Effects of Higher Abstraction Level Driving Information in a High-speed Train Interface: Cognitive Modelling and Experimental Evaluation

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Abstract

The present paper examines effects of higher abstraction level driving information in a high-speed train interface not only in terms of operator's performance but also from various aspects characteristics human. For this purpose, we performed an experimental study with four train operators as subjects as well as applying cognitive modelling to the bullet train operation. We discuss advantages disadvantages of both experimental and cognitive modelling and approaches based on the results obtained from these.

Keywords: Higher-level information, High-speed train interface, Workload, Operational performance

1. Introduction

Information technology (IT) has been increasingly widespread not only in computer systems, but also in other high-tech human-machine systems such as aircraft cockpits, control rooms in nuclear power plants and high-speed trains. Like in aviation, such IT applications enable operators to perform more efficient and adaptive control of trains in the high-speed railway ever than before. A Japanese high-speed train, "Tokaido Shinkansen", is running between Tokyo and Osaka (approximately 550 km distance) at the maximum speed of 270 km/h for two and a half hours. The first generation of the bullet train interface had only primitive information, i.e., at the physical form level in Rasmussen's (1986) abstraction hierarchy. In the present train, information at the physical function level, such as transition of ATC signal and forecast of speed reduction pattern has been presented. Subsequently, it becomes technologically possible to equip several information pieces at higher abstraction level in the instrumental console.

As one of the most promising information at higher abstraction level, the "optimal speed", which leads the train to reach the next station in time, is planned to install in the next generation interface. This information, on the one hand, enables the train operator to make free from frequent mental processing, e.g., speed calculation – that is primarily based on the distance and the available time to the next station and the speed limit on the track. In the present train, these information pieces must be also calculated from lower-level information sources such as the planned time schedule on the operation chart, markers of the present position, the present time and train speed in a display or speedometer. On the other hand, there might be a possibility that higher-level information brings the operator undesirable side effects. For example, he or she may be under-loaded and thus in a monotonous state simply by following its indication in the console, and that consequently it leads to unreliable operations.

The present paper examines effects of higher-level driving information on operators' performance and human characteristics during train operations in a normal condition. Employing an experimental approach, performance and work-related measures are examined in terms not only of efficiency and accuracy but also workload, fatigue and subjective evaluation when operating with three interfaces having different levels of information. Cognitive modelling approach is also applied to the train operation to estimate operation time and reliability for an entire driving task and its subtasks.

2. Experiment

Four male bullet train operators participated as subjects in the experiment, in which they performed a series of driving sessions using a bullet train simulator. Their ages ranged from 38 to 42 years old, and all of them had more than ten year experiences of the bullet train operation. The simulator handled the dynamic behaviour of the bullet train equipping a VCR-projected screen approximately 1.5 metres in front of the operator. The simulator provided the identical interface to that in the actual train cockpit. The configuration of driving information in the train interface – having two major displays: a speedometer and a navigation display – was adapted according to experimental conditions. Most information pieces indispensable for the driving operations of the bullet train, e.g., speed indicators, ATC signal indicators, and several emergency lamps, were presented in the speedometer. The navigation display included information on driving states to maintain the operator's situation awareness, e.g., ATC signal transition chart, forecast of speed reduction pattern and distance and time to the next station. The subject's task was driving operations in a normal situation, viz., to operate the bullet train for the same driving area – 70km distance taking 15-20 minutes – with various driving scenarios to follow the planned time schedule as precisely as possible.

The train interfaces examined in this study are (1) primitive interface: one having only a speedometer – including only primitive driving information at the physical form level, (2) physical function interface: one identical to the present interface – including information at the physical function level, and (3) general function interface: the present interface plus indication of the optimal speed and time slack to the next station. The latter information is constantly indicated as allowance time estimated from the present location to the next station assuming that a train is driven at the upper speed limit.

