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A Practical Solution for HVAC Life Estimation Using Failure Models

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Abstract **– Heating, ventilation, and air conditioning (HVAC) is the technology of indoor and vehicular environmental comfort. The objectives of HVAC systems are to provide an acceptable level of occupancy comfort and process function, to maintain good indoor air quality, and to keep system costs and energy requirements to a minimum. Performing a reliability prediction provides an awareness of potential equipment degradation during the equipment life cycle. Reliability under a range of conditions is one of the most important requirements to guarantee in HVAC installed on trains. Predicting the reliability of mechanical equipment requires the consideration of its exposure to the environment and subjection to a wide range of stress levels such as impact loading. Often analysist find an unavailability of failure data in handbooks and problems for acquiring data for mechanical components, so the mentioned problems demonstrates the need for reliability prediction models. The paper deals with a HVAC installed on a high-speed train and evaluates the failure rates through the failure rate models suggested by the handbooks in order to assess a model which includes all the mechanical parts.**

Keywords – Reliability; Diagnostic; Railway engineering; failure rate; HVAC; useful life

I. INTRODUCTION

A reliability prediction is performed in the early stages of a development program to support the design process [1]–[3]. Performing a reliability prediction provides for visibility of equipment reliability requirements in the early development phase. A well-done prediction also provides an awareness of potential equipment degradation during the equipment life cycle. A commonly accepted method for predicting the reliability of mechanical equipment based on data banks has not been possible because of the wide dispersion of failure rates which occur for apparently similar components. Inconsistencies in failure rates for mechanical equipment are the result of several basic characteristics of mechanical components[1], [4]:

- Individual mechanical components such as valves and gearboxes often perform more than one function and failure data for specific applications of nonstandard components are seldom available.
- Failure rates of mechanical components are not usually described by a constant failure rate distribution because of wear, fatigue and other stress-related failure mechanisms resulting in equipment degradation. Data gathering is complicated when the constant failure rate distribution cannot be assumed and individual times to failure must be recorded in addition to total operating hours and total failures.
- Mechanical equipment reliability is more sensitive to loading, operating mode and utilization rate than electronic equipment reliability. Failure rate data based on operating time alone are usually inadequate for a reliability prediction of mechanical equipment
- Definition of failure for mechanical equipment depends upon its application. Lack of such information in a failure rate data bank limits its usefulness.

The above listed problems associated with acquiring failure rate data for mechanical components demonstrates the need for reliability prediction models that do not rely solely on existing failure rate data banks[5], [6]. Predicting the reliability of mechanical equipment requires the consideration of its exposure to the environment and subjection to a wide range of stress levels such as impact loading. The combination of these factors permits the use of engineering design parameters to determine the design life of the equipment in its intended operating environment and the rate and pattern of failures during the design life. The equation derived from design information and experimental data as contained in published technical reports and journal, there were simplified to retain those variables affecting reliability as indicated from field experience data. Modification factors were then compiled for each variable to reflect its quantitative impact on the failure rate of an individual component part. The total failure rate of the component is the sum of the failure rates for the component parts for a particular time period in

question.
The most critical components of an Heating, Ventilation and Air Conditioning (HVAC) system are the compressor, the heat exchanger and the blower[7], [8]. In order to improve the failure rate of these items, the relative failure models have been analysed in the following sections.

II. HVAC FOR HIGH SPEED TRAIN

Efficient temperature regulation is becoming a necessity in the face of strong competition and overcrowded carriages [9]–[11]. As take-up increases and the technology behind high-speed rail becomes even more viable in a wide range of regions, passengers are accepting trains as a primary form of mass transit. As such, competition is growing and rail operators are looking for new ways to enrich the passenger experience and separate themselves from the competition [12]. With hundreds of commuters often crowded onto train carriages during peak hours, passenger comfort is a major concern for operators around the world. The fear is that customers driven to the edge by sweltering temperatures and claustrophobic conditions might well decide that risking traffic jams on the road is a more attractive option after all. While train carriages can mitigate some of the misery of overcrowding with good design and punctual service, an efficient heating, ventilation and air conditioning system (HVAC) is the best way of regulating temperature and air quality on crowded trains battling with accumulated body heat[13]. One of the most important guarantees that rail operators or manufacturers should look for when deciding on air conditioning systems either for retro fit into existing rolling stock or to install on new carriages is reliability under a range of conditions. There is no single HVAC system appropriate to all rail situations, so a great deal of thought needs to be put into the beginning stages of an air conditioning upgrade project[9], [14]. Parameters such as air temperature and humidity at different times of day and year, the changing levels of heat transference into the carriage through windows, air flow and noise levels should be measured and referenced with relevant industry standards, which gauges acceptable levels of passenger comfort for air conditioned rolling stock. As well as being a vital component of passenger comfort, HVAC systems can also play a central role in onboard safety. Sophisticated air control systems can manage the flow of air so that in the event of a fire, the spread of smoke among passengers is minimised.

