Risk Assessment of a Tunnelling Process Using Machinery Failure Mode and Effects Analysis (MFMEA)

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Abstract

In recent years, risk management associated with safety and reliability of the process especially in oil and gas industry has been widely used. For this purpose, different methods of risk analysis have been developed and successfully applied. Greater levels of complexity in tunnelling using TBM (Tunnel Boring Machine) especially in gassy tunnels with a large volume of water coming out of them, allow higher chances of failure that may increase the potential for tunnelling facilities to become more hazardous. When there is an ever increasing awareness of hazardous risks that need to be managed by the industrial community, the risks need to be analyzed. This paper presents the results of a study on risk management in a tunnel excavation with TBM. MFMEA was applied to analyze the risks of a tunnelling process. In order to apply MFMEA, 7 main systems and components involved in a tunnelling process were selected and split into subsystems. In total, 71 failure modes were then postulated for all subsystems. In the next step, the effects of every failure of each subsystem were listed. Safeguards or controls that might prevent or mitigate the effects of each failure were then listed. In the final step, essential remedial actions to prevent or mitigate the failure were recommended. Risk Matrix was developed for each possible failure to be used for risk ranking. For this purpose the Risk Priority Number (RPN) was estimated for each failure mode to identify the most critical failures. The results revealed that, the failure of the ventilation system (RPN=480) is the most critical failure. The TBM failure due to bad rock condition (RPN=240) and rolling stock failure due to unleveled rails (RPN= 200) are the next significant critical failures. The findings from this study were applied to a long tunnel under construction and significantly reduced the accidents during the tunnelling period. Tracking of the accidents occurred during the next 2 years showed that MFMEA is a perfect method for risk management in tunnelling process as well.

Key Words: Hazards Identification; Risk Analysis; Risk Management, Tunnelling.

Introduction

Accidents in tunnels and underground spaces under construction may lead to major consequences. Tunnelling projects are very expensive; therefore, any failure during construction may lead to serious human, property and investment losses. For this reason, risk management is essential in tunnelling projects (Eskesene, 2004, Kouty, 2005).

Accidents in tunnel, mine and underground space works may lead to catastrophe if they are not precisely predicted and effectively controlled in advance. In 1949 in north-east China, 1,549 miners were killed in one accident. During 2004, in China 6,300 miners were killed in accidents. In 2003 in the BobNizo mine located in south east Iran, 9 miners were killed in an explosion incident. In 2006 in a tunnel excavation in Iran, 4 people died from deadly Hydrogen Disulfide (H_2S) gas emission. In the tunnelling work of a dam project in the south of Iran started in 2005, 22 workers died in 2 years in different accidents (Gharari, 2007). Other countries experience similar incidents.

Greater levels of complexity in tunnelling using TBM, especially in gassy tunnels with a large volume of water coming out of them, allow higher chances of failure that may increase the potential for tunnelling facilities to become more hazardous. When there is an ever increasing awareness of hazardous risks that need to be managed by the industrial community, the risks need to be analyzed. This includes Hazard Identification, Risk Assessment and Risk Management (Gharari, 2007, Hyatt, 2003 & Brauer, 1998).

Risk cannot be evaluated without first identifying the hazards involved. Many of the hazards will be identified by conducting a PHA (Process Hazard Analysis), such as HAZOP (Hazard and Operability Analysis), What If/Checklist or FMEA. The hazards may arise from a wide range of sources. They have the potential to harm people, property and the environment, but at the identification stage there is no clear or concise picture of what this danger might be or how often it might occur. At this stage it may be felt that the use of a risk matrix of severity versus likelihood provides an adequate pseudo-measure or approximate gauging of risk so that a full quantification of the risk would not be necessary.

Widely used methodologies to identify hazards include the following (Brauer, 1998):

- Preliminary Hazards Analysis (PrHA). Also known as Screening Level Risk Analysis (SLRA).

- Hazard and Operability Analysis (HAZOP).
- Failure Mode and Effects Analysis (FMEA).
- What If Analysis
- Checklist
- What If + Checklist

Among these methodologies, FMEA is used to analyze specific systems or items of equipment that are best handled as objects rather than by the use of parameters or operations (Hyatt, 2003). FMEA is also used for analyzing pumps, compressors, fans and items of equipment having interactive mechanical and/or electrical components. Many authors, including, Hyatt (2003) believe that FMEA is very good for analyzing complex equipment items where the failure of a component may have a major consequences. Some authors believe that FMEA does not relate to specific failures that have common causes. In such cases, it needs to be used with Fault Tree Analysis to broaden the scope.