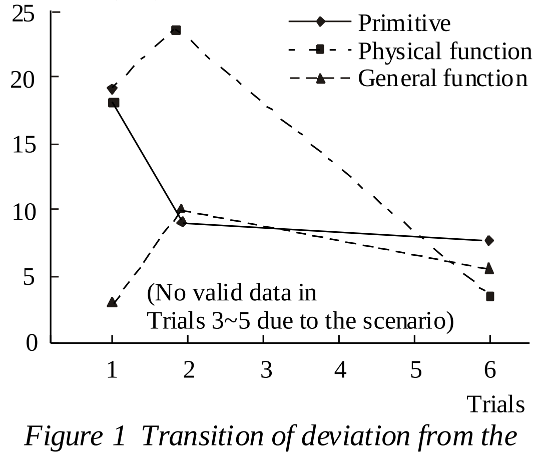
The experiment was carried out with these three interfaces for successive two days for each subject. The order of experimental sessions with each interface was counter balanced between the subjects. As a standard procedure of the experiment in each day, a subject performed one or two blocks of the experimental sessions, each of which comprised six trials successively for approximately one hour and 40 minutes – this time interval was almost identical to the actual driving hour for a single duty. After each experimental block, we obtained the subject's questionnaire responses on transitions of perceived mental states: vigilance, fatigue, monotonousness or boringness, workload, time pressure, etc. during the train operation with each interface. Then, he took a break for approximately one hour. At the end of the day after the experimental sessions were completed, the subject performed an eye-tracking session that includes one or two trials with different interfaces having a NAC Model 8 system to record his eye-tracking data. In Day 1, the subject received a training session, i.e., performing a single trial with each interface to get familiar with it. After the training session, he commenced to perform a single experimental block and then proceeded to an eye-tracking session. In Day 2, he performed two blocks of experimental trials as well as two eye-tracking sessions. At the end of Day 2, we asked the subject to make overall subjective evaluation on the interface examined in this study: preference among three interfaces, use of higher-level information, etc. as well as the same mental states mentioned above.

As experimental data, we recorded the subject's heart rates every 15 seconds, and eye blinks by a VCR – from which a blink rate was calculated every minute – as well as operation and system logs, e.g., positions (levels) of acceleration and brake levers, train speed and ATC signal, during an experimental trail. Based on the operation and system log, we calculated performance measures such as deviation from the planned time schedule and frequency of control operations. The subject was also provided with a secondary task, i.e., selective reaction to two different frequency sounds, using a dual task procedure for the purpose of measuring his workload level.

3. Results

3.1 Performance Measures

There were significant differences in the deviation from the planned time schedule both between the interfaces ($F(2, 12) = 5.10$, $p<0.05$) and between the trials, i.e., learning effect ($F(2, 12) = 6.06$, $p<0.05$). Transition of this measure with trials is depicted for each interface in Figure 1. As can be seen in this figure, the deviation when driving with the general function interface, which includes the optimal speed indicator, was significantly smaller than that with the physical function interface while there was no significant difference between the latter interface and the primitive interface that has only the speedometer. Regarding another performance measure, the frequency of manipulating an acceleration lever, there was no significant difference between the interfaces ($F(2, 24) = 2.48$, $p>0.05$). However, a learning effect was identified in this measure ($F(4, 24) = 9.14$, $p<0.05$), that is, more frequent control actions were taken at an early stage of experimental trials (cf. Figure 2).



(No valid data in Trials 3~5 due to the scenario)

Figure 1 Transition of deviation from the planned time schedule with each interface

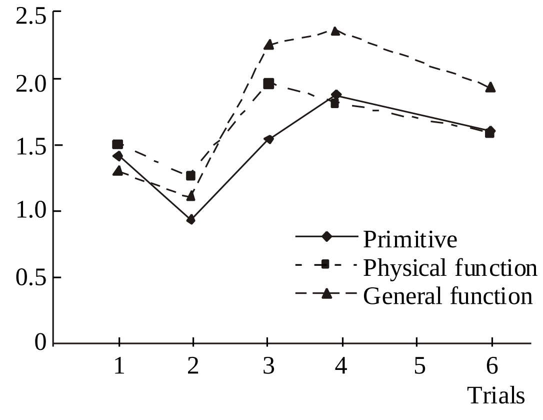


Figure 2 Frequency of manipulating an acceleration lever with each interface

3.2 Workload and Fatigue

As one of the workload measures, the subject’s reaction time for the secondary task was examined in this study. No significant difference was observed in the reaction time between the interfaces ($F(2, 30) = 0.08$, $p>0.05$). However, a significant difference was observed between the trials ($F(5, 30) = 7.71$, $p<0.01$).

