Proceedings of COBEM 2007
Copyright © 2007 by ABCM

19th International Congress of Mechanical Engineering
November 5-9, 2007, Brasília, DF

RELIABILITY ANALYSIS IN MECHANICAL FAILURE DIAGNOSIS FOR AUTOMOTIVE AIR CONDITIONING SYSTEMS

Sérgio Libanio Campos, slcampos@cefet-rj.br
José Luiz Fernandes, jluizfernandes@gmail.com
Centro Federal de Educação Tecnológica Celso Suckow da Fonseca (CEFET-RJ)
Departamento de Engenharia de Produção - Departamento de Pesquisa e PósGraduação
Av. Macacanã, 229 – Maracanã - Rio de Janeiro

José Alberto Reis Parise, parise@mec.puc-rio.br
Pontifica Universidade Católica do Rio de Janeiro (PUC-RJ)
Departamento de Engenharia Mecânica
Rua Marquês de São Vicente , 225 – Rio de Janeiro

Abstract. *The present paper aims at evaluating, through reliability analysis, what are the most relevant variables to be observed when automotive air conditioning systems are subjected to typical mechanical failures. A review identified the most common mechanical failures in automotive A/C systems. Tables were elaborated based on data acquired from a test bench. A vapor compression refrigeration cycle, simulating an automotive air conditioning system, worked fault-free and then subjected to the most common failures that occur is such systems. Based on the experimental data acquired and on the use of the software "Statistica", it was possible to elaborate functions that define what are the operating variables, of the automotive A/C system, that are more important to be considered during the failures treated in the present work, allowing for a more straighfoward diagnosis to be carried out by technicians.*

Keywords*: Reliability, Automotive Air Conditioning, Fault Diagnosis*

1. INTRODUCTION

According to Bhatti (1999), automotive air conditioning systems have, besides promoting comfort, an important role on car safety – defogging – and, nowadays, they belong to the group of the most solicited optional items to the vehicle in the world market. According to Brown et al. (2002) and Kiatsirioroat and Euakit (1997), their environmental impact can be reduced by the use of environmentally benign refrigerants, improved energetic efficiency and proper maintenance procedures. Concerning refrigerants, CFC12 has been replaced, since 1995, by HFC134a which, in spite of being ozone-friendly, presents an appreciable global warming impact. Other refrigerants, like CO_2 and refrigerant mixtures, have been considered for replacement in the near future (Brown et al., 2002; Kiatsirioroat and Euakit, 1997).

The predominantly used refrigeration cycle in motor-vehicle air conditioning systems is the engine-driven vapor compression cycle – see, for example, Lee (2000). Maintenance is of crucial importance for the proper operation of such systems. Fault and performance diagnosis is mostly done with the help of basic instrumentation, which comprises two pressure manometers, for condensing and evaporating pressures, and two temperature sensors, for ambient and supply air temperatures. The basic combination of these four readings provides the technician with the information for a fault and performance diagnosis. Note that not even ambient air humidity is measured, in spite of its effect on system performance (Whitchurch, 1997).

2. BASICS OF AIR CONDITIONING FAILURE ANALYSIS

2.1. System components

The vapor compression cycle of an automotive air conditioning system is composed, according to Fig. 1, by the compressor, condenser, expansion device, fans, controls, filter-dryer, hoses and connections. The compressor is of the positive displacement reciprocating multi-piston wobble-plate type. Condenser is, of course, air cooled and is placed ahead of the engine radiator. The evaporator provides cool air to the cabin. The expansion device can be a thermal expansion valve (TXV) or a fixed area orifice.

2.2. Expected system failures

According to Von Glehn and Badan (1999), typical system failures include: ice formation on evaporator surface, faulty driving clutch, slippery compressor driving belt, obstructed filter-dryer, obstructed expansion device, ice formation on expansion device, defective thermostat control, excess fouling on heat exchangers, non-condensable air in refrigerant circuit, excessive or insufficient refrigerant charge, leaking compressor seals, refrigerant leakage and refrigerant-side fouling. All these failures and malfunctions reflect on the measured values of the condensing and evaporating pressures as well as the temperature of the vehicle cabin, T_{cab}, and of the cold air supplied to it, T_{sup}. These are the measured parameters accessible to the technician.