Different standards including MIL STD1629A, SAE ARP 5580 and SAE J1739 describe the methodology for applying FMEA (Gharari, 2007, SAE J1739 & MIL-STD-1629A, 1998). Others, including the following, have it as a part of their mandate along with other PHAs:

- AIAG, APQP Manual
- FDA, GMP, QS Regulation Title 21, CFR Part 820
- ISO 9001 2000
- IATF,, ISO/TS 16949
- PSM CFR 1910, 119
- QS 9000

There are six types of FMEA namely machinery-FMEA, design-FMEA, system-FMEA, process-FMEA, application-FMEA, and product-FMEA. The nature of the study and the stage of the process life cycle when it is conducted, determines the type of FMEA to be used. Each FMEA follows the same approach. The nature, purpose and scope of the study dictate which type of FMEA and to what extent of detail is used.

In order to modify the safety of operator, reliability and operability of machinery MFMEA (Machinery FMEA) is a standard technique for equipment failures assessment. This technique fits well with the objectives of present study to assess the risks of different machinery used in the tunnelling process.

In Iran, many researchers, including, Pourparand (1993), Kakavandi (1995), Ali Mohammadi (1997), Azar Barzine (2000), and Naderi (2005) applied FMEA to assess safety status of different manufacturing processes. In all of these studies Risk Matrix was used for risk ranking. For this purpose RPN was estimated to identify the most critical failures. None of these studies applied to tunnelling Gharari, 2007. All of these works have been published in Farsi.

In other countries different studies, including Abdul-Nour et al (1998), Pinna et al (1998), Sankar and Prabhu (2001), Scipioni et al (2002), Price and Taylor (2002), Seung and Ishii (2003), Seyyed-Hosseini (2005), Dominguez et al (2006), Burgazzi et al (2006), and Eti et al (2006) used FMEA to analyze the safety of different processes. None of these processes included tunnelling. In most of these studies RPN was calculated and then the safety status was assessed. In 2004 Working Group 2 of the International Tunnel Association issued guidelines for tunnelling risk assessment (Eskesene, 2004). These guidelines are considered for the risks integrated with other systems and are useful for both consultants and contractors.

The Tehran–North freeway is one of the largest road projects in Iran. Many tunnels, including the longest national road tunnel are under construction in this project. This tunnel, called Alborz, is located at 2,400 m higher than sea level and is 6,350 m in length with maximum 850 m of over burden. The tunnel consists of 3 bores, two main tunnels with a pilot tunnel between them. The pilot tunnel is under excavation using TBM to gather geotechnical data for the main tunnel design. The pilot tunnel will be used as a service tunnel during the tunnel operation.

Pro-excavation geological data showed that gas emission and water flow was expected in the tunnel. Methane (CH4) and Hydrogen Disulfide (H2S) emissions in very high concentrations were recorded before applying this risk analysis. TBM stop due to bad rock condition was also expected. The TBM used in this project was not originally designed for gassy tunnels. It was also not designed to work in a tunnel with a large volume of water coming out of it. Therefore, MFMEA was applied to assess the tunnelling risks in the Alborz Tunnel.

Material and Methods

In the present study, Machinery Failure Mode and Effects Analysis (MFMEA) was applied to identify failures, evaluate the effects of the failures and prioritize the failures according to the severity of effects during the excavation of a long tunnel with TBM. For prioritization or risk ranking, Risk Matrix (Risk Priority Number) was used.

For application of MFMEA, pertinent information e.g. site plans, charts, operations information, procedures, relevant data, and design plan were collected. In the next step the purpose, scope, depth of the study, associated costs, expertise, experience available and so on were established. The system was broken into logical and manageable items by function or area location. In total 7 main components were studied. All of this information was recorded in FMEA Tabular format. All potential failure modes for each item were identified. The causes of each failure mode were determined. All current controls were identified and listed. A rating for severity, occurrence and detection of each failure was assigned. All correction actions were determined. In the final step, the recommendations were carried out.

Risk Matrix was used for prioritizing risks. Risk Matrix is developed using severity, likelihood and detection parameters. These need to be estimated in order to estimate Risk Priority Number (RPN). In the present study, the severity parameter was ranked according to QS9000 and SAE.J1739 recommendations. Table 1, shows severity ranking used in this study.

Table 1

The MTBF (Mean Time Between Failures) is used for likelihood ranking (Hyatt, 2003 & SAE J1739). In the present study this information was estimated from available site data including previous incidents, maintenance periods, operator's experiences and etc. According to QS9000 recommendations MTBF was used for likelihood ranking. Table 2 shows likelihood ranking used in the present study.

Table 2

Detection is ranked using a number which is estimated from failure detection and control levels available on each system or subsystem. In the present study the detection ranking was used according to QS 9000 and SAE J1739 recommendations. Table 3 shows the detection ranking used in the present study. Risks are categorized using Risk Priority Number (RPN). RPN is calculated using the following equation.

$$RPN = Severity\ Number \times Likelihood\ Number \times Detection\ Number \quad (1)$$

Risk Matrix is developed using likelihood and severity parameters. The Risk Ranking is categorized according to the RPN calculated for each failure.

