

Determining the probability of failure for a diesel electric locomotive 060-DA using fault tree analysis

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Abstract. The "fault tree" analysis is one of the most commonly used methods for determining reliability, calculating the probability of failure and thereby determining risk. The primary purpose of this analysis is to evaluate, using analytical and statistical methods, the likelihood of an unfavorable event occurring. These calculations involve the knowledge of system reliability data such as probability of failure, failure rate, time to failure, repair rate etc. Building a "fault tree" model can provide insight into how to pinpoint potential deficiencies within a functional system. In this paper, a defective tree structure was made for the main components of the 060-DA electric diesel locomotive. Five types of equipment part of the locomotive were taken into consideration: mechanical, pneumatic, thermal, power and auxiliary electrical. Each of these contains, in turn, other subassemblies and components. For the latter, some parameters needed to draw the fault tree diagrams were calculated on a statistical basis. In this way, the probability of the locomotive exiting operation was determined as a result of the defects that occurred in the component parts.

1. Determination of risk based on the "fault tree" methodology (FT)

The fault tree methodology accomplishes the effect-to-cause analysis [9.4]. It starts with the top event and goes back to identify the component whose failure may cause the system to shut down. Therefore, the fault tree is a graphical method of presenting how the failure of the system can result from the failure of the components. Figure 1 shows a block diagram for a simplified "fault tree". Only defects are included in this tree, more precisely non-yielding is excluded. In a malfunctioning tree structure, AND and OR (AND and OR) are the "linking" tools between events. An 'AND' gate implies that the actions above the gate will only appear if all the below events occur. An 'OR' gate implies that any of the events below can trigger the events above the gate. Passing through an 'AND' gate involves the multiplication rule for the associated event probabilities. Passing through an 'OR' gate involves summing up the probabilities (events are supposed to be independent). Time dependency can be included, as failures are not necessarily immediate. In such cases, sequential evaluation ("time frames") is made with the probability of failure of the appropriate time-dependent components.

The limits of the fault tree methods are partly intrinsic and partly practical. The algorithms used in the fault tree analysis are based on the assumption that a component either works or crashes and can always be in only one of these two states within a certain probability. Possible intermediate cases are not subject to specific treatment. It is assumed that the primary events contributing to the failure are independent, which is not always the case.



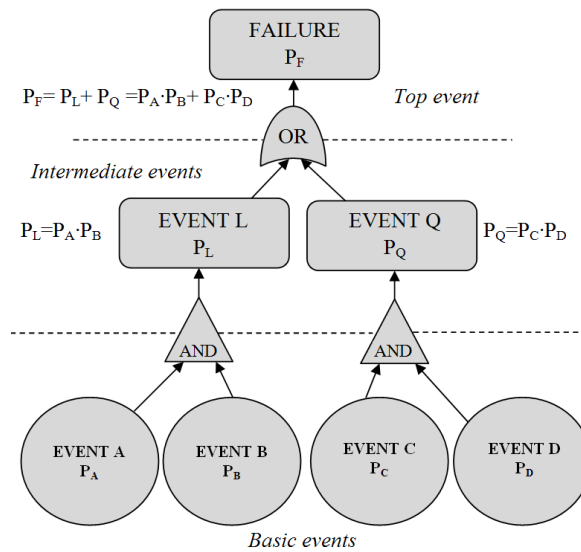


Figure 1. Simplified diagram of a fault tree.

In practice, fault trees are formed from hundreds of elements (primary and intermediate events). In a fault tree diagram, a "fail-to-fail" space is considered and the failure combination system is tracked. Traditionally, fault tree analysis has been used to access fixed probabilities (for example, each event involving a fault tree has a fixed probability).

2. Designing and making a fault tree diagram

The program used in this work was purchased from the ITEM Company. The structure of a fault tree can be relatively ample (laborious), containing a significant number of primary events. As a result of running the program with the data entered for primary events, results are obtained both for the main event (the occurrence of the failure in this case) and for the secondary or intermediate events. Characteristics of the models used to characterize primary events are various: Fixed Rate, Normal, Uniform, etc. In this paper, fixed models and rates were used.