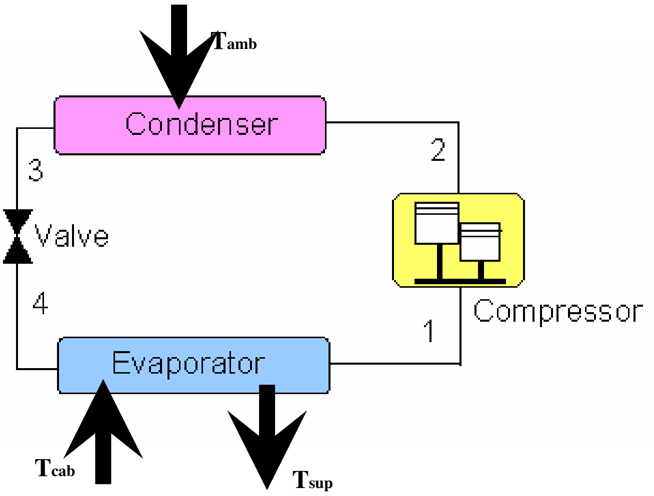

Figure 1. Vapor compression refrigeration cycle.

The present paper will focus on failure by heat exchanger blockage, condenser or evaporator, due to excessive fouling or due to the presence of an object or debris, partially obstructing the air passage.

2.3. Simulation of system failures

Campos et al. (2006) developed a basic simulation model to analyze mechanical failures in automotive air-conditioning systems. Figs. 2 and 3 show the predicted condensing and evaporating pressures with reducing heat exchanger effectiveness, simulating a blockage consequence. The simulation effort was carried out for three different ambient air temperatures. The observed trends agree with the behavior expected from practice.

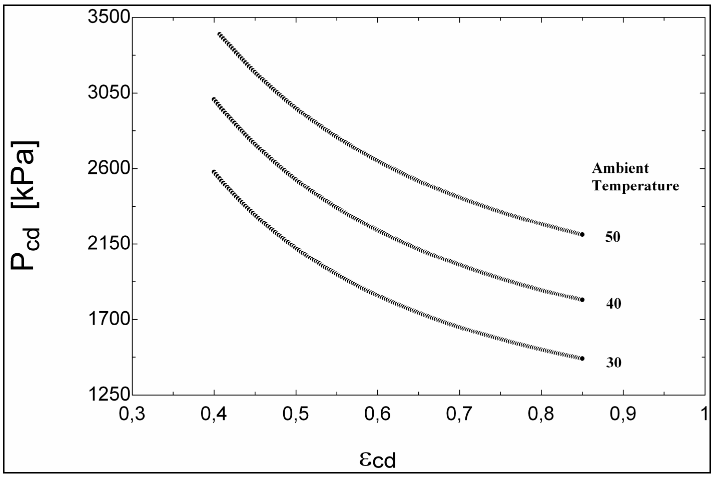

Figure 2. Variation of the condensing pressure with condenser effectiveness and ambient temperature.

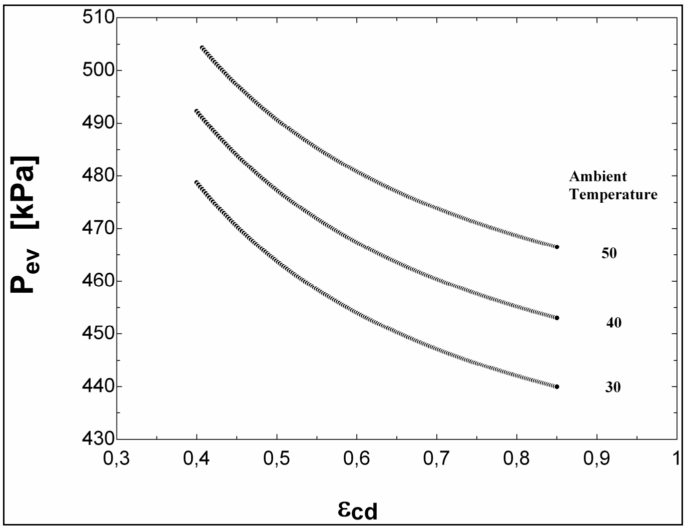

Figure 3. Variation of the evaporating pressure with condenser effectiveness and ambient temperature.

3. EXPERIMENTS

3.1. Methodology for planning experiments

According to Montgomery (1997), the definition and choice of variables for an experiment, as well as responses of the factorial design of experiments do not belong to the statistical field, being related to the specialty of the experiment. This technique is subject to certain factors, which are not predicted by the experiment. Due to this, the values chosen as main parameters for the analysis should be carefully measured to avoid systematic errors in the results.