Table 3

Different measures are considered to decide whether it is necessary to intervene for modification or prevention of failures. Review of failure characteristics including critical condition, controlling possibilities, safety or severity and an acceptable RPN could be considered as a measure of decision making for modification or prevention of failures.

Acceptable RPN varies from a plant to plant. Naderi (2005) considered it to be 100 for analysis of a lift. The number was obtained from multiplying 4×5×5. Ulrich Hussels used the RPN of 108 as an acceptable level in a vehicle cooling system analysis. This number was obtained from 3×4×9 (Gharari, 2007). It is believed that when the range of severity, likelihood and detection is from 1 to 10 a risk with its RPN ≥100 is a high risk failure and if the severity is more than 5, then modifying the design work is essential (Gharari, 2007). Acceptable RPN is usually considered according to engineering decisions, regulatory restrictions, safety standards, financial status of the organization and etc. Considering these measures, an acceptable RPN of 80 was determined in the present study. The acceptable RPN was based on multiplying 5×4×4 = 80.

Failure modes with higher RPN were categorized critical failures then.

Results and Discussion

In total 7 main systems were studied. Table 4 shows the systems that were studied in this analysis. A total number of 71 potential failure modes were identified and studied for all 7 main components. For each system and subsystem a Tabular form similar to Table (A) in the appendix was completed. As it is shown in this Table, the modification and control actions which could be applied to reduce the RPN of each failure were also recommended by the related expertise team with its effect on final RPN. The severity, likelihood and detection rating for each failure at existing condition and after recommended control actions taken were estimated. Risk Priority Number of each failure mode was then calculated.

Table 5 shows MFMEA results of electric system and subsystems. According to this Table, low output voltage from transformers had a Risk Priority Number of greater than acceptable level which needed to be modified. Power generator, short circuit in secondary windings of the transformer, high voltage drop along the power distribution line or getting high current from the system may lead to a low output voltage.

Table 5

This failure can effect electric consuming subsystems or burn the transformer and finally stop the TBM. It can be prevented or discovered through applying voltage control relays, breakers sensitive to voltage in main circuit breakers, and phase controlling relays. The related expertise team suggested applying Programmable Logic Circuit (PLC) for design modification and controlling this failure mode. They believe that the application of PLC will reduce the RPN from 90 to an acceptable level of 60.

Table 6 shows the MFMEA results of TBM Hydraulic System. According to these results, in TBM Hydraulic system, all failure modes except the starting defect of pressure supplier (RPN=96) were low risk failure modes. The high likelihood number of this failure means that the probability of its occurrence is relatively high. This failure mode that can stop the TBM may be caused mainly due to defective electromotor, defective circulation pump problems in main circuit or lose fittings. The related expertise team recommended an appropriate preventive maintenance program in order to control this failure. The application of an appropriate preventive maintenance is expected to reduce the likelihood number from 8 to 5 and the RPN from 96 to 40.

Table 6

Table 7 shows the MFMEA results of TBM Pneumatic system. The results show that, considering Risk Priority Numbers, defective opening of high pressure tank is the only high risk failure mode in the pneumatic system. Corrosion, humidity and any obstacle in the tap may lead to this failure. The failure will increase the pressure of the tank and burst it which will finally stop the TBM. At present, the pressure gauges on air tanks and in TBM control rooms are used to detect this failure.

Table 7

The MFMEA expertise team recommended preventive maintenance, periodical checks, and punctual replacement of the appropriate parts to control this failure. The application of these recommendations is expected to reduce the RPN of this failure mode from 108 to 54. The control actions will not reduce the severity number. A modification design for the opening mechanism of the high pressure tank is required to reduce severity number.

The results also show that in the TBM pneumatic system 3 failure modes had severity numbers higher than 5. They included electric coil breakdown, starting defect of air supplier and opening defect of pressure tank. If the electric coil of air supplier breaks down, it will not have any local effects but it will stop the compressor which will consequently stop the TBM. At present, PLC is applied to detect this failure. The expertise team believed that an appropriate preventive maintenance program will reduce its likelihood and detection numbers leading to a reduction of RPN from 56 to 14. The control actions will not reduce the severity number, thus modification of electric coil design seems to be essential.

Starting defect in air supplier will not have a local effect, but it will stop the compressor which will consequently stop the TBM. Any defects in PLC, burning of contactor blades, sulfating, dust and any electrical or mechanical defectives in electromotor may lead to this failure mode. Presently, PLC is used to detect this failure. Preventive maintenance is suggested to reduce RPN from 54 to 24, but it will not reduce the severity number. A modification of starting design is recommended to reduce severity number.