III. COMPRESSOR MODEL

A compressor system is made up of one or more stages. The compressor compresses the gas, increasing its temperature and pressure [1], [15]. The total compressor may be comprised of elements or groups of elements in series to form a multistage compressor based on the change in temperature and pressure across each stage.
Every compressor to be analyzed for reliability will be a unique design and comprised of many different components. The following equation will need to be modified for the particular compressor design.

$$\lambda_C = (\lambda_{FD} \cdot C_{SF}) + \lambda_{CA} + \lambda_{BE} + \lambda_{VA} + \lambda_{SE} + \lambda_{SH} \qquad (1)$$

Where:
- λ_C is the total failure rate of compressor
- λ_{FD} is failure rate of fluid driver
- C_{SF} is the compressor service multiplying factor
- λ_{CA} is the failure rate of the compressor casing
- λ_{BE} is the total failure rate of compressor shaft bearings
- λ_{VA} is the total failure rate of control valve assemblies
- λ_{SE} is the total failure rate of compressor seals
- λ_{SH} is the failure rate of compressor shaft

Different compressor configurations such as piston, rotary screw and centrifugal have different parts within the total compressor and it is important to obtain a parts list for the compressor prior to estimating its reliability. The failure rate for each part comprising the compressor must be determined before the entire compressor assembly failure rate, λ_C, can be determined. Failure rates for each part will depend on expected operational and environmental factors that exist during compressor operation. It is important to consider each compressor stage in a multi-stage compressor as a separate compressor with the total failure rate as the sum of the failure rates for the individual stages. According to [1] and from the compressor datasheet, the HVAC compressor is a reciprocating, so the corresponding value of the failure rate of the factors are reported in table 1. The total failure rate of compressor shaft bearings is:

$$\lambda_{BE} = \lambda_{BE,B} \cdot C_R \cdot C_V \cdot C_{CW} \cdot C_t \cdot C_{SF} \cdot C_C \qquad (2)$$

Where:
- λ_{BE} is the total failure rate of bearing
- $\lambda_{BE,B}$ is base failure rate
- C_R is life adjustment factor for reliability
- C_V is multiplying factor for lubricant
- C_{CW} is multiplying factor for water contaminant level
- C_t is multiplying factor for operating temperature
- C_{SF} is multiplying factor for operating service conditions
- C_C is multiplying factor for lubrication contamination level

Table 1 – Factors for the evaluation of the compressor failure rate

λ_{FD}	$6.25 \cdot 10^{-6} failure/h$
C_{SF}	1.4
λ_{CA}	$0.010 \cdot 10^{-6} failure/h$

λ_{SE}	$5.47 \cdot 10^{-8} failure/h$
λ_{SH}	$0.89 \cdot 10^{-8} failure/h$

Table 2 – Factors for the evaluation of the bearing failure rate

$\lambda_{BE,B}$	$0.96 \cdot 10^{-6} failure/h$
C_R	1
C_t	1
C_{SF}	1
C_V	0.6
C_{CW}	5
C_C	1.8

Taking into account the values of the influence factors included in table 2, then the total failure rate of bearing is:

$$\lambda_{BE} = 5.18 \cdot 10^{-6} failure/h \quad (3)$$

The total failure rate of control valve assemblies is given by:

$$\lambda_{VA} = \lambda_{PO} + \lambda_{SE} + \lambda_{SP} + \lambda_{SO} + \lambda_{HO} \quad (4)$$