The "Fixed" model is attributed to an event whose probability of occurrence does not vary over time or if the probability of failure and the frequency of occurrence are known, and is used to represent the probability of failure.

The "Rate Model" is a time-dependent model and requires constant rates of failure and constant repair rates, based on the number of hourly failures throughout the system's running time. The inactivity at time t or the probability of failure after time t is given by:

$$Q(t) = \frac{\lambda}{\lambda + \mu} [1 - e^{-(\lambda + \mu)t}] \quad (1)$$

The Frequency of failure from 0 to t is given by:

$$w(t) = (1 - Q(t)) \cdot \lambda \quad (2)$$

where: $Q(t)$ - component unavailability at time t ; λ - component failure rate; μ - component repair rate. The component's failure rate can be calculated by:

$$\lambda = \frac{N_f}{T} \quad (3)$$

where N_f is the total number of failures in the 0-T period, T being the total time taken into account.

The component repair rate is calculated with:

$$\mu_r = \frac{N_r}{T} \quad (4)$$

3. The functional description and analysis for 5 years of the upgraded diesel-electric locomotive 060-DA equipment failures

In the fault tree analysis, an important step is analyzing the operation, knowing the components and determining the fault modes.

The 060-DA electric diesel locomotive is a complex assembly of components and subassemblies that work together or separately. Any failure of the base components may result in total or partial decommissioning or in the non-compliant operation of the 060-DA diesel locomotive.

The components of the locomotive

The Locomotive parts can be divided into two categories: mechanical and electrical. The main parts in a diesel-electric locomotive are as follows: *the bogie, the mounted axle and the locomotive box.*

The 060-DA locomotive is equipped with a two-stage suspension:

- *the primary suspension* - bogie suspension on axles, consisting of helical springs;
- *the secondary suspension* - bogie suspension of the locomotive box, consisting of double springs in sheets.

The brake timing is symmetrical, that is, a pair of diametrically opposed brake blocks operates on each wheel. This braking system (handbrake) can be operated from both driving positions and it is necessary to keep the vehicle in place when the other brakes are out of use, as an additional measure.

Another important part is the *traction pivot*, which transmits the traction and braking forces from the bogie to the locomotive box.

The operation

The electric diesel locomotive 060-DA is a rail vehicle with a power of 2100 hp. The locomotive is designed to tow passenger and freight railway vehicles on non-electrified single and multiple traction portions, as well as heavy maneuvers. The 060-DA electric diesel locomotive consists of a metal box with two cabs at the ends, placed on two bogies, each bogie having three axles. The two bogies are connected by means of a transverse coupling, present beneath the locomotive in the middle. The transmission of the locomotive is electric, of the DC type. (CC - CC). The locomotive energy source is the diesel engine, which drives a DC generator, with electric power being supplied to electric traction motors. These six-stroke engines are present on each axle, driving the mounted axles through a conical gear. Of great importance to the operation of the locomotive is the correct adjustment of the suspension. This adjustment involves the measurement and adjustment of the mechanical gaps. Transmissions can be both fixed and variable. The constant transmission reports are obtained using gears systems, while variable ones are obtained by means of mechanical, hydraulic or electrical transmissions. Mechanical transmissions lead to the slowly torque, while the hydraulic or electric ones lead to a continuous variation.

In order to highlight diesel-electric locomotive conception problems, the authors made a study on the failures of the various equipments that make up a diesel-electric locomotive. In this respect, two cases of the diesel-electric locomotive 060-DA were considered, one partially upgraded with Romanian equipment and the other fully upgraded with General Motors equipment.

Only equipment failures that caused trouble in passenger trains during the period 2006-2010 were taken into account.

We classified the equipment of a diesel-electric locomotive as follows:

- mechanical equipment: bogies with engine axles, locomotive box, collision and binding devices;
- pneumatic equipment: the compressed air production plant and the brake system;
- thermal equipment: diesel engine with its auxiliary plant;
- electrical equipment: the power plant (including power-operated electric machines) and the electrical installation of ancillary services.

