〈Technical Note〉

INVESTIGATING THE APPROPRIATENESS OF THE TACOM MEASURE – APPLICATION TO THE COMPLEXITY OF PROCEDURALIZED TASKS FOR HIGH SPEED TRAIN DRIVERS

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According to wide-spread experience in many industries, a procedure is one of the most effective countermeasures to reduce the possibility of human related problems. Unfortunately, a systematic framework to evaluate the complexity of procedural tasks seems to be very scant. For this reason, the TACOM measure, which can quantify the complexity of procedural tasks, has been developed. In this study, the appropriateness of the TACOM measure is investigated by comparing TACOM scores regarding the procedural tasks of high speed train drivers with the associated workload scores measured by the NASA-TLX technique. As a result, it is observed that there is a meaningful correlation between the TACOM scores and the associated NASA-TLX scores. Therefore, it is expected that the TACOM measure can properly quantify the complexity of procedural tasks.

KEYWORDS : Task Complexity, Proceduralized Task, Subjective Workload, Process Control

1. INTRODUCTION

Operating experience has revealed that human error is one of the radical causes for serious accidents as well as incidents in large and complex systems [1-3]. At the same time, there is no objection about the fact that the provision of well-designed procedures is one of the best ways to reduce human error [4]. This could be especially effective when human operators have to perform process control tasks about complex and safety-critical systems, such as nuclear power plants (NPPs), commercial airplanes, chemical plants, and high speed trains. Accordingly, most of these tasks being carried out by human operators in such systems have been managed in the form of procedures [5,6]. In addition, effective guidelines pertaining to the provision of easy-to-use procedures have been developed by many organizations. Nevertheless, a critical problem still remains in developing useful procedures.

One of the golden rules in developing a useful procedure is "do not provide a complicated task description." It is expected that the amount of effort will be proportional to the complexity of tasks [7]. This means that operating personnel may spend more cognitive resources in the course of carrying out a complicated task, because they need to process more cognitive activities compared to an easy one [8]. Accordingly, operating personnel are apt to show a degraded performance or make a mistake [9,10].

Consequently, most guidelines emphasize the property of procedures including a clear layout and a succinct writing style, etc. For example, a complicated task, such as a lengthy task or a task described by many conditional statements (e.g., IF, AND, OR, NOT), should be rewritten by using one or more simple tasks [11,12]. To this end, it is necessary to answer the critical question "What is a complicated task?" Unfortunately, a proper method that can provide a holistic view about the complexity of procedural tasks seems to be very scant.

For this reason, Park and Jung have developed a measure called TACOM (task complexity) that can quantify the complexity of procedural tasks [13,14]. The validity of the TACOM measure was investigated by comparing TACOM scores with response time data gathered from the simulated emergencies of domestic nuclear power plants [14]. As a result, it was observed that there is a strong correlation between the TACOM scores and the associated response time data. Regarding this result, the next question in validating the appropriateness of the TACOM measure would be obvious – "Can the TACOM measure be used to quantify the complexity of procedural tasks in other industries?" This is because one of the clear benefits in using a procedure is the standardization of human performance [15,16]. In other words, if the TACOM measure can properly evaluate the complexity of procedural tasks, then it is strongly expected that the performance of human operators working in other industries can be explained with the associated TACOM scores.

To answer this question, in this study, the TACOM scores about the procedural tasks of high speed train drivers who work at the domestic railway company are compared with the associated subjective workload scores measured by the NASA-TLX (Task Load Index) technique. Consequently, it is observed that there is a meaningful correlation between the TACOM scores and the associated workload scores. Therefore, it is expected that the TACOM measure can be used as a general tool to quantify the complexity of procedural tasks.

The organization of this paper is as follows. A brief explanation about the TACOM measure is presented in Section 2. Then, in Section 3, the procedural tasks of high speed train drivers, which are quantified by the TACOM measure, are explained with how the associated subjective workload scores are obtained. After that, the result of the comparisons between the TACOM scores and the associated subjective workload scores is presented in Section 4. Finally, the conclusion of this paper is drawn in Section 5 with some discussions about the meaning of these comparisons.