Table 8 shows the MFMEA results of TBM Mechanic system. Cutter head stop is the most severe and highly risk failure mode in this system. High severity and likelihood numbers are the special characteristics of this failure mode. This failure leads to stop the TBM.

Table 8

Bad rock condition is the main reason the cutter head stops. Core drilling is recommended to identify rock condition in advance. This will reduce the likelihood number from 8 to 6 and reduce the detection number from 3 to 2 which all together will reduce the RPN from 240 to 120. This suggestion was applied and reduced the cutter head stop due to rock condition from then on.

Cutter disc wear is the next failure mode with a high RPN and severity number. It may lead to TBM stop. Bad Rock condition and non-standard disc material are the main reasons for this failure. The expertise team recommended using standard discs and periodical checks to prevent this failure. These actions will reduce the likelihood number from 4 to 2 and the detection number from 7 to 5 which will totally reduce the RPN from 168 to 60.

The third failure mode with a RPN higher than 80 is scraper defect (break down and wear). This failure mode will stop the TBM. This failure has a relatively high detection number. Thus periodical checks may help to detect it easier. The team did not make any recommendations.

Table 9 shows the MFMEA results of the ventilation system. According to this Table the most critical failure mode (e.g. high air pressure in duct) is related to this system. This failure is mainly due to duct blockage which will burst the duct. At present, there is almost no controlling mechanism. Using dampers at the jet fan inlet, applying electro-motors with controllable rotation, as well as using standard duct material and proper duct mounting are recommended by the expertise team to prevent this failure. These actions will reduce likelihood number from 8 to 4 and detection number from 6 to 4 which will totally reduce the risk number from 480 to 160. This RPN will still be high.

Table 9

Low air pressure in the ducts is the next failure with a high Risk Priority Number. This failure may be caused by low fan rotation, wrong ventilation design, duct leakage etc. It will lead to insufficient fresh air in the tunnel that can threat the human life in tunnel. Preventive maintenance, periodical checks, and the use of anemometers to measure air velocity at the duct exit are recommended by the expertise team. The application of these recommendations will reduce RPN of this failure from 240 to 60.

Most of the failure modes studied in the ventilation system had the highest severity number. 4 failure modes out of 6 failure modes in this system had the highest severity number. This shows the significant role of ventilation system in gassy and long tunnels such as the Alborz Tunnel. In a similar tunnel with H2S the same failure led to death of 4 people in the east of Iran in 2005. Losing ventilation system for 3 minutes in the Alborz Tunnel caused a fire incidence due to methane gas in tunnel.

Table 10 shows the MFMEA results of Shot Crete system. According to this Table only one failure mode e.g. plastic plate wear has a RPN of higher than 80. It can stop the Shot Crete system and finally stop the TBM. Plastic plate wear is normal during their operation. Preventive maintenance can reduce its RPN from 84 to 20.

Table 10

Table 11 shows the MFMES results of Rolling Stock. All failure modes studied in the Rolling Stock System are high risks (e.g. RPN higher than 80) with the highest severity numbers.

Table 11

High rail width has a RPN of 160. This failure is caused by moving the vehicle on it, defective traverses, poor material, construction and maintenance. This failure can lead to higher wearing of the rail, derailing of vehicles which will affect personnel safety, closing of the rail and finally stopping the TBM. At present monthly periodical checks and measurement of the width of the rail are the methods used to detect and prevent the failure. The expertise team recommended appropriate preventive maintenance, weekly measurement of rail width, supporting of traverses according to their bearing load, selection of the optimum cross section for wheel profile and mounting derailing mechanism to prevent traverse movement. These preventive actions will reduce the RPN from 160 to 40. The severity of the failure will not be reduced by the application of preventive actions. The likelihood and detection numbers will be reduced from 4 to 2.

Low rail width is the next high risk failure mode with a RPN of 120. This failure is caused by increasing road gradient, passing heavy duty vehicles such as loaders over the rail and ballast deficiency between traverses. The local effect of low rail width causes the wheel bandage to wear and finally derails the vehicle. This failure affects the personnel safety and may lead to road closure and stopping the TBM. Monthly checks and rail width measurements are used to detect the failure at present. Appropriate preventive maintenance, weekly rail width measurements, supporting the rail foundation between traverses, and mounting derailing mechanism to prevent traverse movement are the expertise recommendations. The application of these preventive actions is expected to reduce the RPN of this failure from 120 to 40. They will reduce likelihood number from 3 to 2 and the detection number from 4 to 2. These actions will not reduce severity number from 10.