Where:

- λ_{VA} is the total failure rate of total valve assemblies
- λ_{PO} is the failure rate of poppet assembly
- λ_{SE} is the failure rate of the seals
- λ_{SP} is the failure rate of spring(s)
- λ_{SO} is the failure rate of solenoid
- λ_{HO} is the failure rate of valve housing

Therefore, considering the failure rates of the valve subitems provided in table 3, the total failure rate of total valve assemblies is:

$$\lambda_{VA} = 1.66 \cdot 10^{-6} failure/h \quad (5)$$

The total failure rate of compressor is:

$$\lambda_C = 1.56 \cdot 10^{-5} failure/h \quad (6)$$

The duty cycle of the compressor, which is 30%, must be taken into account in order to obtain a more accurate evaluation. Usually, failure rates of components implemented in railway applications are expressed in failure/km or for sake of simplicity FPMK (Failure Per Million Kilometers). Considering an approximate annual distance for high speed train of half a million kilometers, the failure rate of the compressor becomes:

$$\lambda_{Compressor} = 8.22 \cdot 10^{-2}\ FPMK \quad (7)$$

Considering that the failure rate provided by the manufacturer of the HVAC "MERAK" coming from field data and internal company tests is:

$$\lambda_{Compressor,merak} = 7.79 \cdot 10^{-2} FPMK \quad (8)$$

Comparing the two expression (7) and (8), the new equation calculated by the compressor model provides a value higher than that given by the compressor designer.

Table 3 – Factors for the evaluation of the valve failure rate

λ_{PO}	$2.52 \cdot 10^{-11} failure/h$
λ_{SE}	$5.47 \cdot 10^{-8} failure/h$
λ_{SP}	$1.19 \cdot 10^{-7} failure/h$
λ_{SO}	$1.4774 \cdot 10^{-6} failure/h$
λ_{HO}	$0.01 \cdot 10^{-6} failure/h$

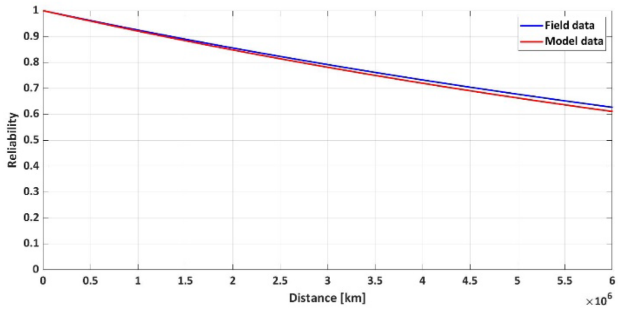

Figure 1 – Reliability curves of the compressor assembly calculated through Merak data and compressor model

The main reason of this decrease is because the model equation considers several variables, while the merak value is a field data.

Figure 1 shows the reliability curves relative to the failure rates of equations (7) and (8), the blue line represents the reliability calculated with the manufacturer "MERAK" failure rate while the red one the reliability calculated with the compressor model. The model curve decreases faster because its failure rate is higher than the MERAK failure rate. Anyway the difference of the two curves is limited, at the beginning the curves are approximately equal then they decrease with different exponential decay rates.

IV. HEAT EXCHANGER MODEL

Heat exchangers are essential part of any kind of HVAC system nowadays. The main function of a heat recovery system is to increase the energy efficiency by reducing energy consumption and also by reducing the cost of operating by transferring heat between two gases or fluids, thus reducing the energy bills. In heat exchangers, as the name suggests, there is a transfer of energy from one fluid to another. Both these fluids are physically separated and there is no direct contact between the fluids. There are different types of heat exchangers such as shell and tube, U tube, shell and coil, helical, plate etc. The transfer of heat can be between steam and water, water and steam, refrigerant and water, refrigerant and air, water and water. The HVAC system's compressor generates heat by compressing refrigerant. This heat can be captured and used for heating domestic water. For this purpose a heat exchanger is placed in between the compressor and the condenser. The water that is to be heated is circulated

though this heat exchanger with the help of a pump whenever the HVAC system is on.
A heat exchanger is composed by a tube and an expansion valve. The failure rate of a fluid conductor is extremely sensitive to the operating environment of the system in which it is installed as compared to the design of the pipe. Each application must be evaluated individually because of the many installation, usage and maintenance variables that affect the failure rate. The failure of a piping assembly depends primarily on the connection joints and it can be estimated with the following equation [1]:

$$\lambda_P = \lambda_{P,B} \cdot C_E = 2.2 \cdot 10^{-6} failure/h \tag{9}$$

Where:

- λ_P is the failure rate of pipe assembly
- $\lambda_{P,B}$ is the base failure rate of pipe assembly, which is $1.57 \cdot 10^{-6} failure/h$
- C_E is the environmental factor equal to 1.4

For the expansion valve the failure rate is provided by [1] and it is $\lambda_{VA} = 4.5 \cdot 10^{-6} failure/h$. Therefore, the whole failure rate of the heat exchanger is given by the sum of the failure rate of the pipe and the failure rate of the valve, each one weighted on its own duty cycle. In particular, the duty cycle of the pipe is 80% while the duty cycle of the valve is 30%. Consequently, the failure rate of the heat exchanger is given by:

$$\lambda_{heat\ exchanger} = 3{,}11 \cdot 10^{-6} failure/h \tag{10}$$

After the conversion in FPMK the failure rate of the heat exchanger is:

$$\lambda_{heat\ exchanger} = 5{,}4 \cdot 10^{-2} FPMK \tag{11}$$

While, the failure rate provided by MERAK based on field data is:

$$\lambda_{heat\ exchanger,merak} = 4{,}124 \cdot 10^{-2} FPMK \tag{12}$$

Figure 2 shows the two different reliability curves, the blue one is related to MERAK data while the red one is related to the model. The model line results a pessimistic estimation also for this component.

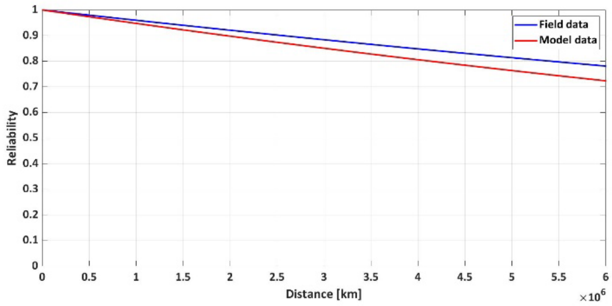

Figure 2 – Reliability curves of the heat exchanger assembly calculated through Merak data and heat exchanger model

The difference between the two curves now is very low, probably for a simpler element like the heat exchanger, the manufacturer MERAK and model lead to a similar result.

V. BLOWER MODEL

One of the most common downfalls of installed HVAC systems is their inability to distribute the correct amount of air to where it's needed most. When systems are restrictive, or blowers aren't powerful enough, the air simply doesn't make it to where it needs to go.
A blower is composed by an AC motor, two bearings and a fan. The failure rate of a motor is affected by such factors as insulation deterioration, wear of sliding parts, bearing deterioration, torque, load size and type, overhung loads, thrust loads and rotational speed. The failure rate model developed is based on a fractional or integral horsepower AC type motor. The reliability of an electric motor is dependent upon the reliability of its parts, which may include bearings, electrical windings, armature/shaft, housing, gears and brushes. Failure mechanisms resulting in part degradation and failure rate distribution (as a function of time) are considered to be independent in each failure rate model. The total motor system failure rate is the sum of the failure rate of each of the parts in the motor:

$$\lambda_{AC-motor} = (\lambda_{M,B} \cdot C_{SF}) + \lambda_{WI} + \lambda_{ST} + \lambda_{AS} + \lambda_{BE} + \lambda_{GR} + \lambda_C \tag{13}$$

Where:

- $\lambda_{AC-motor}$ is the total failure rate for the motor system
- $\lambda_{M,B}$ is the base failure rate of motor
- C_{SF} is the motor load service factor
- λ_{WI} is the failure rate of electric motor windings
- λ_{ST} is the failure rate of the stator housing
- λ_{AS} is the failure rate of the armature shaft
- λ_{BE} is the failure rate of the bearing evaluated using equation (2) and the suitable factors
- λ_{GR} is the failure rate of gears
- λ_C is the failure rate of capacitor

Therefore, considering the parameters included in table 4, the failure rate of the AC motor is:

$$\lambda_{AC-motor} = 1{,}044 \cdot 10^{-5} failure/h \qquad (14)$$

As seen before, the bearings are modelled by equation (2).