According to Fernandes et al. (2004 e 2005), when one performs experiments, he/she aims at studying the effect of one or more factors on a response variable. Each factor contributes to predefined amounts or categories named levels. Every combination of levels of the different factors is termed a combination of treatments. The set of treatment combinations used determines the corresponding experimental design, which is termed a factorial experiment.

For the factorial experiment with two levels, when one analyses, for example, five parameters, the method is named 2^6. The method uses 64 treatments or run combinations for analyzing the parameters of interest. In the case when each treatment combination is repeated *r* times, then the total number of runs will be 64*r. (Montgomery 1997).

According to Draper (1998), the 2^k factorial experiment may be expressed by Eq. 1, where $\hat{\mathbf{y}}$ is the estimated or fitted value for each response, $\hat{\boldsymbol{\alpha}}$ is the estimate of the overall model mean and $\hat{\boldsymbol{\alpha}}_{\mathbf{i,j..k}}$ is half the estimate for the true interaction effect of factors *i, j, ..., k*. It should be emphasized that the parameters of Eq. 1 are unknown, and so they should be estimated from the collected data.

$$\hat{y} = \hat{\alpha} + \frac{1}{2}\left[\sum_{i=1}^{k}\hat{\alpha}_i x_i + \sum_{i=1}^{k}\sum_{j=1}^{k}\hat{\alpha}_{ij} x_i x_j + \ldots + \hat{\alpha}_{12\ldots k} x_1 x_2 \ldots x_k\right] \qquad (1)$$

$\hat{\boldsymbol{\varepsilon}} = \mathbf{y} - \hat{\mathbf{y}}$ is the difference between the observed and the fitted value, and is called the residue. If the effect of the *i*-th factor is not significant, then the α_i will be equal to zero. However, due to the experimental error, the estimate $\hat{\boldsymbol{\alpha}}_{\mathbf{i}}$ will not necessarily be equal to zero: it will take a small value, instead. A hypothesis test, like the F test of the analysis of variance (ANOVA), for instance, will allow for deciding with a slight error (5%, in general) whether $\hat{\boldsymbol{\alpha}}_{\mathbf{i}}$ is significant, that is, equal to zero or not.

3.2. Experimental apparatus and data acquisition

A didactic set up, made by Didacta Italy, model T66D, as shown in Fig. 4, was employed as the test apparatus. Values of pressure and temperature, taken in different points of the refrigerant and air circuits, as well as compressor torque voltage and electric current, were measured for different operational conditions, including those simulating system failures. Air stream velocities were also measured with an anemometer. The experiments provided the necessary data for the verification, through the software "Statistica"®, what are the most relevant variables to be taken into account by technicians when the system is working under failure. In order to achieve this, it was necessary to establish and define the control variables and respective answer variables. The selected variables are shown in the Table 1.

Table 1. Selected variables

CONTROL VARIABLES		ANSWERS VARIABLES	
Compressor rotational speed	(rpm)	Compress torque	(T)
Condenser thermal load	(CT_{CD})	Condensing pressure	(P_A)
Evaporator thermal load	(CT_{EV})	Evaporating pressure	(P_B)
Internal fan velocity	(N)	Cabin temperature	(T_{Cab})
Condenser blockage	(Imp_{CD})		
Evaporator blockage	(Imp_{EV})		

Figure 4. Bench of Tests Model T66D

The experiments were carried, besides under normal operating conditions, under the following conditions:

a) Varying compressor rotational speed, simulating the inherently transient operation of the engine, or slippery driving clutch;
b) Varying condenser thermal load, simulating severe operational conditions such as traffic jams under ambient elevated ambient temperatures;
c) Varying evaporator thermal load, simulating, for example, a vehicle under the sun;
d) Varying evaporator frontal air flow area, simulating blocked air filter or even operation under ice formation on evaporator heat transfer surface;
e) Varying condenser frontal area, simulating scale accumulation on condenser heat transfer surface or the presence of mud, insects or other objects.

4. RESULTS

The experiments were carried out for each operational condition, with compressor rotational speed varying from 800 rpm, idle, to 3000 rpm, maximum speed allowed by the test bench. The answer variables are presented in Table 2, below.

As an example of the experiments, Figure 5 displays the variation of the compressor discharge pressure with compressor and internal fan speeds, under blocked condenser heat transfer area conditions.