2. BACKGROUND OF THE TACOM MEASURE

The TACOM measure is defined by a weighted Euclidean norm in three kinds of complexity dimensions suggested by Harvey and Koubek [17]. These dimensions are: (1) task scope (TS), task structure (TR), and (3) task uncertainty (TU). The complexity score of each dimension is quantified by one or two sub-measures that represent major factors making the performance of procedural tasks complicated. Fig. 1 depicts three complexity dimensions with their meanings and Fig. 2 shows relationships between the three complexity dimensions and the associated sub-measures.

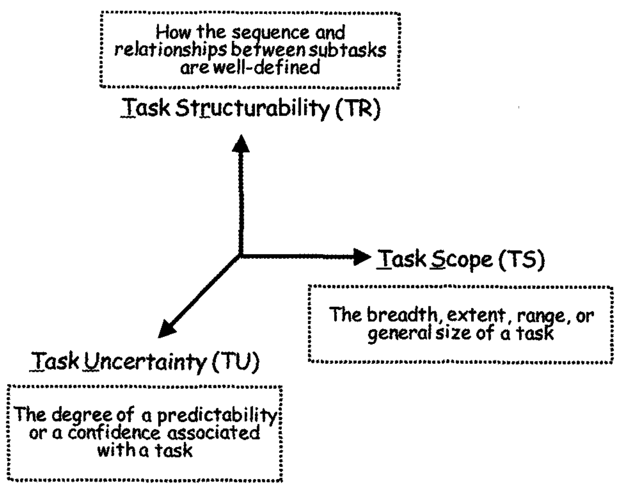


Fig. 1. Three Complexity Dimensions

From Fig. 2, the TACOM measure consists of five sub-measures: (1) step information complexity (SIC), (2) step

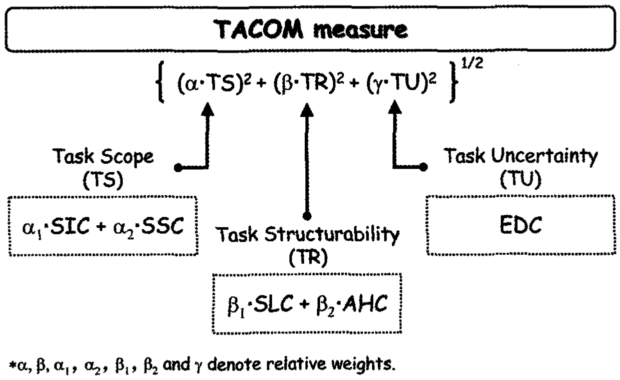


Fig. 2. The Definition of TACOM Measure

Table 1. The Meaning of Sub-measures Constituting TACOM Measure

Designation	Meaning
SIC	Step information complexity (SIC) represents the complexity due to the amount of information to be processed by human operators.
SLC	Step logic complexity (SLC) represents the complexity due to the execution logic of prescribed actions to be sequenced by human operators.
SSC	Step size complexity (SSC) represents the complexity due to the amount of the required actions to be performed by human operators.
AHC	Abstraction hierarchy complexity (AHC) represents the complexity due to the amount of system knowledge that is necessary to identify the problem space of the required operations.
EDC	Engineering decision complexity (EDC) represents the complexity due to the amount of cognitive resources that is necessary to establish the proper decision criterion of the required operations.

