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DESIGN FOR RELIABILITY: A NEW METHODOLOGY FOR THE EVALUATION OF THE IMPACT OF AUTOMOTIVE EXHAUST EMISSIONS ON THE ENVIRONMENT.

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1 Introduction

Over the past few years more attention has being given to the question of the environment, which has led to various legislations "ad hoc" for different industrial sectors regarding methods of production, use of the product and its final disposal.

The product's working life, rather than the actual disposal of the product, often has greatest effects on the environment [1]: if we consider the problems tied to the emission of pollution in the atmosphere by vehicles with an internal combustion engine we realise that there is much we can do to improve the quality of life from the point of view of bettering the environment in which we live.

In the automotive field, as known, the phase of use of the vehicle contributes heavily to the calculated total of emissions during its life cycle. In this context, the automotive industry finds valid support in the approach proposed by DFE (Design for Environment) in confronting all the problems tied to the new and evermore strict EC directives existing about exhaust emissions.

In this memory a new tool named RAEGIE (Reliability Analysis for Exhaust Gas Impact Evaluation) will be proposed for bettering the characteristics of vehicle's environmental compatibility. It is developed in accordance with a modular approach based on the development and integration of some other innovative methodologies. RAEGIE has been created to be applied to any injection system and catalyser, with the purpose of identifying the malfunctions that influence the increase of emissions in the atmosphere and the products compatibility with the norms in force. The method has been demonstrated by means of an application on two different configurations of injection system and catalyser [2]. This "user friendly" approach, integrated with an experimental activity, could be used as a comparison tool for the better choice between different design solutions allowing the improvement of the vehicle environmental efficiency of injection systems and catalyser with reduction of cost and time resources.

2 Method

The proposed method allows the systematic individuation of failures that could occur on the injection system and catalyser of an automotive vehicle classifying the failure effects in terms of emission variation and defining an intervention priority order for the most critical components.

The aim of the method is to direct designers towards the most efficient solution, from the point of view of environmental impact caused by vehicle emissions. The procedure for the development of the analysis can be summarized in the following stages:

1. Top-down Phase
    - Individuation of Top Events relative to emissions
    - FTA for each Top Event
    - Individuation of components which can cause each Top Event
2. Bottom-up Phase
    - FMEA only on critical components
    - Definition of intervention priority order on critical components by means of IPN (Impact Priority Number)

2.1 Top-down Phase

The first step of the method regards the identification of the events directly responsible for the emission variation (example: wrong fuel mixture composition, high temperature in combustion chamber, misfiring, short fuel remaining time in combustion chamber, etc.). In particular, through this approach it is possible to identify the existing ties among the system components and the associated assemblies and sub-assemblies in terms of reliability, examining all the possible combinations of failures which can lead to the Top Event. At the end of this phase the causes of the failures that lead to the Top Event are determined and in this way it is possible to identify the components which directly or indirectly generate it.

2.2 Bottom-up Phase

A more in depth analysis of the cause-mode-effect can be carried out on the components identified in the previous step. This is done by means of a specific FMEA, suited to the evaluation of the environmental impact by substituting the classic RPN with a new parameter representative of effect's environmental severity related to the critical component. This parameter is called IPN (Impact Priority Number) and is calculated as:

$$\mathbf{IPN = I \times C \times F} \qquad (1)$$

where:

- **Impact (I)**, indicates the importance of the emissions in atmosphere caused by a certain malfunctioning or failure. The value is obtained on the basis of the actual environmental condition and on the effects on human health.
- **Compliance (C)**, indicates how far emissions are from legislation limits and if they exceed them. The value range is created starting from the future standards (Euro 4) or from those now in force. This index is very important, as in the automotive sector legislation is continuously changing and can determine whether a vehicle is put on the market or not.
- **Frequency (F)**, indicates the probability that a certain failure could happen and it depends directly on the component's reliability.

2.2.1 Determination of the Impact Index

The first step in determining this index is to subdivide the environmental damage into different impact categories, that is to say into different environmental effects (i.e. acidification, ecotoxicity, land use, respiratory inorganic, ozone layer, etc..).