The values obtained in the all experiments, were used as input to the software “Statistica” in order to get, through the statistic method of 2^n experiments with six control variables, 64 combinations of these variables.

Table 2. List of variables obtained in the experiments

Torque	N.m
Electric motor voltage	Volt
Electric motor current	Ampere
Pressure in the condenser inlet	MPa
Pressure in the condenser outlet	MPa
Pressure in the evaporator inlet	MPa
Pressure in the evaporator outlet	MPa
Refrigerant temperature in the condenser inlet	ºC
Refrigerant temperature in the condenser outlet	ºC
Refrigerant temperature in the evaporator inlet	ºC
Refrigerant temperature in the evaporator outlet	ºC
Air temperature in the condenser	ºC
Air temperature in the cabin	ºC

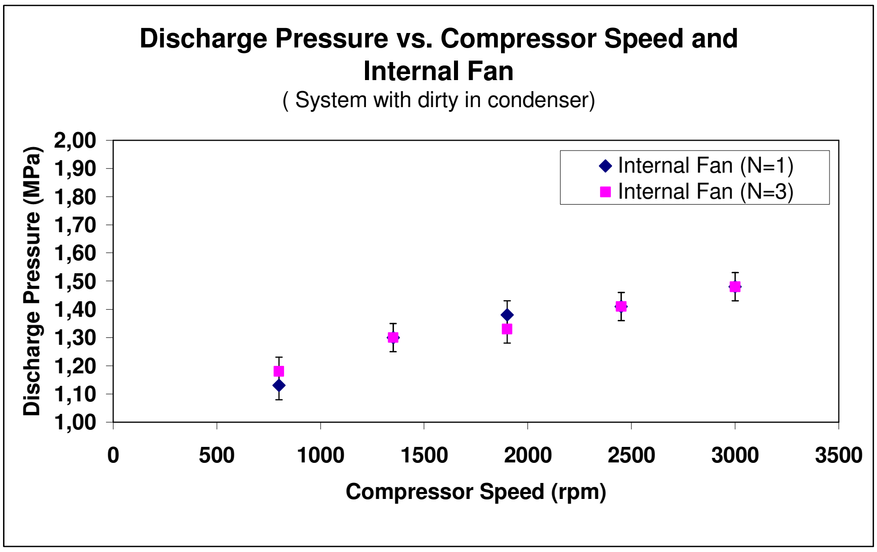

Figure 5. Discharge Pressure vs. Compressor Speed and Internal Fun

The application of the “Statistica”® package on the experimental data provided the reliability functions, Eqs. (2) to (5), that allow for the determination of the most relevant control variables in the air conditioner system (those with greater coefficients). These variables are the ones which should be more carefully evaluated by technicians performing system maintenance. The functions obtained are:

$$Y_T = 3.917 - 10.107\, X_{rpm} + 1.511\, X_{CTCD} - 1.893\, X_{FLOW} - 3.311\, X_{ImpEV} - 2.178\, X_{rpm}.X_{FLOW} + \\ - 3.385\, X_{rpm}.X_{ImpEV} \tag{2}$$

$$Y_{PA} = 2.714 + 3.307\, X_{rpm} - 0.408\, X_{CTEV} + 0.672\, X_{FLOW} + 1.541\, X_{ImpCD} - 0.541\, X_{rpm.}X_{CTEV} + \\ 0.683\, X_{rpm.}X_{FLOW} + 1.413\, X_{rpm.}X_{ImpCD} \tag{3}$$

$$Y_{PB} = - 0.171 - 0.766\, X_{rpm} + 0.173\, X_{CTCD} + 0.120\, X_{CTEV} - 0.102\, X_{FLOW} - 0.194\, X_{ImpEV} + \\ 0.158\, X_{rpm}.X_{CTCD} + 0.116\, X_{rpm}.X_{CTEV} - 0.126\, X_{rpm}.X_{FLOW} - 0.195\, X_{rpm}.X_{ImpEV} \tag{4}$$

$$Y_{Tcab} = 6.667 - 14.229\, X_{rpm} + 17.931\, X_{CTCD} + 6.359\, X_{FLOW} + 20.154\, X_{ImpCD} - 17.081\, X_{ImpEV} + \\ + 14.068\, X_{rpm}\, X_{CTCD} + 15.279\, X_{rpm}\, X_{ImpCD} - 13.806\, X_{rpm}.X_{ImpEV} - 0.725\, X_{CTEV}\, X_{ImpEV} + \\ - 1.307\, X_{FLOW}.X_{ImpEV} \tag{5}$$