4. Applying the fault tree type methodology to determine the probability of failure of the electric diesel locomotive 060-DA

For the drawing and processing of fault tree diagrams, statistical data on the failure of the components specified above was required. Thus, in Tables 1 ÷ 5, the following elements are presented:

- the number of failures per item in each of the years 2006 ÷ 2016;
- The total number of failures during the 5 years considered;
- The total number of repairs performed on each of the components considered;
- Rate of failure λ ;
- Rate of repair μ .

Table 1. Mechanical equipment failures.

Mechanical equipment	Number of failures / Year					Total failures	λ total	μ total	Number of repairs
	'06	'07	'08	'09	'10				
Engine axle bearings	2	3	4	2	3	14	0.0003194	0.000570	25
Drive axle drive	3	1	1	1	-	6	0.0001369	0.000273	12
Suspension elements	1	1	-	1	-	3	6.845E-05	0.000228	10
Brake timing	-	-	-	1	-	1	2.281E-05	9.12E-05	4

Table 2. Pneumatic equipment failures.

Pneumatic equipment	Number of failures / Year					Total failures	λ total	μ total	Number of repairs
	'06	'07	'08	'09	'10				
Compressed air production	-	1	2	2	1	6	0.0001369	0.000296	13
Air command installation	2	-	1	1	-	4	9.127E-05	0.000159	7
Brake installation	1	-	-	1	1	3	6.845E-05	0.000114	5

Table 3. Thermal equipment failures.

Thermal equipment	Number of failures / Year					Total failures	λ total	μ total	Number of repairs
	'06	'07	'08	'09	'10				
The actual diesel engine	3	-	1	-	-	4	9.127E-05	0.0002053	9
Lubrication system	-	1	1	1	2	5	0.0001140	0.0002510	11
Fuel system	2	4	1	1	2	10	0.0002281	0.0004791	21
Cooling system	4	1	3	3	1	12	0.0002738	0.0006161	27
Supply air installation	-	-	-	-	1	1	2.281E-05	6.845E-05	3
Mechanical regulator	1	-	-	-	1	2	4.563E-05	0.0001597	7
Hydrostatic installation	2	-	1	3	-	6	0.0001369	0.0003879	17

Table 4. Electrical power equipment failures.

Electrical power equipment	Number of failures / Year					Total failures	λ total	μ total	Number of repairs
	'06	'07	'08	'09	'10				
Power circuit breakers	-	1	1	1	1	4	9.127E-05	0.0002053	9
Main generator and overloaded traction motors	-	1	2	1	2	6	0.0001369	0.0002510	11
Electric traction motors	7	1	8	6	6	28	0.0006389	0.0007986 49	35
Main Generator	1	1	1	-	-	3	6.845E-05	0.0001140	5
Train heating installation	-	2	1	1	1	5	0.0001140	0.0001597	7

Table 5. Auxiliary electrical equipment failures.

Auxiliary electrical equipment	Number of failures / Year					Total failures	λ total	μ total	Number of repairs
	'06	'07	'08	'09	'10				
Main generator excitation circuit	3	3	5	4	5	20	0.0004563	0.0006617	29
Batteries	3	6	4	-	5	18	0.0004107	0.0007301	32
Auxiliary generator	-	-	-	-	1	1	2.281E-05	9.127E-05	4
Automatic fuses and switches	1	2	2	-	2	7	0.0001597	0.0003650	16
Electric motors auxiliary services	4	5	3	4	3	19	0.0004335	0.0007758	34
Contactors and relays	8	6	3	3	2	22	0.0005020	0.0006845	30
Command, signaling and control installations	5	-	6	3	11	25	0.0005704	0.0008442	37
INDUSI and DSV installations	-	-	1	-	1	2	4.563E-05	0.0001140	5

In Figure 2, with the Item Toolkit software, separate fault trees diagram were created for a part of the assemblies or sub-assemblies described above. The other components are directly comprised of the complete fault trees structure shown in Figure 3.

For both the top event and the logical gates, the following are set in the program area shown in Figures 2 and 3: gate type, defect name and description of the type of non-compliance.

For each base event in the program area shown in Figures 2 and 3, the following features are presented: event type, event name, failure mode based on patterns used for primary events, and other features that are set to be implicit in the program, but which can be modified.