Lateral unleveled traverse with a RPN of 200 is the next high risk failure. Improper construction and maintenance, uneven foundation, inflation due to iced water, bent rails, old traverses and unstable ground are the main causes of this failure. This failure causes discomfort for commuters in vehicles and may lead to derailment of vehicles. It also affects personnel safety, road closure and stopping the TBM. The MFMEA team recommended an appropriate preventive maintenance program, weekly periodical checks, supporting the rail foundation with suitable soil, the mounting of a derailing mechanism to prevent traverse movement and using standard traverses. The application of these recommendations is expected to reduce the failures' RPN from 200 to 60. They will reduce the likelihood number of this failure from 5 to 3 and detection number from 4 to 2. The recommendations will not reduce the severity number.

Rail defect with a RPN of 200 is also a high risk failure. This failure is caused by improper construction and maintenance, uneven foundation, inflation due to iced water, bent rails, defected traverses and dirty ballast. Rail defect can move one rail with respect to the other rail, move a rail in any direction and derail the vehicle. The consequences of this failure can affect personnel safety, close the rail road and stop the TBM. Monthly periodical checks and rail measurements are the means of detecting the failure at present. The expertise team recommended correcting improper rail rotations in road bends, weekly periodical checks, adjusting rotation with proper equipment, the mounting of derailing mechanism to prevent traverse movement, using standard traverses and to tampon when the season changes. The application of recommendations is expected to reduce the failures' RPN from 200 to 60. The RPN will be reduced mainly due to likelihood and detection number reduction (table 11).

Lateral deflection of lever with a RPN of 160 is the next high risk failure. This failure is caused by thermal variation of rails, improper bolts and connections or low resistance ballast. This failure may derail the vehicle which consequently will affect personnel safety, close the rail road and stop the TBM. At present, monthly periodical checks and rail measurements are the means of detecting this failure. Expertise MFMEA team recommended an appropriate levering program, weekly periodical checks and lever adjustments according to guidelines. The application of these recommendations is expected to reduce the RPN of this failure from 160 to 40 (table 11).

Longitudinal Rail Cracks with a RPN of 120 also constitute a high risk failure. Normal operation, passing heavy duty vehicles over the rail, old rails and corrosion are the main causes of this failure which can break the rail or its crown and derail the vehicle. Consequently this may affect the personnel safety, close the rail road and stop the TBM. Visual checks are the only means to detect this failure at present. The MFMEA team recommended using ultrasonic instrumentation to check the rail cracks.

The application of this instrumentation is expected to reduce the RPN of this failure from 120 to 20 (table 11).

No blade contact with a RPN of 120 is another high risk failure. An unbalanced needle (laterally and longitudinally unbalanced rail guide), existence of metallic chips around the needle or a bent needle can cause this failure. This failure may derail the vehicle which will affect personnel safety, close the rail road and stop the TBM. Monthly periodical checks are the only means of investigating this failure. The expertise team recommended a daily preventive maintenance program to reduce the likelihood and detection numbers of this failure (table 11). The application of a daily preventive maintenance program will reduce the Risk Priority Number from 120 to 40.

Wheel wear with a RPN of 180 is the last high risk failure in railway system. Mismatching between wheel and rail hardness, nonstandard profile, wrong rail geometry and reduction in bend radius can lead to wheel wear. This failure can derail the vehicle and affect personnel safety, close the rail road and stop the TBM. Daily checks are the only means of detecting wheel wears. MFMEA team recommended appropriated preventive maintenance, selecting the optimum cross section and standard material for wheels, oiling the rails at bends, not applying extra width at bends and using automatic greasing instruments for better detection and likelihood parameter. The application of these recommendations is expected to reduce the RPN from 180 to 90.

A Risk Priority Number of 80 was considered as an acceptable level. According to this level, 18 failure modes with higher RPN were categorized unacceptable failures. Table 12 shows these failure modes with their codes. The results show that even after modification and applying control measures, 3 failure modes will still have a RPN of higher than 80. These failure modes are high air pressure in ventilation duct, cutter head stop and locomotive wheel wear.

Table 12

The Risk Priority Number of these failure modes before and after control application is tabulated in Table 13.

Table 13

In total 21 failure modes had severity numbers higher than 5. The systems in which these failures are expected need to be redesigned. These failure modes are listed in Table 14.

Table 14

The accidents occurred in next two years were tracked. The results revealed that, modification of the process and equipment reduced the accidents significantly. One small fire incident due to ventilation failure (for 1 minuet), 3 TBM stops due to bad rock condition and 3 derailing due to unleveled rails were the most major accidents occurred during next two years. The consequences of these accidents were negligible. The comparison of the accidents (numbers and consequences) with similar projects shows that this project was successful in accident prevention.