Regarding the heart rate, there were significant differences between the interfaces ($F(2, 120) = 27.93$, $p<0.01$) and between the trials ($F(4, 120) = 4.07$, $p<0.01$). The transition of the heart rate with trials is shown in Figure 3. As can be seen in this figure, we identified a similar pattern on the difference between the three interfaces to that in the deviation from the planned time schedule mentioned above. That is, there was no significant difference between the physical function interface and the primitive interface. However, the subject’s heart rate when driving with the optimal speed indicator was significantly less frequent by approximately 10 cycles per minute than that with the other interfaces. From these results, it may be suggested that the optimal speed indicator contributes to reduction of the train operator’s workload and stress level.

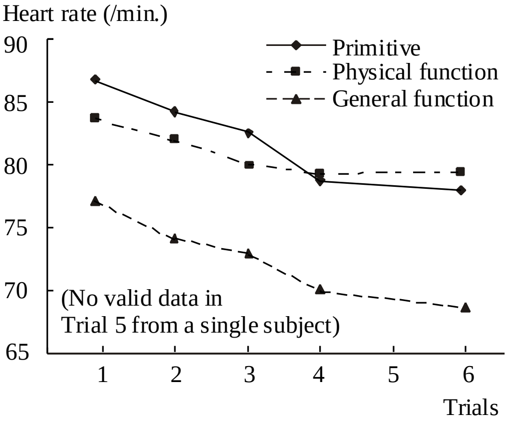


Figure 3 Transition of heart rate with each interface

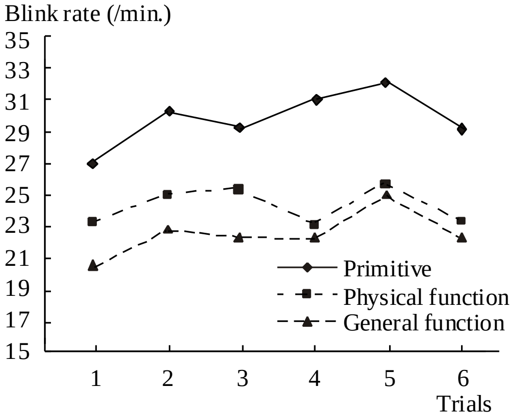


Figure 4 Transition of blink rate with each interface

Significant differences were observed in the blink rate both between the interfaces ($F(2, 30) = 63.91$, $p<0.01$) and between the trials ($F(5, 30) = 4.60$, $p<0.01$). As indicated the transition of this index with trials in Figure 4, the subject’s blink rate with the general function interface was the least frequent of the three interfaces. It was approximately 7 cycles per minute lower, compared to a driving condition with the primitive interface. From these results, higher-level information may contribute to reduction of visual fatigue level since a look-at the optimal speed indicator compensates the train operator for frequent gazes at other relevant information sources on a display, e.g., speed indicator, ATC signal transition chart and speed reduction pattern.

3.3 Subjective Ratings

Table 1 indicates subjects’ preferences of the three interfaces and usage of higher-level information examined in this study. All the subjects preferred the general function interface and frequently used the optimal speed indication in this interface. In contrast, usage of the other higher-level information, time slack, varies depending on the subject.

Subjective ratings on the impact of the optimal speed are shown in Figure 5. As can be seen in this figure, all the subjects provided positive responses to the optimal speed indication for most of question items. They perceived less workload, time pressure and fatigue when driving a train with the optimal speed indication, comparing to driving without this information. These results of subjective ratings are coincident with those obtained from the experiment. Half of subjects stated that this information allowed them to make less frequent speed calculation. However, half of the subjects provided a statement on increased monotonousness with this information. In addition, three out of four subjects had their feeling that driving with the optimal speed indication leads slightly to reduced vigilance level.

