A STUDY OF FAILURE MODE, EFFECTS AND CRITICALITY ANALYSIS PROCESS FOR THE RAILROAD SYSTEM

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ABSTRACT

This study investigates the Failure Modes, Effects and Criticality Analysis (FMECA) Method for the railroad vehicle. Recently, RAMS (Reliability, Availability, Maintainability and Safety) is one of the most important issues in the railroad industry. FMECA is prerequisite for the RAMS Analysis, and it is a procedure to identify the potential failure modes and their effects and to reduce or mitigate the critical effects on the system. FMECA is used in various industries and it is specialized in each industry. For instance, MIL-1629a and SAE-J1739 are specialized FMECA method for Military industry and Automotive industry, respectively. Although the railroad industry requires the high reliability system, it does not have a specialized FMECA yet. Thus, in this paper, an FMECA method specialized to the railroad vehicle was proposed through analyses and comparison of the MIL-1629a, SAE-J1739 and IEC-60812 standards.

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1. INTRODUCTION

As technologies have evolved, high quality of products is demanded by customers.[1] Consequently, manufacturers make more effort to insure the quality of their products, and at the same time they need to have a methodology to assess the quality or reliability. In the past, they focused on the quality control to reduce the number of inferior quality products, but recently they focus on a reliability analysis to improve the quality and manufacturing efficiency from the beginning of a product development.[2] As early as 1949, the US defense developed FMECA as a means for this sake. FMECA is an analysis methodology by which all potential failure modes are to be found, their causes and effects are to be analyzed, critical failure modes are to be selected, and means to mitigate the effects of critical failure modes are to be provided.[2-5] This analysis methodology was standardized and specified in MIL-1629a by the US defense, which was modified and specified in SAE-J1739 and SAE-ARP5580 later in automotive industry.[2-4] In addition, these specifications were further specialized for each industry sector such as IEC-60812 and STUK-YTO-TR190.[5-6] The main concept and basic procedure are the same in each FMECA specification, but the detailed procedure must be adapted to a specific application in each industry sector. As for railroad systems, they have to provide reliable and safe means of transportation because lots of people and cargoes are transported by the systems, and they also require some methods to control design, manufacturing and maintenance processes to reduce the costs while guaranteeing the reliability because the systems themselves are expensive and maintenance is also costly. However, much research has not been conducted on the FMECA process for railroad systems, and no specialized FMECA specification has been proposed so far. Therefore, in this study by analyzing some FMECA specifications used in other industry sectors and considering the characteristics and the requirements of railroad systems, a specialized FMECA procedure was proposed.

2. METHODS

2.1 The Characteristics of Railroad Systems

In order to propose a specialized FMECA method for railroad systems, first it is necessary to figure out the characteristics of railroad systems. The main objective of railroad systems is to transport people or freight safely and quickly.[7] Thus, the systems should be reliable (as less breakdown especially during transportation as possible), and their safety should be guaranteed. Railroad systems function along with other systems such as traffic signal and control systems, and the system boundary of a train is so wide that it has a great number of parts within the boundary.[7] In addition, since railroad systems are used for a long time (e.g. over 25 years), their maintenance cost is a few times their development and manufacturing cost. Thus, it is necessary to maintain the systems efficiently. Railroad systems transport a long distance, and they may experience different environment conditions such as temperature, humidity. Finally, since different railway authorities ask railroad system manufacturers for different performance requirements, the manufacturers should make the systems accordingly.[8] These characteristics of railroad systems are summarized in Table 1.

Table 1. The characteristics of railroad industry

	The characteristics of railroad industry
1	Require high reliability according to punctuality and rapidity
2	Need high safety
3	Exist many interfaces
4	Very age scale system
5	Cost a great deal in maintenance
6	Various user environmental condition
7	Various orderer demanding condition

2.2 The Characteristics of Each FMEA Standard

FMECA procedures used in other sectors are almost the same in terms of the basic concept and preparation. An FMECA procedure consists of collection of information, creation of documents and preparation of reports.[4-5] In this study, it was believed that the characteristics of each FMECA procedure could be figured out by analyzing the FMECA worksheets. Thus, SAE-J1739 used in automotive industry, MIL-1629a used in military industry, and IEC-60812 used in electronic industry were analyzed.