Table 4 – Factors for the evaluation of the AC motor failure rate

$\lambda_{M,B}$	$6.9 \cdot 10^{-6} failure/h$
C_{SF}	1
λ_{WI}	$1.5 \cdot 10^{-6} failure/h$
λ_{ST}	$0.1 \cdot 10^{-8} failure/h$
λ_{AS}	$0.089 \cdot 10^{-6} failure/h$
λ_{BE}	$1.87 \cdot 10^{-6} failure/h$
λ_{GR}	$5.39 \cdot 10^{-8} failure/h$
λ_{C}	$3.24 \cdot 10^{-8} failure/h$

Considering the suitable influence factors for the blower, the failure rate of the bearing is:

$$\lambda_{bearing} = 1 \cdot 10^{-6} failure/h \qquad (15)$$

The fans are modelled in according to MIL-STD-217F [16] by:

$$\lambda_{Fan} = \left[\frac{t^2}{\alpha_B^3} + \frac{1}{\alpha_W}\right] failure/h \qquad (16)$$

Where:

- t is the motor operating time period
- α_B the Weibull characteristics life for motor bearing
- α_W the Weibull characteristics life for motor windings

Considering a temperature of 25°C, the motor operating time period is t=24h, the Weibull characteristics life for motor bearing is $\alpha_B = 60000$ and the Weibull characteristics life for motor windings is $\alpha_W = 1.2 \cdot 10^6$. Therefore the failure rate of the fan is:

$$\lambda_{Fan} = 8.3334 \cdot 10^{-7} failure/h \qquad (17)$$

The whole blower failure rate is given by the sum of the failure rates of its components, so:

$$\lambda_{Blower} = \lambda_{AC-motor} + 2 \cdot \lambda_{bearing} + \lambda_{Fan} = 1.328 \cdot 10^{-5} failure/h \qquad (18)$$

Then considering the duty cycle of 100% and the conversion in failure/kilometer:

$$\lambda_{Blower} = 2.33 \cdot 10^{-1}\ FPMK \qquad (19)$$

Considering that the failure rate provided by MERAK is:

$$\lambda_{Blower,merak} = 7.97 \cdot 10^{-2}\ FPMK \qquad (20)$$

Figure 3 shows the two reliability curves, the blue one is related to the MERAK data and the red one is related to the model data.

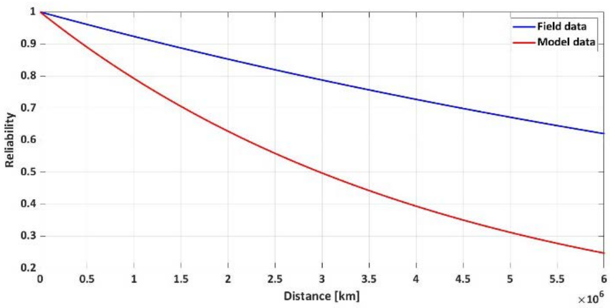

Figure 3 – Reliability curves of the blower assembly calculated through Merak data and blower model

Like for the other components, the reliability calculated through the models provides a pessimistic reliability trend respect the reliability calculated with the field data provided by MERAK.

VI. COMPARISON BETWEEN FIELD DATA AND MODEL DATA

A comparison between the failure estimation of the previous paragraphs and the failure data provided by the manufacturer of the HVAC has been carried out in order to investigate how the model-based failure rates affect the reliability trend of the whole system.

The model-based failure rates of compressor, blower and heat exchanger are used to calculate the whole HVAC reliability together with the failure rate estimation of the other components, which make up the system.

Figure 4 shows two reliability curves, the blue trend is related to the MERAK data while the red one is calculated with the above-mentioned analysis, where the failure rate of the components is calculated using the failure models.

It's possible to note that the model-based failure rates contribute to reduce the reliability and have an important contribution to the whole system reliability.