Then, considering the different substances which together constitute the total emissions (CO, CO_2, NO_x, PM10…), we will assign to each of them a relevant coefficient for each environmental effect as defined before. These coefficients, shown in figure 1, have been calculated by means of the theory of the Eco-indicators implemented in Sima Prò software.[3, 4, 5]

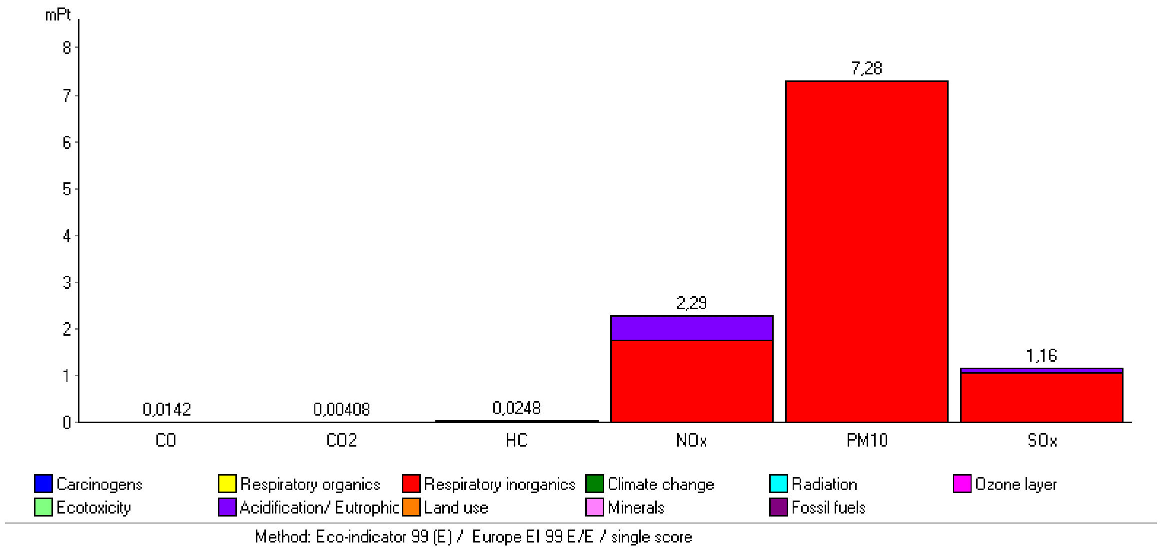

Figure 1. Impact evaluation by means of Ecoindicator 99 implemented in Sima Prò software

In this way it is possible to create a matrix which correlates the emissions with the impact categories, thus to quantify the "absolute" severity of each emission category on the environment. The last column of table 1 shows the total weight, calculated as the sum of the partial weights, of each emission on each impact category.

Table 1. Impact categories

Emissions	Respiratory organic	Respiratory inorganic	Climate change	Acidification/ Eutrophic	Weight (%)
CO		1.42E-5			W_{CO}=0,13
CO_2			4.08E-6		W_{CO2}=0,05
HC	2.48E-5				W_{HC}=0,43
NO_x		0.00173		0.000557	W_{Nox}=21,33
PM10		0.00728			W_{PM10}=67,88
SO_x		0.00106		0.000101	W_{Sox}=10,9

All the values refer to 1g of substance in the air, independent of the source which has produced it. The geographical scenario is Western Europe, in the period 2000/2004.

The next step, in order to define a correlation between the different failure modes and the consequent emissions worsening, is to create the following correlation table where the Top Events are reported in the rows and the emissions in the columns.