2.2.1 SAE-J1739

A worksheet specified in SAE-J1739 is shown in Fig. 1. It is a major characteristic of SAE-J1739 that FMECA actually consists of two analyses; one is FMEA(Failure Modes and Effects Analysis), and the other is CA (Criticality Analysis). As Fig. 1 shows, both the severity, which is an outcome of FMEA, and the criticality, which is an outcome of CA based on the occurrence rate and the detection rate, are considered as RPN (Risk Priority Number) in one worksheet. That is, when the worksheet is used, both FMEA and CA can be conducted at the same time. However, there is a more chance for subjective opinions of people involved in the analysis to play a role because a risk number is determined for every cause of a failure mode. In addition, there are problems in determining RPN which is obtained from the severity (*S*), the occurrence rate (*O*) and the detection rate (*R*) as in Eq. (1).

$$RPN = S \times O \times D \quad (1)$$

The problems of using RPN as a means to represent criticality have been pointed[5,9], and research has been conducted to develop another analysis method without such problems.[10-13] The limitations or problems of using RPN are summarized in Table 2.

In SAE-J1739, FMECA is classified into Designed FMECA and Process FMECA, and explanations are given separately for each FMECA.[2,9] However, the principles in the FMECA's are the same, and the FMECA's are differentiated simply based on which stage in the whole engineering process the FMECA is applied to. Therefore, in this study FMECA was not classified as in SAE-J1739.

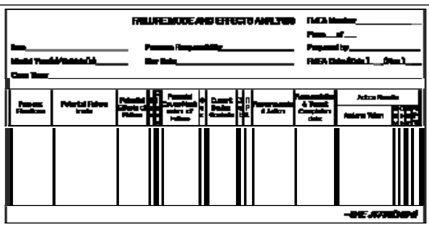

Figure 1. SAE-J1739 worksheet

Table 2. The limits of RPN

	The limits of RPN
1	Severity, Criticality, Detection are evaluated with the same importance.
2	Originally 1000 cases can be existed, but in reality only 120 cases can be created (Same RPN in different cases)
3	It is more sensitive to the variable change in high value than in low value (ex. 2*2*3=12, 2*2*4=16 and 5*5*3=75, 5*5*4=100)

2.2.2 MIL-1629a, IEC-60812

Two specifications, MIL-1629a and IEC-60812, are using similar FMECA methods, and worksheets specified in MIL-1629a and IEC-60812 are shown in Fig. 2 and Fig. 3. Firstly, the main characteristic of these specifications is that they specify both FMECA and CA unlike SAE-J1739. In other words, in MIL-1629a and IEC-60812 serious failure modes are selected first in FMECA, and CA is conducted only for the serious failure modes. Since CA is not conducted for all failure modes, it can be conducted efficiently for a huge system which has many subsystems like railroad systems. In addition, since the railroad service should be reliable and punctual, minor failure modes may be allowed to occur, but serious failures which may stop the railroad service should not be allowed. Thus, it may be better to use FMECA and CA separately as specified in MIL-1629a and IEC-60812 for railroad systems.

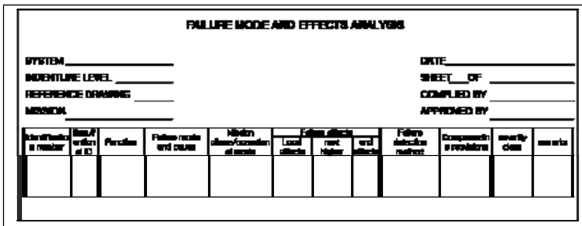

Figure 2. MIL-1629a FMEA worksheet

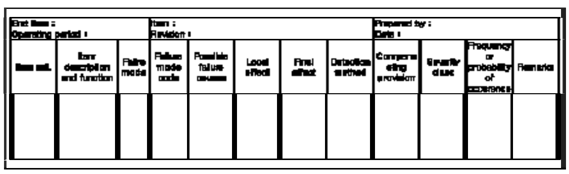

Figure 3. IEC-60812 FMEA worksheet

Secondly, in case of MIL-1629a, MA(Maintainability Analysis) is also specified in a way that MA should be conducted based on the outcomes of FMEA and CA. System designers should mention failure modes, failure indicators, failure effects, severity classes, detection methods, and basic maintenance means for maintenance personnel to use. Thus, through MA, basic maintenance means designers can think of can be delivered to maintenance personnel, and information gathered by maintenance personnel can be delivered to designers. Since maintenance cost in railroad systems is huge, it is necessary to conduct MA specified in MIL-1629a. CA and MA worksheets are shown in Fig. 4 and 5, respectively.