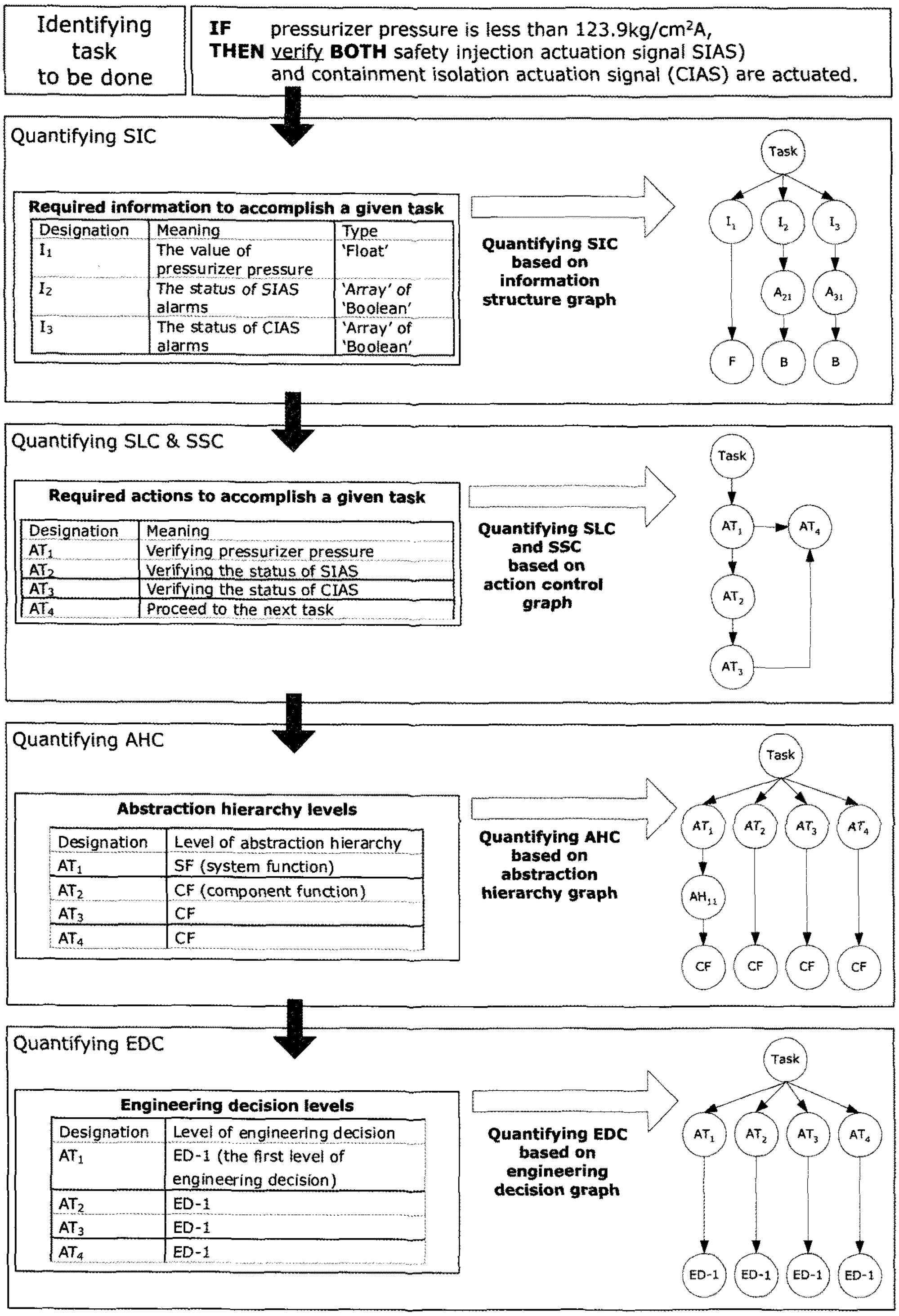


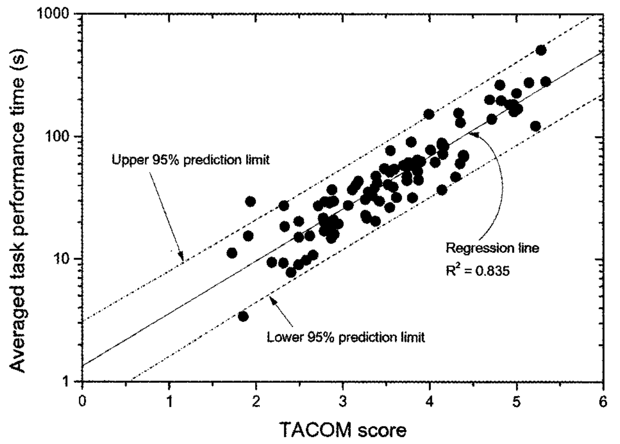
Fig. 3. The Overall Scheme of the TACOM Quantification

size complexity (SSC), (3) step logic complexity (SLC), (4) abstraction hierarchy complexity (AHC), and (5) engineering decision complexity (EDC). Table 1 summarizes the meaning of each sub-measure [14], and Fig. 3 briefly depicts the overall sequence of the TACOM quantification.

First of all, for a given task, a set of required actions that should be performed by operators needs to be identified. In addition, a set of required information that is necessary for accomplishing the required actions is also elucidated. After that, in order to clarify the amount of cognitive efforts to be spent by operators, the levels of abstraction hierarchy as well as those of engineering decision are assigned to the required actions.