Depending on the mode of failure taken into account, the probability of failure, the frequency of occurrence, the repair rate, the standard deviation, the mean value, the lower and upper limits, etc., must be provided. Thus, for the diagrams in Figure 2, for the primary events the "rate model" was used and the release rates and repair rates for each component were provided. In this way, for the top event, the program calculated through processing the unavailability and the frequency for the equipment considered.

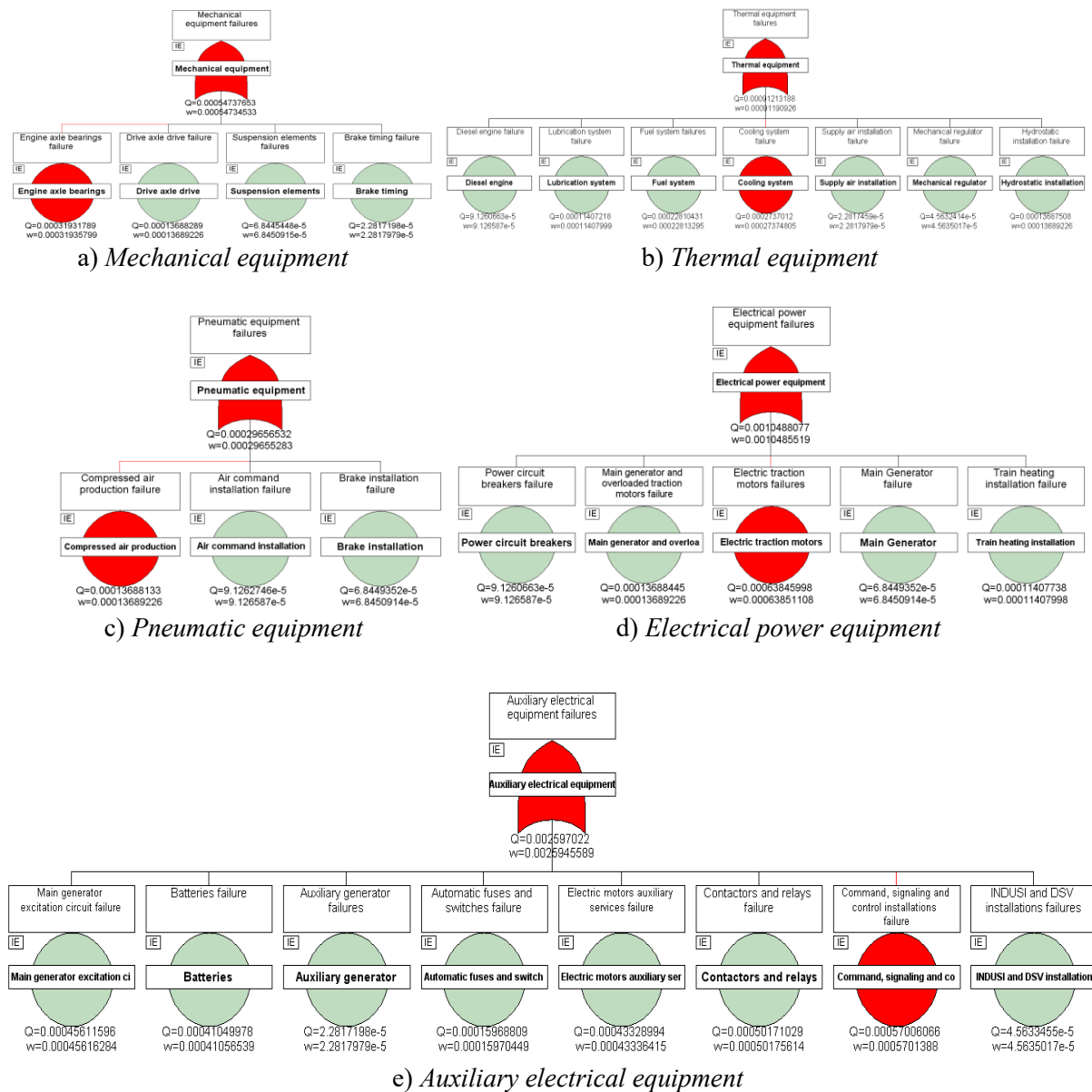


Figure 2. Partial fault tree for each type of equipment considered.