Table A, Appendix

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Table 1: Severity Ranking used in the present study (QS9000 & SAE.J1739)

Rank	Effect	Measure: Severity Effect
10	Maximum Severity	Injury or harm to operating personnel. Failure resulting in hazardous effects almost certain. Non-compliance with government regulations.
9	Extreme Severity	Failure resulting in hazardous effects highly probable. Safety and regulatory concerns.
8	Very High Severity	Significant downtime and major financial impacts. Product inoperable but safe. User very dissatisfied, e.g. TBM stops for longer than 30 days
7	High Severity	Significant downtime. Product performance severely affected. User very dissatisfied, e.g. TBM stops for 10 -30 days
6	Severe	Disruption to downstream process. Product operable and safe but performance degraded. User dissatisfied, e.g. TBM stops for 24 hr -10 days.
5	Moderate	Impacts will be noticeable throughout operations. Reduced performance with gradual performance degradation. User dissatisfied, e.g. TBM stops for 10 to 24 hr
4	Minor	Local and/or downstream process might be affected. User will experience minor negative impact on the product. e.g. TBM stops for 1 to 10 hr.
3	Slight	User will probably notice the effect but the effect is slight e.g. TBM stops for less than 1 hr.

2	Very Slight	No downstream effect. Insignificant / negligible effect. e.g. parameter variation is in control range, adjustments or controls are essential.
1	None	Might be noticeable by the operator. Improbable/not noticeable by the user e.g. parameter variation is in control range, adjustments or controls are not essential or it can be checked during maintenance shift.

Table 2: Likelihood ranking used in the present study (QS9000)

Rank	**Failure Occurrence**	**Failure Rate**
10	Very High, failure almost certain.	MTBF≤1 hr
9	Very high number of failures likely.	2 hr<MTBF≤10 hr
8	High number of failures likely.	11 hr<MTBF≤100 hr
7	Moderately high number of failures likely.	101 hr<MTBF≤400 hr
6	Medium number of failures likely.	401 hr<MTBF≤1000 hr
5	Occasional failures likely.	1001 hr<MTBF≤2000 hr
4	Few failures likely.	2001 hr<MTBF≤3000 hr
3	Very few failures likely.	3001 hr<MTBF≤6000 hr
2	Rare number of failures likely.	6001 hr<MTBF≤10000 hr
1	Failure highly unlikely.	MTBF>10000 hr

Table 3: Detection Ranking used in the present study (QS9000 & SAE.J1739)

Rank	**Effect**	**Measure: Severity Effect**
10	Extremely Unlikely	Controls will almost certainly not detect the existence of a defect, or there are no controls on the equipment.
9	Remote Likelihood	Controls have a very low probability of detecting existence of a defect.
8	Very Low Likelihood	Has lowest effectiveness in each applicable category.
7	Low Likelihood	Has low effectiveness for detection.
6	Moderately Low Likelihood	Has moderately low effectiveness for detection.
5	Medium Likelihood	Has medium effectiveness for detection
4	Moderately High Likelihood	Has moderately high effectiveness for detection.
3	High Likelihood	Has high effectiveness for detection.
2	Very High Likelihood	Controls have very high probability of detecting existence of failure.
1	Extremely Likely	Controls will almost certainly detect the existence of the defect.

Table 4: Studied systems and subsystems

System	System Code	Subsystem	Subsystem Code	Component	Component Code
		Generator	1.1		
TBM Electric		Transformer	1.2		
System	1	Control	1.3		
		Board	1.4		
		Power Board			
		Reservoir	2.1		
TBM		Piping	2.2		
Hydraulic	2	Pump	2.3		
System		Feeding	2.4		
		Pump	2.5		
		Oil Cooler			
		Compressor	3.1	Filter	3.1.1
TBM				Outlet	3.1.2
Pneumatic	3	Electromotor	3.2	Valve	
System		Air Tank	3.3		3.3.2
		Air Screw	3.4	Relief	
		Pump		Valve	
TBM		Grab	4.1		
Mechanical	4	Cutter Head	4.2		
System		Conveyor	4.3		

Tunnel		Electromotor	5.1		
Ventilation	5	Ball Bearing	5.2		
System		Duct	5.3		
		Mixer	6.1		
Shot Crete		Conveyor	6.2		
System	6	Pump	6.3		
		Hose	6.4		
		Nozzle	6.5		
Rolling Stock	7	Rail Road	7.1	Turn Out	7.1.1
		Vehicles	7.2	Wheels	7.2.1

Table 5: MFMEA results of Electric System.