When all the above processes are finished, four kinds of graphs can be constructed. They are: (1) an information structure graph that represents the required information, (2) an action control graph that depicts the required actions with their execution sequences, (3) an abstraction hierarchy graph representing a system knowledge that is necessary to accomplish the required actions, and (4) an engineering decision graph denoting cognitive resources placed on operators. By using these graphs, the values of the five sub-measures (i.e., SIC. SLC, SSC, AHC, and EDC) are quantified by the first and the second order graph entropy. In this way, all the values of the sub-measures for a given task that contains a series of required actions can be quantified. More detailed explanations about the quantification of sub-measures are given in [18].

As mentioned in Section 1, procedures are very effective to reducing the possibility of human errors in a complex process control system. In addition, the role of procedures becomes much more critical when human operators have to carry out their tasks under a stressful environment, including time pressure [19,20]. For this reason, in the case of NPPs, most tasks to be performed under emergency conditions are institutionalized in emergency operating procedures (EOPs). Moreover, in order to maintain the ability of human operators in dealing with emergency conditions, they have to be regularly re-trained using a full scope simulator every six months.



ANOVA table:

Item	DF	SS	MS	F statistic*
Model	1	12.51	12.51	451.97
Error	89	2.46	0.03	
Total	90	14.97		

*$p < 10^{-4}$

Fig. 4. Comparing Averaged Task Performance Time Data with the Associated TACOM Scores

In this regard, the appropriateness of the TACOM measure was investigated by comparing response time data collected under the simulated emergency of NPPs with the TACOM scores of emergency tasks prescribed in EOPs. To this end, a set of task performance times that denote an elapsed time from the commencement of a task to its completion was extracted from the OPERA (operator performance and reliability analysis) database developed by Korea Atomic Energy Research Institute (KAERI) [21].

The purpose of the OPERA database is to provide reliable human performance data, including task performance times, which play a crucial role in conducting human reliability analysis (HRA). In order to develop the OPERA database, more than 100 audio-visual records were secured from retraining sessions for licensed human operators working in the main control room (MCR) of reference NPPs. These records were collected over a period of three years (from September 1999 to April 2001), and in total, 24 different MCR operating crews were trained during this period. In addition, all kinds of design basis accidents (DBAs) have been simulated with various kinds of initiating conditions. Subsequently, a set of useful information has been successfully extracted and stored in the OPERA database.

As a result, it was observed that there is a significant correlation between averaged task performance time data and the associated TACOM scores. In addition, the values of relative weights shown in Fig. 2 were determined from these comparisons. Fig. 4 and Table 2 present the result of comparisons with an ANOVA table and the values of relative weights, respectively [14].

Here, in the course of validating the appropriateness of the TACOM measure, a simple but crucial question arose from Fig. 4 – "Can the TACOM measure be used to quantify the complexity of procedural tasks in other industries?" To answer this question, the TACOM scores for the procedural tasks of high speed train drivers are compared with the associated subjective workload scores.

Table 2. Relative Weights Determined from the Emergency Tasks of NPPs

Designation	Value
α	0.621
α_1	0.716
α_2	0.284
β	0.239
β_1	0.891
β_2	0.109
γ	0.140

3. COMPLEXITY OF TASKS BEING PERFORMED BY KTX DRIVERS

In this study, the tasks of KTX (Korean train express) drivers were considered in order to investigate the appropriateness of the TACOM measure. The following sections clarify the rationale of this selection.

3.1 Emergency Tasks of NPP Operators

When an emergency condition has occurred, NPP operators can find effective instructions to deal with it from EOPs. In general, EOPs consist of optimal recovery procedures (ORPs) and functional recovery procedures (FRPs). If human operators can properly identify the nature of an on-going condition by using a set of plant parameters or alarms, then they can find more condition-specific countermeasures from ORPs. In this regard, ORPs about design basis accidents (DBAs), such as a steam generator tube rupture (SGTR), have been widely used in NPPs.

In contrast, when an emergency condition that is difficult to diagnose has occurred, NPP operators have to use FRPs containing more general tasks to secure the critical safety functions of NPPs. Fig. 5 shows a brief schematic of emergency tasks included in the SGTR ORP of a domestic NPP [22].