The structure of the **complete** fault tree in Figure 3 comprises:

- top event: complete malfunction or faulty behavior of the 060-DA electric diesel locomotive;
- an "OR" logic gate;
- 5 base events whose values for probability of failure and occurrence frequency are determined based on the partial fault trees shown in Figure 2. Within this diagram, the model used to define the mode of failure in the primary events was "fixed".

For the final fault tree diagram, which corresponds to the failure or malfunction of the locomotive, the input data for the primary events were taken from the partial diagrams in Figure 2. These data are: the unavailability at time t or the probability of failure, as well as the frequency of failures for each piece of equipment considered.

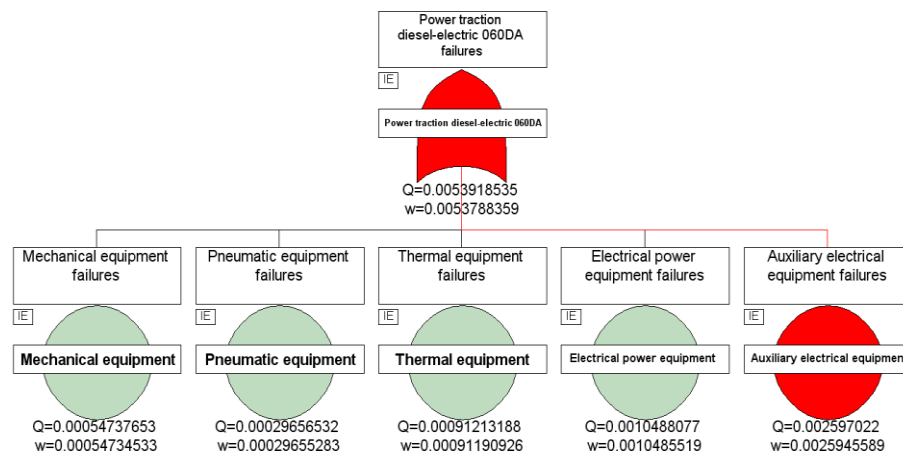


Figure 3. Complete fault tree diagram.

Regardless of the type of failure chosen, after running the program, each base event will be calculated for the probability of failure and the frequency of occurrence - for the "Fixed" model these have been established from the start. Under these conditions, when passing through gates, the probability of failure and the frequency of occurrence will be calculated up to the top event (effect). From the fault tree analysis shown in Figure 3, a probability of failure or malfunctioning of the locomotive, "Q", of 0.539% and a "W" frequency of 0.537% was obtained. Also in Figure 3, it is possible to see the path with the most unfavorable influence in terms of the possibility that the locomotive may fail or not operate at the projected parameters.

Figures 4a, 4b and 4c show the results provided by the program. Thus, it is found that there are 5 paths, ordered according to their contribution (unfavorable) to the probability of manifestation of the nonconformity (malfunctioning or faulty behavior of the locomotive). In this way, we can make an assessment of the risk situations, in order to take action accordingly and diminish the probability of initial manifestation of primary events.

	Summary View							
	Parameter	Value	Mean	Std	5%	50%	95%	99.00%
1	Unavailability Q	0.0053918535	0.0	0.0	0.0	0.0	0.0	0.0
2	Failure Frequency W	0.0053788359	0.0	0.0	0.0	0.0	0.0	0.0
3	Mean Unavailability Qm	0.0053918535						
4	Mean Availability Am	0.99460815						
5	CFI	0.0054079951						
6	Expected Failures	0.0053788359						
7	Unreliability	0.0053933982						
8	Total Down Time (TDT)	0.0053918535						
9	Total Up Time (TUT)	0.99460815						
10	MTBF	185.91383						
11	MTTF	184.91141						
12	MTTR	1.0024201						
13	Availability	0.99460815						
14	Reliability	0.9946066						
15	No of Cut Sets	5						