Figure 5 shows the absolute percentage difference between the two curves, the peak of the curve is 10% for distances between $1.5 \cdot 10^6$ km and $2 \cdot 10^6$ km (around 3 years and 5 years).

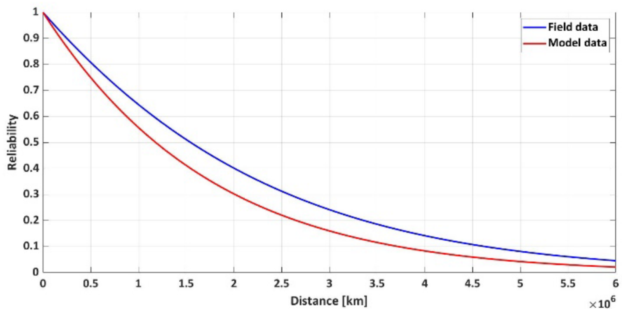

Figure 4 – Reliability curves of the HVAC passenger assembly calculated through Merak data and model data

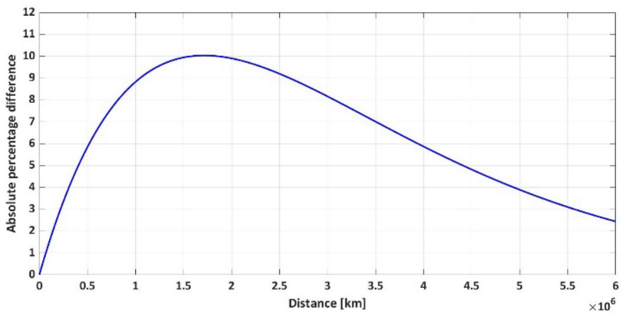

Figure 5 – Absolute percentage difference of reliability curves of the HVAC passenger assembly calculated through Merak data and model data

Table 5 – Reliability data provided by Merak and reliability models

Distance [km]	time	R_{merak}	R_{model}	Difference
$0.5 \cdot 10^6$	1 year	0,80	0,75	5%
$1 \cdot 10^6$	2 years	0,64	0,56	8%
$2 \cdot 10^6$	4 years	0,40	0,30	10%
$3 \cdot 10^6$	6 years	0,24	0,16	8%
$4 \cdot 10^6$	8 years	0,14	0,08	6%
$5 \cdot 10^6$	10 years	0,08	0,04	4%
$6 \cdot 10^6$	12 years	0,05	0,02	3%

In according to the exponential trends, at the beginning the two curves are very similar and the difference is limited, then there's a peak, after that the difference value decreases slowly and the final value, for $6 \cdot 10^6$ km, is 2,5%.
The models provide, for the three cases, pessimistic results and their obtained reliabilities are lower than the reliabilities related to the designer data, necessarily the whole reliability will result lower than the reliability with the field failure rates.
Table 5 contain all data related to the HVAC reliability, in particular the third column contain some reliability values calculated with field data, while the fourth column shows the reliability value calculated with the models exposed above.

VII. CONCLUSION

The paper deals with a Heating, ventilation, and air conditioning (HVAC) mounted on a high-speed train. The architecture of an HVAC system includes several components, some of that are: a fan (blower) to circulate the supply and return air, heat exchangers such as a refrigerant evaporator and condenser coil for cooling or a furnace for heating and a compressor to compress the refrigerant vapour and pump the refrigerant around the refrigeration system.
A detailed study on the failure rates of the HVAC most critical components is presented in this paper. Compressor, heat exchanger and blower show a model-based reliability lower than the field data reliability provided by the manufacturer of the HVAC "MERAK". The final analysis shows how the model failure rates affect the whole HVAC reliability; the result is that the failure model analysis reduces the whole reliability up to a maximum difference of 10%. The model-based failure rate provides a pessimistic result because it considers every possible failure modes and failure mechanisms of each subitem that make up the component. Despite this, it could be not so realistic since it doesn't properly consider the real operating conditions of the system under test. Quite the opposite, the reliability evaluated using the field data takes into account the real context of the HVAC but some of the failure mechanisms might be not occur during the observed time interval. For these reasons, it is fundamental to analyze the reliability of such complex system integrating both techniques.

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