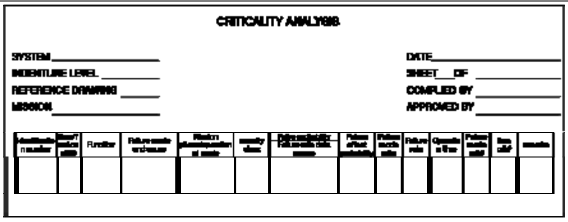

Figure 4. MIL-1629a CA worksheet

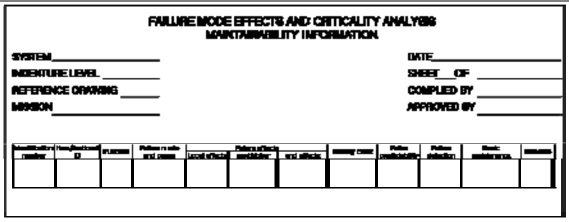

Figure 5. MIL-1629a Maintainability worksheet

Thirdly, another characteristic of MIL-1629a and IEC-60812 is that the failure effects are elucidated specifically as the local effect, the next level effect and the end effect. The local effect means the effect that the failure mode affects to the same hierarchical structure, the next level effect means the effect that the failure mode affects to next hierarchical structure, and the end effect means the effect that failure mode affects to the final hierarchical structure. By this specific description of failure effects, the relationship between failure cause and effect can be seen in detail in each hierarchical structure. Thus, it is needed in large scale industry with many interfaces like railroad systems.

Last characteristic of MIL-1629a and IEC-60812 is that criticality is assigned not to a failure cause but to a failure mode unlike SAE-J1739. The criticality can be calculated as in Eq. (2) [4,5]

$$C_m = \lambda \times \alpha \times \beta \times t \qquad (2)$$

Here, λ is the failure rate for a failure mode, α is a rate of failure of a cause if there are many causes for the same failure mode (for some systems, the probability of failure of causes is in database [14]), β is the conditional probability, and t is the duration of applicable mission phase usually expressed in hours or number of operating cycles. Thus, MIL-1629a and IEC-60812 decide the criticality for each failure mode so that the criticality is calculated more objectively. MIL-1629a and IEC-60812 have similarities, but differences is whether the criticality is quantitative or qualitative. In MIL-1629a, it indicates the criticality calculated by using only quantitative method in criticality matrix as shown in Fig. 6. However, in IEC-60812 it converts the value calculated by using quantitative method to the occurrence probability by using the Eq. (3) as shown below. Afterward, according to the criteria of Table 3, it converts the quantitative value to qualitative value and uses the criticality matrix as shown in Fig. 7

$$P_i = 1 - e^{-C_m} \qquad (3)$$

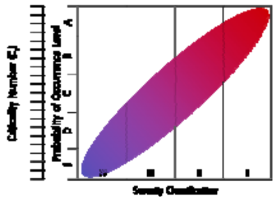

Figure 6. MIL-1629a CA matrix

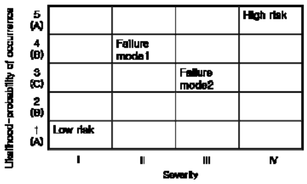

Figure 7. IEC-60812 CA matrix

2.3 FMECA Procedure Specialized for Railroad Systems

Based on the characteristics of MIL-1629a, IEC-60812 and SAE-J1738 analyzed in the previous sections, a specialized FMECA procedure for railroad systems was proposed in this study, and a proposed FMECA worksheet is shown in Fig. 8.

The characteristic is that the method is proposed to perform the FMEA and CA in one analysis worksheet like SAE-J1738. Major objective of railroad systems is to transport many passengers or freight to the destination in a punctual time safely. Thus, reliability and safety are very important so that it is proposed to analyze the failure mode through FMEA and to indicate the criticality of failure mode in aspects of safety enhancement regarding failure cause and effect. In FMEA analysis, it is proposed to mention the local effect, the next level effect and the end effect as specified in MIL-1629a and IEC-60812. In railroad systems, there are many interrelationships such as interfaces between trains and signal and control systems, it is necessary to clarify the effect of a failure between interfaces. And, in CA for criticality, it is proposed to apply the quantitative value divided by qualitative criteria regarding one failure mode like IEC-60812 as explained above. Lastly, maintenance items are added to perform the additional maintenance analysis regarding analyzed failure mode like MIL-1629a. In railroad systems, it costs a great deal in maintenance, so that the maintainability is very important. Accordingly if MA is performed by using FMEA results, developer's opinion should be delivered to maintenance man directly so that the maintenance can be performed efficiently and accurately.

