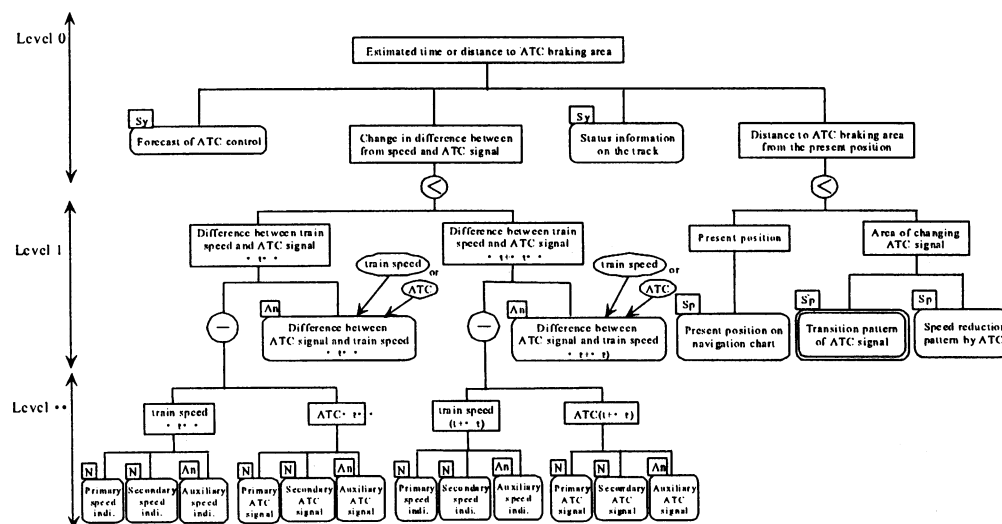


Figure 2 Hierarchical description of driving information for Activity 3

themselves displayed in the train interface and the others are generated by one or multiple Level 1 information pieces. As such, Level 2 information pieces are subordinate ones immediately to Level 1. In this hierarchical description, an information piece displayed in the interface is described in a node with round-shaped corners while one depicted in a rectangle node is generated by the driver's mental operation. For information pieces presented in the interface, this figure also describes their displaying form: analogue (abbreviated as "An" in Figure 2), digital or numerical (N), verbal (V), symbolic (Sy), temporal (T), and spatial (Sp) representation. Through this information generation process, we assume that the driver performs only simple arithmetic and relational operations to produce a higher level of information piece. For example, the information piece on "the difference between the train speed and the ATC signal", which is laid at Level 1 in Figure 2, is generated by an arithmetic operation, subtraction, from two lower level information pieces, "the train speed" and "the ATC signal". The latter two information pieces are laid at Level 2, and these can be obtained from either one of three ATC/speed indicators

2.3 Calculation of Gaze Relevance Metrics

A schematic example of gaze relevance metrics calculation is shown in Figure 3. For gaze economy, a calculation scope is spanned from the start of cue input for a particular activity to its completion, i.e., at the moment when enough information is acquired to achieve the activity. The gaze economy is defined as percentage fixation(s) at information piece(s) required for an activity over total fixations during this interval. Applying the number-based procedure, the gaze economy ratio is calculated as the number of fixations at required information divided by the total number of fixations to complete the activity. In the example shown in Figure 3, only the third fixation in the sequence, Gaze No.3, looking at "Forecast of ATC control", was required enough to achieve this activity, i.e., for the first inspection, while Gazes No.1 to 3 were performed during this interval. Accordingly, the ratio is calculated as $1/3=33\%$. In calculating a duration-based ratio, data on the gaze duration are applied to instead of those of the number of fixations. In this example, the duration-based gaze economy ratio is obtained by $0.20/(0.52+0.32+0.20)=19\%$.