Code	Failure Mode	Existing Condition				After Control			
		SV	LN	DN	RPN	SV	LN	DN	RPN
1.1	High Voltage	8	2	3	48	5	1	2	10
1.1	Low Voltage	2	6	4	48	2	5	3	30
1.1	High Current	3	4	2	24	3	3	2	18
1.1	Low Current	2	4	2	16	-	-	-	-
1.2	HV Leakage	7	3	3	63	7	2	2	28
1.2	LV Disconnection	5	4	3	60	5	2	2	20
1.2	No Voltage	3	1	3	9	3	1	2	6
1.2	Low Output Voltage	5	6	3	90	5	6	2	60

1.2	High Output Voltage	5	2	3	30	5	2	1	10
1.2	Missing Dynamo Layers	8	1	3	24	8	1	2	16
1.2	Dirty Contactors	3	3	4	36	3	2	2	12
1.2	Leakage	3	2	4	24	3	1	2	6
1.3	Wire Corrosion	4	2	4	32	4	1	2	8
1.4	Phase to Phase Connection	4	1	3	12	4	1	2	8
1.4	Broken Internal Parts	4	3	2	24	4	2	1	8
1.4	Phase to Earth Connection	4	3	3	36	4	2	1	8

Table 6: MFMEA results of TBM Hydraulic System.

Code	**Failure Mode**	**Existing Condition**				**After Control**			
		SV	**LN**	**DN**	**RPN**	**SV**	**LN**	**DN**	**RPN**
2.1	Bubble forming	2	2	8	32	-	-	-	-
2.1.1	Dirty Oil	2	2	4	16	-	-	-	-
2.2	Leakage	4	1	3	12	4	1	2	8
2.3	External Leakage	4	3	3	36	4	2	2	16
2.3	Starting Defect	4	8	3	96	4	5	2	40
2.3	Turning Off Defect	4	2	3	24	4	1	2	8
2.3	Uncontrollable	4	2	5	40	-	-	-	-
2.4	Starting Defect	4	2	3	24	4	1	2	8
2.4	Turning Off Defect	4	2	3	24	4	1	2	8
2.4	Coupling Breakdown	4	2	5	40	-	-	-	-

Table 7: MFMEA results of TBM Pneumatic System.

Code	Failure Mode	Existing Condition				After Control			
		SV	LN	DN	RPN	SV	LN	DN	RPN
3.1	Ball Bearing Defect	-	-	-	-	-	-	-	-
3.1	Electric Coil Breakdown	7	2	4	56	7	1	2	14
3.1	Starting Defect	6	3	3	54	6	2	3	24
3.1.1	Dirty Filter	3	4	3	36	3	2	2	12
3.1.2	External Air Leakage	4	3	4	48	4	2	2	16
3.2	Ball Bearing Defect	-	-	-	-	-	-	-	-
3.2	Shorting Coil	4	2	2	16	4	1	2	8
3.2	Two Phase Electricity	4	3	2	24	4	1	1	4
3.3	Air Leakage	3	3	3	27	3	1	1	3
3.3.1	Air Leakage	3	3	4	36	-	-	-	-
3.3.1	Opening Defect	9	3	4	108	9	2	3	54
3.3.1	Closing Defect	4	3	4	48	4	2	2	16
3.4	Ball Bearing Wear	-	-	-	-	-	-	-	-
3.4	Starting Defect	5	3	3	30	5	2	2	20

Table 8: MFMEA results of TBM Mechanic System.

Code	Failure Mode	Existing Condition				After Control			
		SV	LN	DN	RPN	SV	LN	DN	RPN
4.1	Packing Run away	5	4	3	60	5	3	3	30
4.1	Inlet Tap Breakdown	4	4	3	48	4	3	2	24
4.1	Electric Tap Breakdown	6	4	2	48	6	2	2	24
4.2	Cutter Head Stop	10	8	3	240	10	6	2	120
4.2	Cutter Disc Wear	6	4	7	168	6	2	5	60
4.2	Scraper Defect	5	3	6	90	-	-	-	-
4.3	Ball Bearing Breakdown	5	4	4	80	5	2	4	40
4.3	Belt Tear	4	6	3	72	-	-	-	-

Table 9: MFMEA results of Ventilation System.

Code	Failure Mode	Existing Condition				After Control			
		SV	LN	DN	RPN	SV	LN	DN	RPN
5.1	Starting Failure	10	3	1	30	10	2	1	20
5.1	Over Load	4	4	3	48	4	3	2	24
5.1	Low Voltage	10	3	2	60	10	2	1	20
5.2	Ball Bearing Breakdown	4	2	5	40	4	1	3	12
5.3	Low Air Pressure	10	6	4	240	10	2	3	60
5.3	High Air Pressure	10	8	6	480	10	4	4	160

Table 10: MFMEA results of Shot Crete System.

Code	Failure Mode	Existing Condition				After Control			
		SV	LN	DN	RPN	SV	LN	DN	RPN
6.1	Mixer Blade Binding	4	6	3	72	4	4	3	32
6.2	Belt Tear	5	2	3	30	5	1	2	10
6.3	Plastic Plates Wear	4	7	3	84	2	5	2	20
6.3	Cylinder Plate Break down	4	2	4	32	4	1	3	12
6.4	External Leakage	4	8	2	64	4	4	2	32
6.4	Hose Tear	4	5	1	20	4	3	1	12
6.4	Coupling Leakage	4	5	2	40	4	3	1	12
6.5	Water Tap Breakdown	3	7	1	21	-	-	-	-

Table 11: MFMEA results of Rolling Stock System.