where

X_{rpm}	Compressor rotational speed
X_{ImpEV}	Amount of evaporator surface blockage
X_{ImpCD}	Amount of condenser surface blockage
X_{CTEV}	Evaporator thermal load
X_{CTCD}	Condenser thermal load
X_{FLOW}	Evaporator air velocity
Y_T	Compressor input torque
Y_{PA}	Discharge pressure
Y_{PB}	Suction pressure
Y_{Tcab}	Cabin air temperature

In line with the reliability theory, Eqs. (2) to (5) lead to the following conclusions:

a) Compressor torque and condensing and evaporating pressures are most influenced by the compressor rotational speed, which is a control variable;

b) Air cabin temperature is predominantly influenced by the condenser thermal load and blockage variables.

5. CONCLUSION

The conclusions above agree, qualitatively, with the findings of the simulation (Campos et al., 2006). And they also agree with the expected trends from practice - for example, Lee and Yoo (2000). Yet, they are still insufficient to provide technicians and engineers with a comprehensive diagnosis tool.

One should bear in mind that the usual approach used by technicians for the maintenance of automotive air conditioning systems is not totally effective, due to: (i) the uncertainties of their instruments (manometers and thermometers); (ii) the lack of standardization in their procedures; and (iii) the number of variables involved, and required, for a proper diagnosis. It is believed that the approach here proposed addresses the latter reason.

The preliminary results obtained from simulation (Campos et al., 2006), as well as the experiments and the reliability method, confirm the potential of the methodology here presented. It can become a useful tool for the improvement of diagnosis procedures for automotive air conditioning systems.

6. REFERENCES

Bhatti, M.S., 1999, “Evolution of Automotive Air Conditioning – Riding in Comfort: Part II”, ASHRAE Journal, 41(9), September 1999.

Brown, J.S., 2002, Yana-Motta, S.F., Domanski, P.A., “Comparative analysis of an automotive air conditioning system operating with CO_2 and R134a”, International Journal of Refrigeration, vol. 25, pp. 19-32.

Campos, S.L., Fernandes, J.L., Parise, J.A.R., “Mechanical Failure Diagnosis in Automotive Air Conditioning Systems through Thermal Measurements”, IMEKO 2006, XVIII IMEKO WORLD CONGRESS Metrology for a Sustainable Development, Rio de Janeiro, September 2006.

Draper, N.R., 1998, Applied Regression Analysis, Wiley

Fernandes, J.L., Melo, P.F.F., Carvajal, S.R., 2005, “A model of fractional design experiments in aircraft components engine”, 18th International Congress of Mechanical Engineering, November 6-11, Ouro Preto, MG, 2005.

Fernandes, J.L., Melo, P.F.F., Payão, J.C. e Carvajal, S.R., 2004, “Comparative Study of Factorial Design Experiments of Optimal Welding Parameters for Commercial Aircraft Components”, 59º Congresso Internacional da Associação Brasileira de Metalurgia e Materiais (ABM), São Paulo (SP), Brasil, 19 a 22 de julho.

Kiatsiriroat, T., Euakit, T., 1997, “Performance Analysis of an Automobile Air-conditioning System with R22/R124/R152a Refrigerant”, Applied Thermal Engineering, vol. 17, no. 11, pp. 1085-1097.

Lee, G.H., Yoo, J.Y., 2000, “Performance Analysis and Simulation of an Automobile Air Conditioning System”, International Journal of Refrigeration, vol. 23, pp. 243-254.

Montgomery, D.C., 1997, “Design and Analysis of Experiments”, Wiley.

Von Glehn, F.R., Badan, M.A.B.C., 1999, Ar Condicionado para Veículos, 1st edition, Ciclo Engenharia, Goiânia, GO, Brazil, in Portuguese, October 1999.

Whitchurch, M.R., Dunn, W.E., Miller, N.R., 1997, “Humidity Effects in Mobile Air-Conditioning Systems”, Air Conditioning and Refrigeration Center, Report ACRC TR-126, University of Illinois at Urbana-Champaign, August.

7. RESPONSIBILITY NOTICE

The author(s) is (are) the only responsible for the printed material included in this paper.