Table 2. Failure mode impact coefficients

Emis. / Top Ev.	CO	CO_2	NO_x	HC	PM10	Total
a > 14,7	$Y_{11}\cdot W_{CO}$	$Y_{12}\cdot W_{CO2}$	$Y_{13}\cdot W_{NOx}$	$Y_{14}\cdot W_{HC}$	$Y_{15}\cdot W_{PM10}$	Y_1
a < 14,7	$Y_{21}\cdot W_{CO}$	$Y_{22}\cdot W_{CO2}$	$Y_{23}\cdot W_{NOx}$	$Y_{24}\cdot W_{HC}$	$Y_{25}\cdot W_{PM10}$	Y_2
high T° in c.c.	$Y_{31}\cdot W_{CO}$	$Y_{32}\cdot W_{CO2}$	$Y_{33}\cdot W_{NOx}$	$Y_{34}\cdot W_{HC}$	$Y_{35}\cdot W_{PM10}$	Y_3
misfiring	$Y_{41}\cdot W_{CO}$	$Y_{42}\cdot W_{CO2}$	$Y_{43}\cdot W_{NOx}$	$Y_{44}\cdot W_{HC}$	$Y_{45}\cdot W_{PM10}$	Y_4
< t.r. in c.c.	$Y_{51}\cdot W_{CO}$	$Y_{52}\cdot W_{CO2}$	$Y_{53}\cdot W_{NOx}$	$Y_{54}\cdot W_{HC}$	$Y_{55}\cdot W_{PM10}$	Y_5

Each coefficient Y_{ij} of the matrix can be evaluated by the integration of empiric-analytic considerations and experimental measurements obtained by opportune monitoring of the emission level and of the system parameters.

Then, multiplying these coefficients by the total weight W_j obtained in table 1 and adding all the numbers in a row, it is possible to obtain, in the last column, for the considered Top Event, a severity impact number. The Impact index can be normalized in a decimal scale (table 3) so that all the factors in the IPN will be in a range of 1-10.

Table 3. “I” index evaluation

Y_n	0-5	5-10	10-20	20-30	30-40	40-50	50-60	60-70	70-80	80-100
I	1	2	3	4	5	6	7	8	9	10

2.2.2 Determination of the Compliance Index

This index is important because of the need to confirm the compliance of the design with the European standards. Particularly, in the method proposed we will refer to the different normative Euro 3 and Euro 4 summarised in the table 4 where are reported the emissions limits in relation to the vehicle type.

Table 4. Automotive standards Euro 3 and Euro 4

Limit Value											
Reference Weight RW (kg)			CO (g/km)		HC (g/km)		NO_X (g/km)		$(HC+NO_X)$ (g/km)		PM10
Category	Class		Petrol	Oil	Petrol	Oil	Petrol	Oil	Petrol	Oil	
Euro 3 vehicle	-	all	2,3	0,64	0,20	-	0,15	0,50	-	0,56	0,05
	I	RW<1305	2,3	0,64	0,20	-	0,15	0,50	-	0,56	0,05
	II	1305<RW<1760	4,17	0,80	0,25	-	0,18	0,65	-	0,72	0,07
	III	1760<RW	5,22	0,96	0,29	-	0,21	0,78	-	0,86	0,10
Euro 3 vehicle	-	all	1,0	0,50	0,10	-	0,06	0,25	-	0,30	0,025
	I	RW<1305	1,0	0,50	0,10	-	0,06	0,25	-	0,30	0,025
	II	1305<RW<1760	1,81	0,63	0,13	-	0,10	0,33	-	0,39	0,04
	III	1760<RW	2,27	0,74	0,16	-	0,11	0,39	-	0,46	0,06

As the considered values should not be exceeded, it will be necessary to give the maximum index value to the maximum emission limit. Moreover, it has been estimated that an engine, after 80’000 km, increases the emission according to the following coefficients (table 5).

Table5. Corrective coefficients

Engine category	**Deterioration Coefficient**		
	CO	**HC+NOx**	**PM10**
Petrol Engine	1,2	1,2	*
Oil Engine	1,1	1,0	1,2

If the emission levels exceed the limits of the normative, this is represented in the method by a negative number (-1). This index is also on a decimal scale: we divide the emission limit in 10 parts and then assign to the measured emissions a value in accordance with this table:

Table 6. "C" index evaluation (100% = limit emission value, standards Euro 3 or Euro 4)

%	<10%	<20%	<30%	<40%	<50%	<60%	<70%	<80%	<90%	<100%	>100%
C	1	2	3	4	5	6	7	8	9	10	-1

2.2.3 Determination of the Frequency Index

The index O is directly correlated to the reliability aspects of the system components and represents the likelihood that a specific cause will result in the failure mode [6, 7, 8, 9]. It is expressed by the following formulation:

$$\mathbf{O} = a \times l \tag{2}$$

Where α represents the likelihood of the failure mode happening (%) and λ is the failure rate (failure/km). Even in this case the occurrence is classified in different categories, each one with a different value in the range 1-10 as shown in table 7.