To produce gaze redundancy and gaze robustness ratios, we need to define the relevance level, i.e., how much time an activity is repeated reliably as multiple inspections. When the relevance level is set at 2, the calculation scope is ranged from the cue input for the activity to the moment when the second inspection is completed, and similarly to the end of the third inspection in the relevance level of 3. The gaze redundancy ratio is calculated by dividing all the fixations at relevant information by the total fixations in the corresponding calculation space. In calculating the gaze robustness, we define a robust information piece as only the first fixation at each relevant information piece in its calculation scope. A gaze robustness ratio can be obtained by dividing a set of robust information by a set of the total fixations. Supposing the relevance level of 3 in the example of Figure 3, the last fixation at "Auxiliary speed indicator", Gaze No. 8, was the second watch in the calculation scope, and therefore it was removed from a set of relevant information to form a set of robust information.

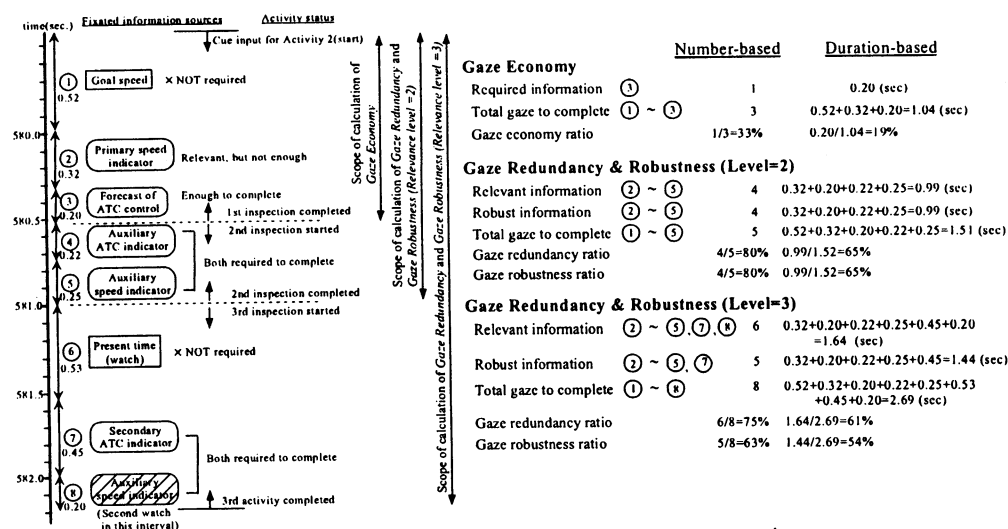


Figure 3 Calculation example of gaze relevance metrics

3. EXPERIMENTS

The bullet train company usually provides drivers with a two-day training programme so that they can well adapt to a new train system and its interface. Following this standard of training systems, drivers' learning processes with the new interface were examined by use of eye-tracking data during two-day experimental trials. Six bullet train drivers participated in the experiment, in which they performed a series of driving sessions with a NAC eye-mark recorder (Model 8) using a bullet train simulator. They ranged from age 25 to 45 years (averaged 35.3 years) with 2-19 year experiences of bullet train operations (averaged 9.2 years). All the participants had normal vision without correction.

The simulator handled the dynamic behaviour of the bullet train with a VCR-projected screen approximately 1.5 metres in front of the driver. The simulator equipped the identical interface to that in the actual train cockpit except for

an instrument console designed for the new ATC system. The instrument console examined in the experiment had two major displays, a speedometer and a navigation display, as shown in Figure 4. The speedometer included most information pieces indispensable for driving operations of the bullet train, e.g., speed indicators, ATC signal indicators, and several emergency lamps. The navigation display presents a driver higher abstraction level and detailed information on driving states which helps him to maintain his situation awareness, e.g., ATC signal transition chart and forecast of speed reduction pattern and distance and time to the next station.

A task performed in the experiment was driving operations in the normal situation, viz., to operate the bullet train to follow the planned time schedule as precisely as possible for the same driving area – ca. 70 km distance taking 15-20 minutes – with various driving scenarios. Each scenario included descriptions of a planned time schedule, thus allowance time to the next station, position of slow-down area or no such an area, congestion state on the track, and whether to be passed or stopped at the next station. We selected seven typical scenario for experimental sessions: four standard scenarios having moderate time allowance (15 seconds – one minute), two longer allowance scenarios (3-4 minutes), and two stressful scenarios running on the congested track.