Most emergency tasks prescribed in the EOPs are carried out by operating crews working in the main control room. Although there are several different types of crew organizations [23], a four-person crew has been adopted in the domestic NPP. Under this crew organization, the four major operators–a senior reactor operator (SRO), a reactor operator (RO), a turbine operator (TO) and a safety supervisor (SS)–conduct their distinct duties. For example, the SRO has responsibility for all the operations carried out in an emergency condition while the RO, TO, and SS have limited responsibility for supporting the SRO. In other words, all detailed activities to be done under an emergency condition should be carried out by the SRO's command and/or confirmation.

For example, let us consider the required activities about "Provide a sufficient safety injection (SI) flow" task in Fig. 5. In order to accomplish this task, the SRO has to conduct the fourth and fifth procedural step. At first, the SRO needs to know the value of the pressurizer pressure because the commencement of the fourth procedural step is to check it. In this case, the SRO commands the RO to read the pressurizer pressure. Then the RO informs the SRO of the required information after reading the appropriate indicator. According to the RO's report, the SRO decides the next action to be carried out. That is, if the pressure is less than 123.9 kg_f/cm^2, the next action is to check whether a safety injection actuation signal (SIAS) as well as a containment isolation actuation signal (CIAS) has been automatically generated. If all the signals are properly generated, then the next activity is to move to the next procedural step (i.e., the fifth procedural step). If not, the SRO needs to conduct an alternative activity in the "Contingency actions" column, such as "Manually actuate SIAS and CIAS." Accordingly, it is not surprising that most of the burden which may arise during the performance of emergency tasks is put on the SRO [23,24].

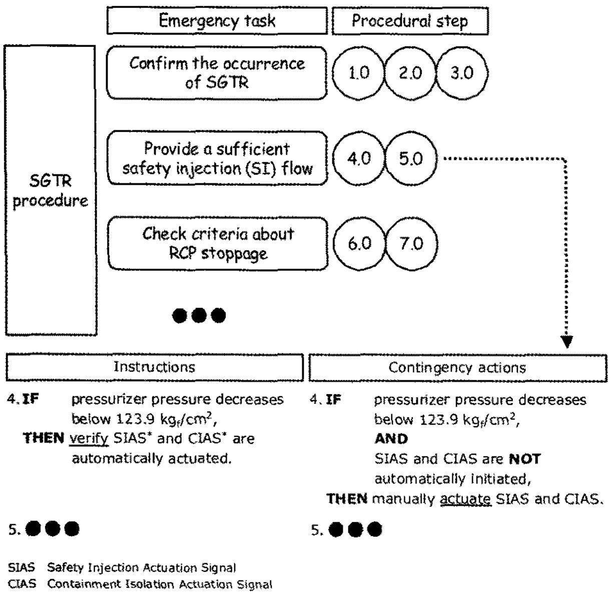


Fig. 5. A Brief Schematic of Emergency Tasks Included in SGTR Procedure

3.2 Tasks of KTX Drivers

Although the definition of a high speed train differs from country to country, a high speed train generally means a train that can run at least 200 km/h [25]. In the case of KTX managed by a public enterprise in South Korea, it

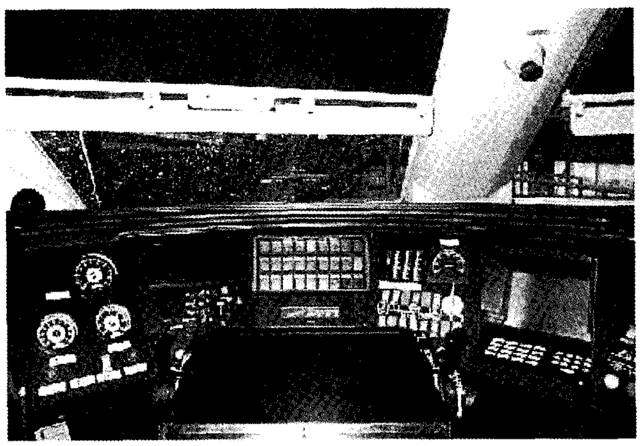


Fig. 6. The Cab of KTX – Its Layout

is designed to run at 350 km/h with 935 passengers by using high-pressure electricity (about 25,000V). The commercial operation of KTX was started on 1 April 2004, and about one hundred thousand passengers a day have used KTX since 2007 [26].

The operation of KTX is conducted by one driver working in the cab. Fig. 6 shows the layout of the cab, which consists of many indicators, controllers, and visual display units (VDTs) [27].