Table 3. IEC-60812 occurrence frequency conversion criteria

Criticality number	Probability of occurrence
1 or E	$0 \leq P_i < 0.001$
2 or D	$0.001 \leq P_i < 0.01$
3 or C	$0.01 \leq P_i < 0.1$
4 or B	$0.1 \leq P_i < 0.2$
5 or A	$P_i > 0.2$

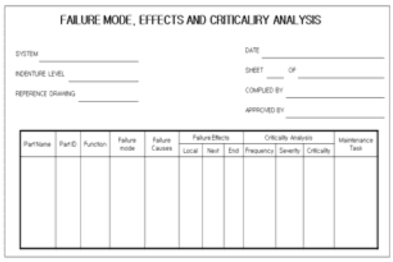

Figure 8. FMEA worksheet specialized in railroad system

As an example, the FMEA for an air-brake system in the locomotive is performed by using the proposed railroad system FMEA worksheet. Firstly, the diagram of an air-brake system in locomotive is shown in Fig.9. The air-brake system in locomotive is composed in 29 subordinate devices such as ECU, BOU(pressure sensor unit, EP valve, variable load valve, pressure regulating valve) and basic brake devices(air compressor, air dryer, disc and lining). The FMEA is performed for these 29 subordinate devices of air-brake system as shown in Fig.10.

Even in case of one subordinate device there exist several failure modes and causes. For example, 'service analog converter' and 'emergency valve' in EP valve have several failure modes and causes. In case of 'bad de-energized position' failure mode, coil failure was the cause, and in case of 'bad energized position' failure mode, spool valve failure was the cause. In addition, in case of 'air leakage' failure mode, the bad seal in 'service analog converter' and 'emergency valve' was the cause. In case of 'main air compressor', which is another main subordinate device in air-brake system, it has two failure modes such as 'oil tank drain plug leakage' and 'oil temperature rise,' and the failure causes were 'oil tank drain plug unlocked' and 'oil shortage'. The proposed FMEA in this paper for the 29 subordinate devices in the air-brake system shows that subordinate devices have total 60 failure modes and causes. Among them 16 subordinate devices have the same failure causes as coil failure and bad seal. Thus, in case of an air-brake system in locomotive, it may be said that coil failure and bad seal are the main failure mode causes. However, the FMEA and CA show that each failure mode has different effect and criticality toward system. In the proposed FMEA method of this paper, failure effect is divided in three parts as the local effect, the next effect and the end effect. Thus, in case of air-brake system, the local effect is defined as the effect among each subordinate device, the next effect is defined as air-brake system, and the end effect is defined as the effect toward locomotive.

For example, as a result of failure effect analysis in 'service analog converter' of EP valve, in case of 'bad de-energized position' failure mode according to coil failure, it has the local effect as 'failure to create service brake', the next effect as 'failure to operate service brake' and the end effect as 'failure to operate brake' sequentially. Also, in case of 'bad energized position' failure mode in the spool valve failure, it has the local effect as 'failure to release brake', the next effect as 'failure to release brake', and the end effect as 'failure to operate brake'. In addition, in case of 'air leakage' failure mode in the bad seal failure, 'air leakage', 'increase in valve operation time', and 'malfunction to operate brake' are matched to the local effect, the next effect, and the end effect, respectively.

According to the IEC-62278, which is a railroad system RAMS standard, system criticality is divided as shown in Fig.11.[8] It is efficient to use the rank sorting criteria regarding frequency as a formal standard, so that it is needed to convert the quantitative value to qualitative criteria. Thus, in this paper the method to convert the quantitative criteria to qualitative ones by using IEC standard Eq. (3) as explained above is chosen. The result of failure effect and criticality analysis in 'emergency valve' and 'main air compressor' of EP valve is shown in Fig.10

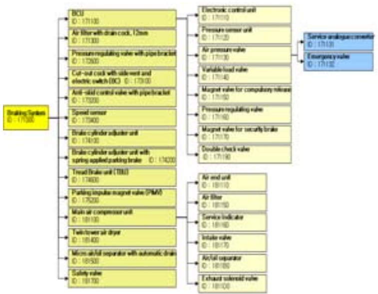

Figure 9. Locomotive air-brake system diagram

Figure 10. Locomotive air-brake system FMEA analysis sample

Figure 11. Risk Matrix

3. CONCLUSIONS

In this paper the FMEA standards proposed and used in other industries, especially MIL-1629a in Military industry, SAE-J1739 in Automotive industry, and IEC-60812 in Electronic industry were compared and analyzed, and the characteristics, strength and weakness of each standard were figured out. In addition, the characteristics of the railroad system were analyzed. Based on these, an FMEA standard specialized in railroad systems was proposed.

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