Table 7. "F" index evaluation

Probability	Remote	Low		Moderate			High		Very High	
O	<1 in 200000 km	<1 in 180000 km	<1 in 160000 km	<1 in 140000 km	<1 in 120000 km	<1 in 100000 km	<1 in 80000 km	<1 in 60000 km	<1 in 40000 km	<1 20000 km
F	1	2	3	4	5	6	7	8	9	10

3 Application

The methodology described has been theoretically applied to an injection system and catalyser mounted on a 6 cylinder petrol engine, chosen as reference to consider all the devices of a latest generation engine (figure 2).

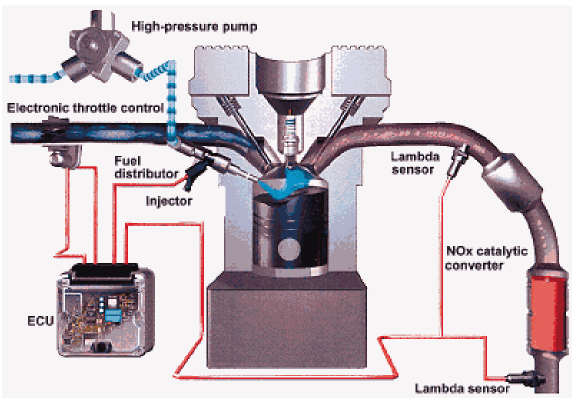

Figure 2. Schematic representation of an injection system and catalyser

In particular, two different configurations of catalysers have been considered:

1. under-floor
2. double catalyser close coupled and under-floor with on board diagnosis system (OBD).

The first solution is no longer used, actually, but it is useful in order to evidence the differences with the newer one.
The first stage of the method's application has permitted the identification of the following Top Events: stoichiometric ratio alteration, high temperature in combustion chamber, short remaining time in combustion chamber, misfiring (as already shown in table 2).

As an example, the case a < 14,7 will be analysed. From the results of the FTA (figure 3), among the different failure causes, we will consider the contamination of the Lambda oxygen sensor, which determinates a change in the fuel mixture ratio, or a change in the frequency at which it sends information to the ECU, depending on the contaminating substance. We consider the hypothesis that the mistake in the mixture, due to lead contamination, is 1% in enrichment and that the catalyser is perfectly efficient.