During a two-day experiment - taking about eight hours a day - each subject was instructed on the new ATC system and its interface design as well as the experimental procedure for approximately one hour. Then he performed two training sessions without an eye-mark recorder to learn the new interface. During these sessions, the experimenters provided the subject with suggestions, e.g., on how to operate new interfaces and how the train behaved in the new ATC system, when he needed. After the training sessions, he performed 13 experimental sessions in total, during which his eye-movement data were recorded. As a standard procedure of the experiment, he performed a block of two or three sessions successively for about one hour. After each block of experimental sessions, he took a one hour break, during which he was checked by the experimenters how well he could adapt to the new interface and was provided with the instruction on the interface repeatedly. Then, he returned to the next block of experimental sessions. He performed five experimental sessions in the first day, and the rest of experimental sessions were performed on the next day. After the subject completed the experimental sessions, we obtained his subjective preferences on the new interface design and his comments on how easily he adapted to the new interface both using questionnaire and by a debriefing process with replaying eye-tracking video.

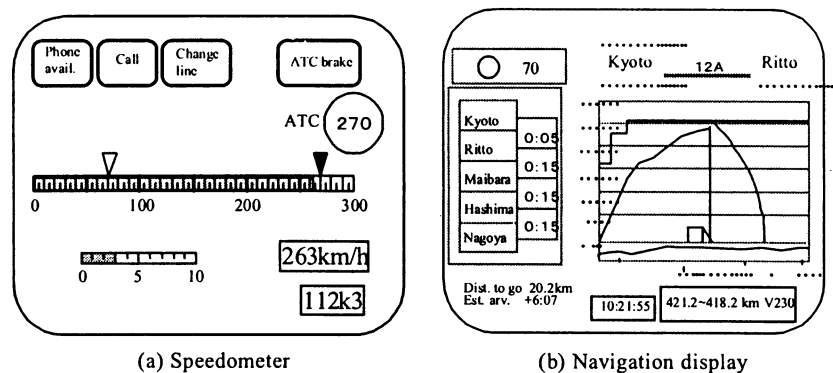


Figure 4 Designed interface of bullet train

4. RESULTS

Transitions of the gaze relevance metrics with sessions are shown applying the duration-based calculation for two subjects in Figure 5. In this figure, averaged ratios over Activities 1 through 6 are plotted with sessions for the three metrics in the relevance level of 2 for gaze redundancy and gaze robustness. In several sessions, all the activities, 1 through 6, were not performed during an entire period, and such sessions were excluded from graph plotting in this figure. As for the gaze economy, Subject 2 (S2) employed a slightly more efficient gaze strategy than Subject 1 (S1). From the transition of this metric with sessions, S1, who had the shortest professional experience of the subjects, does not seem to have learned with the new interface until Session 5. After this session, however, this metric was improved with session, particularly the ratio in the last session was very high despite using the most difficult scenario. For the gaze economy of S2's, who had the longest experience, a changing point exists between Sessions 3 and 4. Until Session 3, its ratio was about 10% lower than the later sessions, where the ratio was almost constant at higher level. This may indicate that this subject could adapt well to the new interface after the fourth trial. For example, the gaze economy is increased by 15% after his leaning, comparing by the same difficult scenario (Sessions 3 and 13).