Code	Failure Mode	Existing Condition				After Control			
		SV	LN	DN	RPN	SV	LN	DN	RPN
7.1	High Rail Width	10	4	4	160	10	2	2	40
7.1	Low Rail Width	10	3	4	120	10	2	2	40
7.1	Lateral Unleveled Traverse	10	5	4	200	10	3	2	60
7.1	Rail Defect	10	5	4	200	10	3	2	60
7.1	Lever Deflection	10	4	4	160	10	2	2	40
7.1	Longitudinal Rail Cracks	10	2	6	120	10	1	2	20
7.1.1	No Blade Contact	10	3	4	120	10	2	2	40

7.2.1	Wheel Wear	10	6	3	180	10	3	3	90

Table 12: Unacceptable Failure Modes (e.g. RPN>80).

Code	Failure Mode	Existing Condition	After Control
1.2	Low Output Voltage	90	60
2.3	Starting Defect	96	40
3.3.1	Opening Defect	108	54
4.2	Cutter Head Stop	240	120
4.2	Worn Cutter Disc	168	60
4.2	Scraper Defect	90	0
4.3	Ball Bearing Breakdown	80	40
5.3	Low Air Pressure	240	60
5.3	High Air Pressure	480	160
6.3	Plastic Plates Wear	84	20
7.1	High Rail Width	160	40
7.1	Low Rail Width	120	40
7.1	Lateral Unleveled Traverse	200	60
7.1	Rail Defect	200	60
7.1	Lever Defection	160	40
7.1	Rail Cracks	120	20
7.1.1	No Blade Contact	120	40
7.2.1	Wheel Wear	180	90

Table 13: Risk Priority Numbers of Critical Failure Modes

Code	Failure Mode	Existing Condition				After Control			
		SV	LN	DN	RPN	SV	LN	DN	RPN
4.2	Cutter Head Stop	10	8	3	240	10	6	2	120
5.3	High Air Pressure	10	8	6	480	10	4	4	160
7.2.1	Wheel Wear	10	6	3	180	10	3	3	90

Table 14: Failure Modes that require modification due to high Severity parameter

Code	Failure Mode	Existing Condition				After Control			
		SV	LN	DN	RPN	SV	LN	DN	RPN
1.1	High Voltage	8	2	3	48	5	1	2	10
1.2	HV Leakage	7	3	3	63	7	2	2	28
1.2	Missing Dynamo Layers	8	1	3	24	8	1	2	16
3.1	Electric Coil Breakdown	7	2	4	56	7	1	2	14
3.1	Starting Defect	6	3	3	54	6	2	3	24
3.3.1	Opening Defect	9	3	4	108	9	2	3	54
4.1	Electric Tap Breakdown	6	4	2	48	6	2	2	24
4.2	Cutter Head Stop	10	8	3	240	10	6	2	120
4.2	Cutter Disc Wear	6	4	7	168	6	2	5	60
5.1	Starting Failure	10	3	1	30	10	2	1	20
5.1	Low Voltage	10	3	2	60	10	2	1	20
5.3	Low Air Pressure	10	6	4	240	10	2	3	60

5.3	High Air Pressure	10	8	6	480	10	4	4	160
7.1	High Rail Width	10	4	4	160	10	2	2	40
7.1	Low Rail Width	10	3	4	120	10	2	2	40
7.1	Lateral Unleveled Traverse	10	5	4	200	10	3	2	60
7.1	Rail Defect	10	5	4	200	10	3	2	60
7.1	Lever Defection	10	4	4	160	10	2	2	40
7.1	Rail Cracks	10	2	6	120	10	1	2	20
7.1.1	No Blade Contact	10	3	4	120	10	2	2	40
7.2.1	Wheel Wear	10	6	3	180	10	3	3	90

Appendix

Table A: Machinery Failure Mode and Effects Analysis Form

Prepared by: ---------

No of MFMEA: ------

Page ---- of -----Pages

Date: -------

System: ------------

Subsystem: --------------

Department: --------------

FMEA Team: -------------

Code	**Perf**	**Failure**	**Failure Effects**			**SN**	**Failure Reason**	**LN**	**Existing DPC**	**DN**	**RPN**	**RAT**	**Results of Actions**			
			Local Effects	**Other Parts**	**SEP**								**SN**	**LN**	**DN**	**RPN**

SEP: Subsystem, Environment and Personnel

DPC: Detecting, Preventing and Controls

RAT: Recommended Actions Take