According to a recent study, the tasks of KTX drivers can be classified into 14 general tasks [28]. They are: (1) "Attending the work," (2) "Moving to the train," (3) "Checking train before departure," (4) "Departure," (5) "Acceleration," (6) "Deceleration," (7) "Passing through the dead section of a conventional line," (8) "Passing through the dead section of a high speed line," (9) "Proceeding from a conventional line to a high speed line," (10) "Proceeding from a high speed line to a conventional line," (11) "Stopping the train at an intermediate station," (12) "Stopping the train at the terminal station," (13) "Handing over the train and reporting the arrival of the train," and (14) "Subordinate shunting." For example, Fig. 7 depicts a part of the required activities included in the third and the ninth generic tasks.

Unfortunately, in the course of operating KTX, it is very difficult to identify the required activities from the procedure. This is very similar to reading a book or using a mobile phone while driving a car. Accordingly, KTX drivers have been trained to memorize all the required activities pertaining to the associated generic tasks. In addition, in order to maintain the ability of a KTX operation, KTX drivers should be regularly re-trained every two years.

4. COMPARING TACOM SCORES WITH SUBJECTIVE WORKLOAD SCORES

Over the past decades, many kinds of techniques for measuring a subjective workload have been proposed [29,30]. Although there are some different opinions about the measurement of workload scores by subjective ratings, the subjective workload has emerged as the primary source of information about the workload of human operators.

Of many assessment techniques, in this study, the NASA-TLX (task load index) was selected because it is known as one of the most suitable techniques in evaluating an experienced workload [31,32]. Under the NASA-TLX scheme, a workload score is quantified by the weighted average of ratings on six sub-dimensions, such as mental demands, physical demands, temporal demands, own performance, effort, and frustration [33]. Therefore, based on personal experience regarding generic tasks, KTX drivers were asked to rate six sub-dimensions on an arbitrary scale ranging from 0 to 100. In total 136 KTX drivers participated in these evaluations.

In measuring subjective workload scores, it should be noted that half of the generic tasks were discarded from the evaluation. According to existing literature, a process control task consists of five primitive sub-tasks (or actions) to deal with a dynamic physical system evolving over time. The meanings of the five primitive actions are as follows [34].

- Decision: An action generating conclusions or hypotheses that satisfy given constraints or specifications.
- Prediction: An action generating future states from the

Checking out the train before departure	Proceeding from conventional line to high speed line
1. Check the external appearance of the driving power car. 2. Check the status of components in the driving power room as well as the machinery room. 3. Check the status of the cab. 4. Compare the status of indication lamps with the log book. ...	1. Verify the indication lamp of the pantograph down precaution (LS-DW-PTG-01) is turned on. 2. Verify the precaution post about the "pantograph down" located on the track side. 3. Put the main control lever (MC-IC-01) to the '0' position. 4. Verify the position indication lamp of the main control lever (LS-CO-TT-01) is turned on. 5. Pull down the main circuit breaker switch (SW-VCB-01) to the 'off' position. ...

Fig. 7. Detailed Actions about "Checking out Train before Departure" and "Proceeding from a Conventional Line to a High Speed Line" Task

present observed state using an implicit or explicit model of the system.

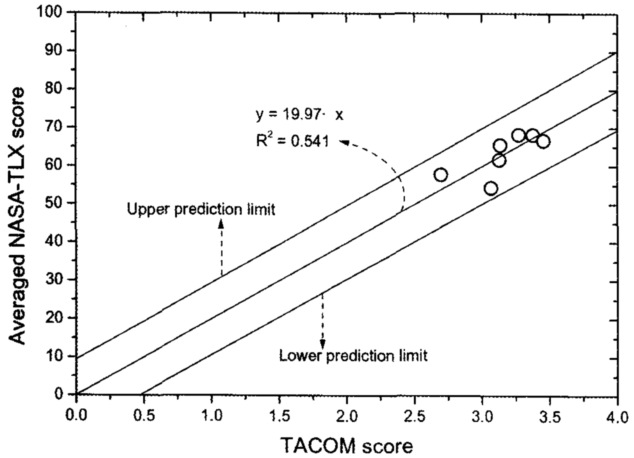
- Identification: An action related to the process of determining unknown or unmeasurable past or present states from known or assumed current observed state.
- Interpretation: An action involving the generation of situation descriptions, in terms of the system states, from observable data.
- Execution: An action related to actuations with a target system.