Similar patterns can be seen for S1's transitions of the gaze redundancy and gaze robustness, with the latter metric about 10 % lower than the former. Like his gaze economy, the ratios of these two metrics in the first half were changed up and down and then improved in the later sessions. Integrating this result with that of gaze economy, this subject may have needed more learning sessions to adapt to the new interface. In contrast, S2's gaze redundancy was constant at higher rate having a little deviation. Regarding his gaze robustness, it seemed to be decreased until Session 3, and then to be increased after this session. All these three metrics can be influenced not only by the learning level but also by other individual and task factors. The scenario used in Sessions 3 and 13 was the most difficult while those of Sessions 1 and 2 were the easiest to follow the planned time schedule. This may have affected to Session 3 as decrement ratio of

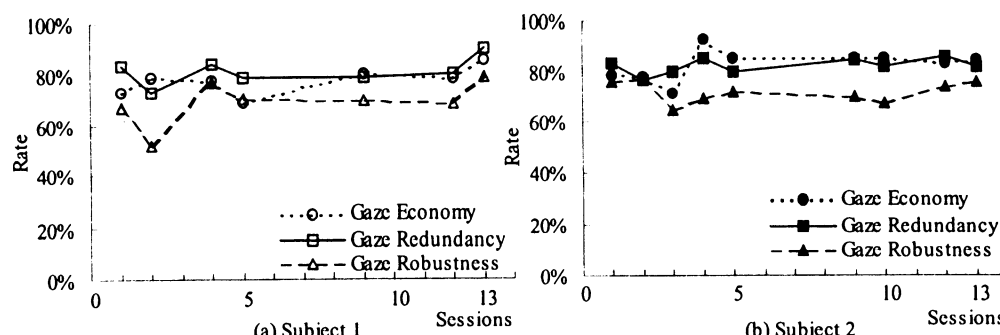


Figure 5. Transition of gaze relevance metrics with session

the gaze robustness. As his learning effect, the gaze robustness ratio was improved with sessions using the same scenarios, e.g., Sessions 3 and 13; Sessions 4 and 12.

In the metrics calculation mentioned in this section so far, the duration-based procedure was applied to the two subjects' eye-tracking data. To discuss compatibility between the number- and the duration-based calculations, we performed the correlation analysis using data samples of combination of subjects, sessions and activities. As a result, highly significant correlations were obtained in the three gaze relevance metrics: $r=0.926$ (gaze economy), 0.932 (gaze redundancy), and 0.964 (gaze robustness). This may suggest to have possibility to apply the number-based procedure, which is more time-saving, to eye-tracking data with enough reliability in analysing human cognitive performance.

5. CONCLUSION

In the present paper, we proposed a principle of "Gaze Relevance" and its calculation procedures for analysing a well-defined cognitive task, following a normative approach. This principle was applied to analysis of the bullet train drivers' learning processes with the new ATC adapted interface for managing its effective replacement from the present system, including design of a training programme. In addition to this analysis, the drivers' learning processes were also uncovered from macro-scope viewpoint by using eye-movement data during an entire task though we did not mention it. As one such analysis, transition networks of attention allocation during an entire task were generated to represent the driver's overall performance in state monitoring process. As a performance index on stability of attention allocation, entropy was calculated based on the transition network. Also, a distribution of eye-gaze duration allowed us to speculate some characteristics of a particular information piece such as its degrees of importance, usefulness, ease of use and visual complexity in the instrument console.

The present project had two other different objectives on installing the new interface to the bullet train. For these objectives, we also conducted a series of eye-tracking experiments to evaluate alternative interfaces. As another IT application to the interface design, we examined effects of a higher level driving information, e.g., the optimal speed which guides the train to reach the next station in time, not only on operating performance but also on other human characteristics such as vigilance, workload, fatigue and subjective preferences. The proposed principle of gaze relevance and its analysis procedure were also applied to these project objectives, and several useful suggestions were obtained for design of the new bullet train interface.

In a future project, we will tackle with another category of bullet train operations, namely so-called *ill-structured* tasks. A typical example of this category is operations in an emergency situation such as treatment of control system's sudden malfunction or fault in the train cockpit. In this situation, task goal as well as its constraints can neither be defined in advance. Nor its procedure exists before such an event takes place. There may be many possibilities of actions to treat with this situation and its outcome may depend on which action sequence is taken. For these characteristics, we plan to apply a *formative approach* (Vicente, 1999), which describes requirements that must be satisfied so that a new train interface and a driver can behave in a desired way, to cognitive task analysis of operations in abnormal situations.

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