a) Top event data

	Fault Tree Cut Set View		
	Unavailability (Q)	Frequency (W)	Events
1	0.002597022	0.0025945589	Auxiliary electrical equipmen
2	0.0010488077	0.0010485519	Electrical power equipment
3	0.00091213188	0.00091190926	Thermal equipment
4	0.00054737653	0.00054734533	Mechanical equipment
5	0.00029656532	0.00029655283	Pneumatic equipment

b) Base event data

	Fault Tree Importance View			
	Event	F-Vesely	Birnbaum	B-Proshan
1	Auxiliary electrical equipmen	0.48076054	1	0.48057014
2	Electrical power equipment	0.19415521	1	0.19421518
3	Thermal equipment	0.16885379	1	0.16890592
4	Mechanical equipment	0.10133031	1	0.10138056
5	Pneumatic equipment	0.054900152	1	0.054928194

c) Criteria of importance for basic events

Figure 4. Results provided by ITEM Toolkit.

It is obvious that, first, we will consider the most influential path, figure 3. This is represented by the possibility of failure of auxiliary electrical equipment. On the other hand, the figure 2e shows that the control, signaling and control devices are more susceptible to malfunction in this equipment. Under these circumstances, an evaluation of all the paths within the fault trees and a hierarchy made should be made, in order of importance in terms of the possibility of occurrence of faults. Under these circumstances, it will be known on which systems or components to act first for repair interventions, in order to reduce the chance of failure. On the other hand, the cost of these measures should not be too high. Consequently, an assessment is made to diminish the chances of manifesting primary events or influencing them through their gates on the top event.

Figure 4a shows the magnitude of the probability of failure (availability at time t), the frequency, the risk, the reliability, etc., which characterize the top event. All sizes presented here are important and should be considered from the perspective of the assumed risk. Please note here that, for the intermediate diagrams in Figure 2, ITEM Toolkit also provides data of this type.

Figure 4b shows the list of base events in order of their (unfavorable) contribution to the likelihood and frequency of occurrence of the top event.

Figure 4c shows the list of base events and the importance criteria for their contribution are given. The measurement of importance based on the F-Vesely criterion (Fussell-Vesely) is the contribution of that event to the failure of the system. The Birnbaum criterion applied to an event is a measure of the susceptibility of the system's failure, taking into accounts the failures / failures of the components or the probability of failure in each event, whether basic or intermediate. Measuring the significance of the event based on the B-Proshan criterion (Barlow-Proshan) takes into account (in its calculation) different sequence of failures in primary or intermediate events.

5. Conclusions

1. The "fault tree" is one of the most commonly used methods for reliability analysis and for calculating the probability of failure.
2. The purpose of the fault tree analysis is to evaluate the likelihood of a top event occurring using analytical and statistical methods. Fault tree resolution involves knowledge of system reliability data, such as quantitative and maintenance data, probability of failure, failure rate, time to failure and repair rate.
3. Building a fault tree model can provide insight into the system that highlights potential flaws.
4. The ultimate goal is to analyze reliability but also to prevent defects based on fault tree type charts.
5. In the case of the analysis in this paper, a hierarchy table can be made that contains all the paths leading to system failure. Under these conditions, it will be possible to know which components, sub-systems or systems first act or intervene by monitoring or repair to reduce the probability of inoperative locomotion.

6. References

- [1] Stamatelatos M 2002 Fault Tree Handbook with Aerospace Applications *Prepared for NASA Office of Safety and Mission Assurance, NASA Headquarters Washington August* DC 20546
- [2] Jinglun Z and Quan S 1998 Reliability analysis based on binary decision diagrams *Journal of Quality in Maintenance, Engineering* **4 No. 2** pp. 150-161
- [3] Hosseini H.S.M. and Takahashi M 2007 Combining Static/Dynamic Fault Trees and Event Trees Using Bayesian Networks *F. Saglietti and N. Oster (Eds.): SAFECOMP 2007 LNCS* **4680** pp. 93-99
- [4] Goanță V and Palihovici V 2006 *Expertize în Ingineria Mecanică* Ed. Tehnopress – Iași
- [5] Carlier J and Lucet C 1996 A decomposition algorithm for network reliability evaluation *Discrete Appl. Math.* **65** pp. 141-156