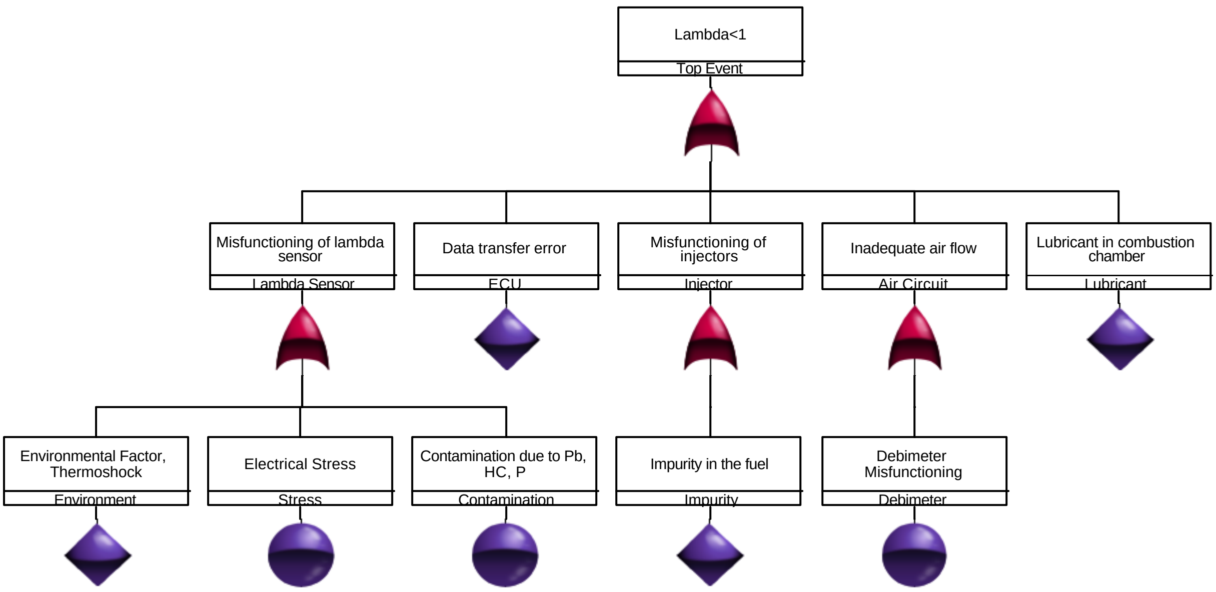

Figure 3. FTA on Top Event λ<1

Notoriously, the catalyser needs a good exhaust mixture composition, and the treated gas should be produced by a stoichiometric combustion. The efficiency of emission reduction of each polluter is function of the stoichiometric ratio in combustion chamber (figure 4).

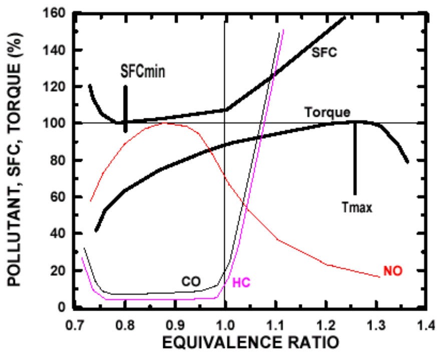

Figure 4. Efficiency of the catalyser

If the equivalence ratio ($\lambda = \alpha/\alpha_{stech}$) is almost 1, the emission reductions considered are: 90% CO_x; 87% NO_x; 84% HC. If the stoichiometric ratio α is known, the real emission reduction and the function of the dependence of the efficiency from the stoichiometric ratio can be obtained from the same figure. This index, multiplied by the environmental severity (W_j) of the considered polluter, represents one of the factor which will constitute the Impact index referring to a non-stoichiometric α, and it is evaluated differently for each emission according to the following formula:

$$Y_{1j} = \frac{CE_i(l \approx 1) - CE_i(l \neq 1)}{CE_i(l \approx 1)} \cdot E_{FTP} \tag{3}$$

where CE_i is the catalyser efficiency relative to the i^{th} polluter and E_{FTP} is the amount of the polluter (g/mile) relative to the standard emission cycle FTP 75. In this way it is possible to correlate the emission increase due to the worsening of the catalyzer efficiency.
Applying, for example, this formula to the NO_x emissions, we have:

$$Y_{13} = \frac{93-87}{87} \cdot 21{,}33 \cdot 0{,}126 = 0{,}185$$

and, in case 2:

$$Y_{13} = \frac{93-87}{87} \cdot 21{,}33 \cdot 0{,}018 = 0{,}026$$

Extending this calculation to all the other emissions and summing the coefficient obtained, from table 1 we obtain I=2 for the under-floor configuration and I=1 for the close coupled.
Regarding the compliance index “C”, the limits, for the EURO 4 standard, are 2,91 g/mile for CO and 0,21 g/mile for HC; known the emissions after misfunctioning (0,15 g CO - 0,08 g HC; 0,07 g CO- 0,036 g HC), it is possible to evaluate the “C” index as follows:

$$0{,}15 \cdot \frac{100-62}{100-90} = 0{,}57 \text{ g(CO)/mile correspondent to C = 2}$$

$$0{,}08 \cdot \frac{100-71}{100-84} = 0{,}145 \text{ g(HC)/mile correspondent to C = 7}$$

so, for the under-floor configuration we will consider the worst case: C=7.

For the case 2 it is considered

$$0{,}07 \cdot \frac{100-62}{100-90} = 0{,}266 \text{ g(CO)/mile correspondent to C = 1}$$

$$0{,}036 \cdot \frac{100-71}{100-84} = 0{,}09 \text{ g(HC)/mile correspondent to C = 5}$$

then the assumed value is C = 5.