Accordingly, if there is a task that contains any activity not belonging to one of the five primitive actions, then it is difficult to regard this task as a process control task. For example, detailed activities shown in Fig. 5 include: (1) "verify the pressurizer pressure decreases below 123.9kg$_f$/cm^2," and (2) "manually actuate SIAS and CIAS," which correspond to the identification and the execution action, respectively.

In this sense, let us consider two tasks illustrated in Fig. 7. It is evident that the "Proceeding from a conventional line to a high speed line" task corresponds to the process control task because it consists of a series of activities belonging to one of the five primitive actions. Meanwhile, the "Checking the train before departure" task is not a process control task because several activities (such as "Check the external appearance of the driving power car") do not belong to one of the five primitive actions.

Consequently, the TACOM scores about generic tasks that are classified as a process control task were calculated using the same weights shown in Table 2. Although the rest of the generic tasks can be quantified by the TACOM measure, their meaning seems to be less effective because the relative weights were determined from the response time data of the OPERA database, which has been observed in the course of conducting process control tasks. As a result, Table 3 summarizes the averaged NASA-TLX scores with the associated TACOM scores. In addition, Fig. 8 depicts the result of comparisons between the NASA-TLX scores and the associated TACOM scores.

From Fig. 8, it seems that the NASA-TLX scores are susceptible to the TACOM scores, because there is a statistically meaningful correlation between the NASA-TLX scores and the associated TACOM scores.



ANOVA table

Item	DF	SS	MS	F Statistic*
Model	1	91.454	91.454	6.281
Error	6	87.369	14.561	
Total	7	178.823		

*p = 0.046

Fig. 8. Comparing NASA-TLX Scores with the Associated TACOM Scores

5. DISCUSSIONS AND CONCLUSION

The purpose of this study is to investigate whether the TACOM measure can quantify the complexity of procedural tasks in other industries. To this end, the complexity scores of seven generic tasks being carried out by KTX drivers

Table 3. NASA-TLX Scores with the Associated TACOM Scores

ID	Generic task	TACOM score	NASA-TLX score	
			Average	SD*
5	Acceleration	2.698	57.8	14.6
6	Deceleration	3.130	61.7	12.9
7	Passing through the dead section of conventional line	3.137	65.5	11.7
8	Passing through the dead section of high speed line	3.070	54.3	15.9
9	Proceeding from conventional line to high speed line	3.378	68.2	11.1
10	Proceeding from high speed line to conventional line	3.273	68.3	10.7
11	Stopping the train at the intermediate station	3.456	66.7	11.0

*Standard deviation

are quantified by the TACOM measure. In addition, subjective workload scores measured by the NASA-TLX technique are collected with the cooperation of 136 KTX drivers. Then the NASA-TLX scores are compared with the associated TACOM scores. As a result, it is observed that the increase of NASA-TLX scores is proportional to that of the TACOM scores.

In order to confirm this result, however, it may be indispensable to answer two crucial questions. The first one is "Why are the identical weights used for the emergency tasks of NPP operators applied to the selected generic tasks of KTX drivers?" Regarding this question, the results of previous studies provide an important clue; they commonly pointed out that the complexity of tasks can be largely determined by task characteristics such as the number of required actions or the number of stimuli [35,36]. In addition, the concept of an iso-complexity curve was suggested based on the number of functions and the degree of interactions [37,38]. These strongly imply that, as stated in the beginning of Section 4, the use of identical weights seems to be an appropriate approach because the nature of tasks to be done by both NPP operators and KTX drivers seems to be similar (i.e., the process control task). To address this problem, it is helpful to compare common features between the emergency tasks of NPP operators and the generic tasks of KTX drivers.

First of all, KTX is a safety-critical system because it carries many passengers at a very high speed. That is, even a trivial event (such as a small pebble on the tracks) can result in a terrible consequence. Second, one of the dominant causes resulting in unwanted consequences is human error. According to recent reports, the contribution of human errors to railway accidents varies from 38% to 70% [39,40]. Consequently, the reduction of the possibility of human error is very important to secure the safety of KTX. Third, it is anticipated that KTX drivers conduct their tasks under a high time pressure because: (1) they have to safely control KTX moving at a very high speed, and (2) they have to run KTX in accordance with a predetermined timetable. As for the last, since all the generic tasks were carried out by a single KTX driver, the whole workload in the course of operating the train is placed on the KTX driver.