Table 1 Preference and use of information (No. of respondents)

(a) Preference of interface

Interfaces \ Rank	1 (better)	2	3 (worse)
Primitive			4
Physical function		4	
General function	4		

(b) Use of higher driving information

	Optimal speed	Time slack
Frequently use	2	1
Sometimes use	2	1
Neutral		1
Seldom use		1
Never use		

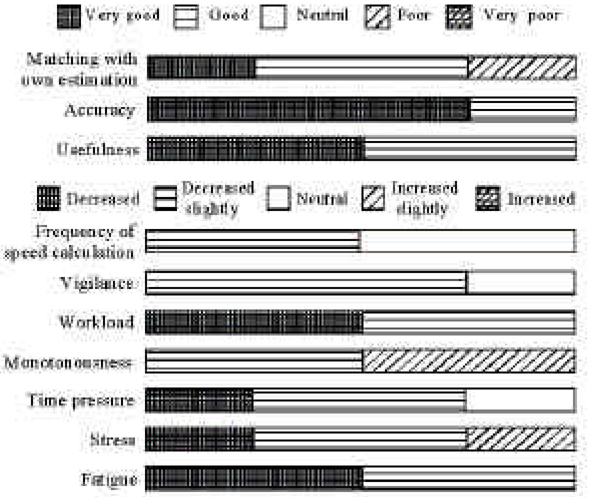


Figure 5 Subjective ratings of the optimal speed in terms of impact to train operation

4. Cognitive Modelling

An adapted scheme of the Information Flow Modelling (Itoh, 1998) was applied to construction of a task model for the driving operation of the bullet train. In the modelling scheme, a human activity is modelled in a sequence or network form of the information states in the STM and other sources such as the long term memory (LTM) and displays in the interface which are represented in corresponding shaped nodes. One or multiple information states are connected to a succeeding state which is generated by a unit processing of cognition or perception. The unit processing is represented as a labelled arc and is called an information processing unit (IPU). IPUs are classified into five types in terms of transformation of information and storage location: (a) perception of target item(s), (b) generation of relevant information, (c) memory storage (into LTM), (d) memory retrieval (from LTM) and (e) initiation of motor action. Assigning unit processing times and accuracy magnitudes to all the types of IPUs, operation time and reliability can be estimated according to the task structure of the model.

As mentioned previously, this study focuses on operations in the normal situation since the higher-level information examined here, i.e., the optimal speed and time slack, is applicable only in this situation where the operator drives the bullet train as precisely as possible to follow the planned time schedule. For the punctual transportation, with the primitive interface, he/she sets several checkpoints between successive two stations – typically in 5 or 10 km interval from the next station – and there he/she checks the current driving states in progress. Based on the present states and other information such as slow-down area, he/she decides the running speed to the next station, and adjusts it with an acceleration lever according to the current state of the slope, of the track and so forth. Based on more detailed statements of the driving process acquired by task analysis. Task models were developed with all the interfaces examined in this study. As an example, a part – determination of the train speed – of task model with the primitive interface was depicted in Figure 6.

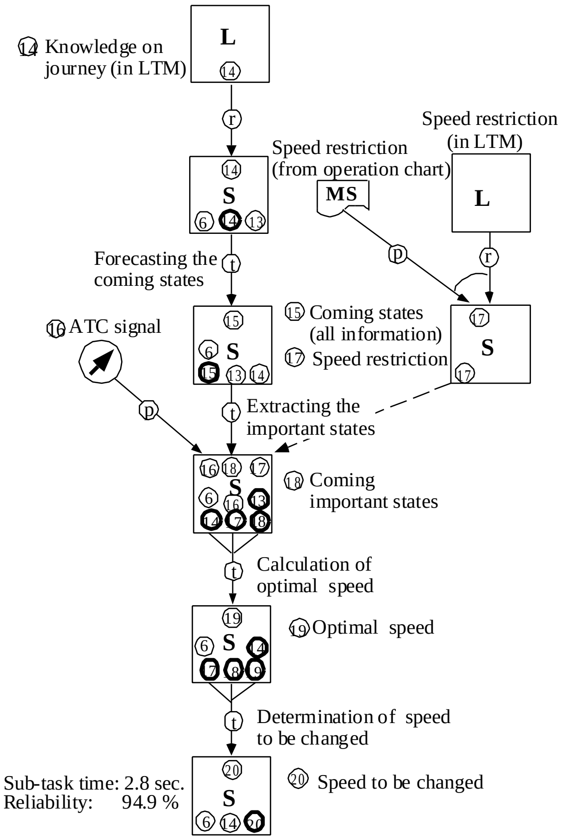


Figure 6 Modelled process for train speed determination with the primitive interface