For the frequency index the failure rate of the Lambda oxygen sensor is needed: considering from reliability databases a failure every 100’000 km, then the F index is 6.
In table 8 is shown an extract of the FMEA [10] carried on the oxygen sensor in the two configurations, in which it is evidenced the IPN number evaluation:

Table 8. Extract of the FMEA carried on the oxygen sensor

<table>
<tr><th>Component</th><th>Mode</th><th>Effects</th><th>Cause</th><th>I</th><th>F</th><th>C</th><th>IPN</th><th>Recommended actions</th></tr>
<tr><td>Lambda oxygen sensor (underfloor)</td><td rowspan="2">Contamination with lead from leaded gasoline, phosphorous from excessive oil consumption, or silicone from internal coolant leaks or using silicone sprays or gasket sealers on the engine.</td><td rowspan="2">Uncorrected air/fuel mixture enrichment</td><td rowspan="2">Environmental factors (road splash, salt, oil, and dirt), mechanical stress or mishandling.</td><td>2</td><td>6</td><td>7</td><td>84</td><td>A dead sensor will prevent the onboard computer from making the necessary air/fuel corrections, causing the air/fuel mixture to run rich in the "open loop" mode operation, resulting in much higher fuel consumption and emissions.</td></tr>
<tr><td>Lambda oxygen sensor (close coupled)</td><td>1</td><td>6</td><td>5</td><td>30</td><td></td></tr>
</table>

4 Conclusions

The aims definition of a design in the automotive sector comprehends the environmental impact aspect of the vehicle during its complete life cycle. The functioning period, however, is the most effective one among the total of the emissions produced in the life cycle of the automobile. In this context, in the Ecodesign environment, a new methodology has been developed, whose name is RAEGIE, to allow the evaluation of the environmental impact of exhaust gas from vehicle.

This new approach focuses particularly on the influence of the injection system and catalyser on exhaust quality and on the possible environmental effects caused by their malfunctioning or failures. The designer can apply this method from the very beginning of the design stage, by defining the goals in terms of environmental efficiency and compliance to the normative of the automotive sector.

This methodology can be used, integrated with experimental analysis values, in two ways:

- to identify the most critical components of a system, in environmental point of view
- to compare design alternatives, for a fast selection of the better one.

This process starts from early design stages and is continuously updated, to fastener design changes. This brings both to productivity bettering and to emissions compliance to the European standards.

References

[1] M. Lindahl, J. Tingstrom, C. Jensen, "A comparison between the Environmental Effect Analysis and the Life Cycle Assessment methods - Based on four case studies", Proceedings of the 7th International seminar on life cycle engineering, life cycle planning, design and management for eco-products and systems, The University of Tokio, November 27-29, 2000.

[2] Juhani Laurikko, "Exhaust emissions from medium and high-mileage in-service cars with three-way catalytic emissions control system driven under Nordic driving conditions", Seoul 2000 FISITA World Automotive Congress, 12-15 Giugno, 2000, Seoul, Corea.

[3] "The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment – Manual for Designer", Prè product ecology consultants (2000).

[4] "The Eco-indicator 99: A damage oriented method for Life Cycle Impact Assessment – Methodology Report", Prè product ecology consultants (2000).

[5] ISO 14040. Environmental Management - Life Cycle Assessment - Principles and Framework, 1997.

[6] “Potential Failure Mode and Effects Analysis in Design and Potential Failure Mode and Effects Analysis in Manufacturing and Assembly Processes Reference Manual”, SAE J1739.

[7] Lazor J. D., “Failure Mode and Effects Analysis (FMEA) and Fault Tree Analysis (FTA) (Success Tree Analysis-STA)” in: Ireson W. G., Coolombs C. F., Moss R. Y.: Handbook of reliability engineering and management, Mc Graw-Hill, 1996.

[8] W.Grant Ireson, "Handbook of reliability and management", McGraw-Hill, 1996.

[9] Department of the Army, "Guide to RCM for fielded equipment”, 1982.

[10] "Procedures for performing a Failure Mode, Effect and Criticality Analysis", MIL-STD-1629A, U.S. Department of Defense, 1980.

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