It is very interesting to note that the above features are directly comparable to those of NPP operators, because many existing literatures indicate that:

- A NPP is one of the most canonical safety-critical systems in the world;
- One of the determinants affecting the safety of NPPs is human performance related problems (i.e., human errors) [41,42];
- NPP operators have to accomplish a set of emergency tasks in order to lead a rapidly changing NPP to a safe condition within an allowable time [43,44].
- Most of the burden which may arise during the performance of emergency tasks is put on the SRO of an operating crew [23,24].

This strongly implies that the overall task features of KTX drivers are very similar to those of NPP operators conducting emergency tasks. Accordingly, it is reasonable to expect that the relative weights shown in Table 2 are also meaningful in quantifying the complexity of generic tasks being carried out by KTX drivers.

The second question is related to the consistency of the NASA-TLX scores. That is, since KTX drivers subjectively rated six sub-dimensions based on their experience, the NASA-TLX scores could be changed by various reasons, such as personality or motivation. Accordingly, if there is a huge variance among the NASA-TLX scores, then it is difficult to confirm the result of this study.

To answer this question, an intra-class correlation (ICC) coefficient was adopted. The ICC coefficient is a well-known statistical index determining the level of consistency [45]. The value of the ICC coefficient lies between [-∞,1], and the closer the value of the ICC coefficient is to 1, the more the level of a consistency increases. In general, the classification of Table 4 is adopted to interpret the value of the ICC coefficient [46]. In addition, the consistency could be expected when the value of the ICC coefficient is at least larger than 0.41 [46]. In this regard, the values of the ICC coefficient about the NASA-TLX scores are calculated (Table 5).

As shown in Table 5, all the values are on either the 'Moderate' or 'Substantial' level. Subsequently, it is anticipated that the result of comparisons between the NASA-TLX scores and the associated TACOM scores is reliable. If the TACOM scores can properly reflect the change of subjective workload scores, then it is expected that the TACOM measure can be used as a 'general probe' to quantify the complexity of procedural tasks prescribed in a procedure.

In studying the performance of human operators, one of the important findings is that "the performance of human operators would be predictable when they carry out similar tasks" [47-51]. That is, if human operators have to conduct a set of tasks of which the complexity levels are similar, then it is also expected that their performance would be similar. One plausible explanation about this finding is that "procedures strongly affect the actual behavior of

Table 4. The Values of ICC Coefficient with their Meaning

Range	Meaning
[-∞, 0]	Poor
[0, 0.2]	Slight
[0.21, 0.4]	Fair
[0.41, 0.6]	Moderate
[0.61, 0.8]	Substantial
[0.81, 1.0]	Almost perfect

Table 5. The Values of ICC Coefficient about Selected Generic Tasks

ID	Generic task	ICC coefficient
5	Acceleration	0.57
6	Deceleration	0.63
7	Passing through the insulated section of conventional line	0.70
8	Passing through the insulated section of high speed line	0.52
9	Proceeding from conventional line to high speed line	0.74
10	Proceeding from high speed line to conventional line	0.73
11	Stopping the train in the station on the route	0.73

human operators by institutionalizing detailed instructions." In other words, since instructions specify "what is to be done" and "how to do it," it is assumed that the behavior as well as the performance of human operators is, to some extent, predictable. Actually, the results of many studies provide a rationale justifying this assumption [52-54].

Therefore, if there is a measure that quantifies the complexity of procedural tasks, then it should at least satisfy two properties: (1) task complexity scores should correlate to the level of a workload placed on human operators, and (2) task complexity scores about the procedural tasks of other industries should be quantified by the identical measure. If not, the developed measure is less meaningful because it probably misses important complexity factors that are related to the basic functions of procedural tasks – providing "what is to be done" and "how to do it." Regarding these properties, the result of this study is very insightful because: (1) there is a significant correlation between subjective workload scores and the associated TACOM scores, and (2) the TACOM scores that were calculated by the identical weights about the emergency tasks of NPPs are meaningful in measuring the complexity of tasks to be done by KTX drivers.

It is evident that additional efforts are indispensable to ensure the TACOM measure as a general tool to quantify the complexity of procedural tasks. However, it is also evident that the above-mentioned discussions at least provide a reliable clue supporting the following conclusion: "The TACOM measure can be properly used to quantify the complexity of procedural tasks."

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