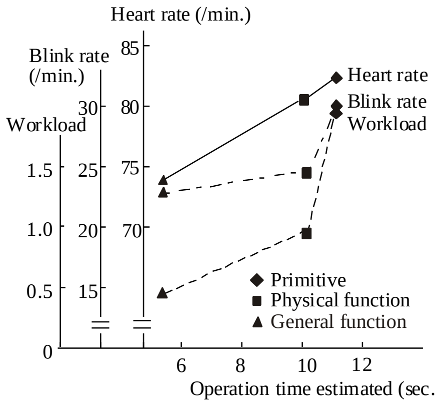


Figure 7 Relation between operation time and workload measures

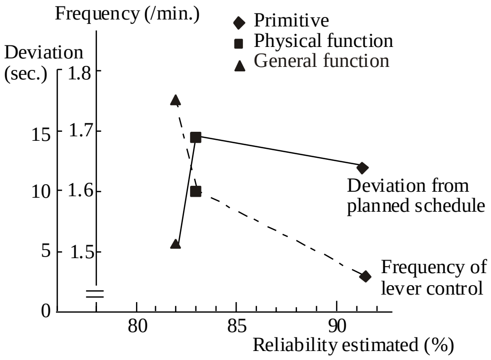


Figure 8 Relation between reliability and work quality measures

Applying a prototypical database on unit processing time and accuracy magnitude to each IPU (Itoh, 1998), the cognitive model estimated 11.1 seconds for an operation time of train control – from the time point when the operator identifies his/her checkpoint till completion of control action for changing the speed – with the primitive interface. With the physical function and the general function interfaces, the cognitive models anticipate time reduction to 10.3 and 4.9 seconds for the same operation, respectively. This estimation indicates that the optimal speed contributes to about 50% lower action density, compared to the primitive interface. Regarding the operation reliability when driving either with the primitive interface or with the physical function interface, it was calculated as 82% or 83%. The cognitive model suggested approximately 10% reliability improvement by adding the optimal speed indication, i.e., 91%.

To examine relations between experimental results and model estimation, Figure 7 indicates the graph plotting of three interfaces in terms of the estimated operation time and work-related measures and subjective rating on workload. This may suggest that operation time estimated by the cognitive model can predict operators’ workload or fatigue level. Similarly, the reliability index may have prediction capability for operation quality, – for example, more flexible and smooth control can be performed by frequent control manipulation –, as this relationship is depicted in Figure 8.

5. Conclusion

In the present paper, we examined effects of higher-level driving information displayed in a bullet train interface on the operator’s performance and human characteristics, primarily applying an experimental approach with four actual train operators to a driving task in a normal situation. Since the number of subjects was not large due to the time and cost constraints of train operators, we need a further study with more subjects to derive sound conclusion. However, we obtained a useful hypothesis concerning effects of higher-level information for the bullet train operation from the present study: Higher-level information contributes not only to better operating performance as well as desirable subjective evaluation but also to reduced workload, stress and time pressure. In addition, it may slightly but not greatly bring the operator negative side effects such as monotonousness or vigilance during train operation.

We applied a cognitive modelling approach to quantitative estimation of performance measures when driving with a specific interface. Comparing the operation time and its reliability estimated by the cognitive model with experimental results, the task model constructed in this study seems to have reasonable ability to make quantitative speculation of the operator’s decision making process. Besides quantitative performance estimation, the cognitive model also identified several issues on driving operations with each interface by graphical representation of a task model. For example, the low reliability with the primitive interface might be caused by over-dependency on the train operator’s short-term memory (STM). With this interface, the cognitive model included considerable mental actions involved with multiple inputs from indicators and outside scene. Finally, visual description of this task modelling with each interface is coincident with rationale of installing the optimal speed indicator in the near future.

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