

Extending the Role of Interface Analysis within a Systems Engineering Approach to the Design of Robust and Reliable Automotive Product

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ABSTRACT

Automotive design is becoming ever more complex with software controlled electromechanical systems becoming the norm in order to meet ever increasingly stringent legislative requirements and increasing customer expectations. Efficient design of such inherently complex systems calls for improvement to the engineering design process if robust and reliable product is to be designed. There is a tendency for such improvement to reflect the increased complexity of the designed systems with the design process itself becoming increasingly complex. This has been seen where a Failure Mode Avoidance (FMA) approach is used within product design with some of the individual FMA tools requiring increasing amounts of detail with this increasing complexity resulting in tools becoming progressively more cumbersome to use. A restricted toolset is often used and tools tend to be used non-synergistically with limited attention paid to the Systems Engineering demands of product design. The approach presented in this paper while detailed and rigorous leads to efficiencies in the overall FMA process in the area of robust countermeasure development both by reducing redundancy of information, and increasing the coherency of information flow, between the different tools resulting in a simplification of the overall FMA process. An automotive case study is used to demonstrate the central role that interface analysis plays in the process.

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INTRODUCTION

Rising customer expectations and more stringent environmental requirements have driven significantly increased complexity of automotive product. Competitive pressures demand that this increasingly complex product is designed within stable, if not reducing, time and cost constraints. Resolution of this apparent paradox requires a product development process that remains both lean and efficient. The Failure Mode Avoidance (FMA) strategy was introduced as an approach to enhance the effectiveness of the product development process through the identification and resolution early in the design process of potential design deficiencies that can subsequently lead to product failure [1, 2, 3].

Enhancement to the application of FMA has tended to focus on improvements to the individual tools that are used within the approach, particularly FMEA. For example, considerable effort has been directed at improvement to the application of the rating scales within FMEA [4]. Improvement of individual tools in isolation of each other can lead to duplication of effort between tools with a tendency to use specific tools to deliver greater detail than appropriate for that tool. Increasing the number of unique types of information contained in an individual tool can make the tool more cumbersome

to use and such enhancements tend to increase the complexity of the overall FMA process which is at odds with the need to maintain a lean and efficient product development process.

A 4-Step FMA process [5] in which a series of structured tools such as P-Diagram, Failure Mode and Effects Analysis (FMEA) and Robustness Checklist (RCL) are used in a coherent and integrated manner was developed to overcome perceived weaknesses, and hence inefficiencies, in the application of FMA. Perceived weaknesses included a lack of integration between tools and differences of approach in application within different engineering disciplines [6]. The 4-Step process is used within a systems engineering framework [7] to facilitate effective integration of components, subsystems and systems so addressing an observed limitation in the application of FMA of a lack of integration between FMA and systems engineering design [8, 9]. The 4-Step process was based on the use of an existing FMA toolset [3] with the toolset supplemented by the use of the System State Flow Diagram to facilitate a more rigorous and comprehensive approach to functional decomposition [6]. The choice of an existing FMA toolset was deliberate in order that the introduction of the 4-Step process would be seen by those who would potentially use it as an evolution of an existing approach to FMA rather than as a totally new approach so making the process more readily acceptable. It was recognised at the time of developing the

process that the use of the existing tool set resulted in some incongruities in the process. This view has subsequently been reinforced through the experience of the authors in facilitating engineering teams in applying the process within a leading automotive OEM. A sizeable number of engineers who have used the process believe that the manner in which the P-Diagram, FMEA and RCL tools associated directly with improving design robustness and reliability are applied involve some redundancy of effort and information. Given the authors' experience of the positive response to the use of the 4-Step process as one which is generally both straight forward and logical it was felt opportune to address this matter in a way which both eliminates the incongruities and maintains the pragmatic basis of the existing process.

The aim of this paper is to present an enhancement to the existing 4-Step FMA process centred on the manner in which product design robustness and reliability is achieved. This will be illustrated through a case study which considers the design analysis of a diesel exhaust system. The case study is presented in two parts with the first part considering the application of the existing 4-Step process in respect of the identification of robustness improvement opportunities and the establishment of countermeasures to failure followed by the application of the alternative process to the same area of design analysis. This allows a direct comparison of the existing and alternative methodologies to be made. The 4-step FMA process and the systems engineering framework in which it is conducted is summarised first in the context of the case study. The paper then concentrates on those aspects of the process and framework that are most relevant to the establishment of robust countermeasures.

APPLICATION OF CURRENT 4-STEP FMA PROCESS WITHIN A SYSTEMS ENGINEERING FRAMEWORK

The Systems Engineering Framework and 4-Step Process

The case study is based on the application of the 4-Step FMA process to the design of a new exhaust system for a new diesel engine. From the case study perspective the systems engineering framework is defined at the three distinct levels with the levels being illustrated by design elements corresponding to that level as defined in [table 1](#):

Table 1. Definition of system levels within case study

System Level	Design Element
System	Powertrain
Subsystem	Exhaust Aftertreatment
Component	Turbocharger to Exhaust Aftertreatment Joint

The overall application of the FMA process within the system engineering framework is illustrated in [figure 1](#) which shows the 4 steps of *Function Analysis*, *Function Failure Analysis*, *Robust Countermeasure Development* and *Robust Design Verification* being repeated at each of the system levels, recognising the development of robust countermeasures can generally only be implemented at component level while the need to develop such measures is planned at the higher levels (6).

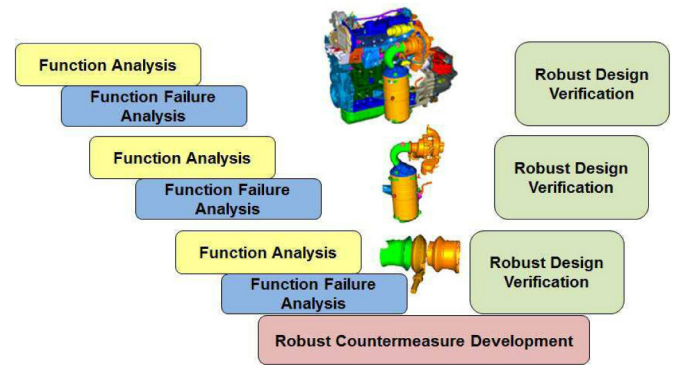


Figure 1. Graphical representation of 4-Step FMA process conducted within systems engineering framework

System and Subsystem Level Analysis

Since product robustness and reliability is largely achieved as a part of the component level design analysis the case study will focus particularly on this level of analysis. It is important to note, however, that to be effective such component level analysis is conducted within a system engineering framework and so follows on from system and subsystem level analysis. The system and subsystem level analysis most relevant to the case study is represented by [figures 2 & 3](#) and [tables 2 & 3](#).

[Figure 2](#) shows the System State Flow Diagrams (SSFD) for a simplified Powertrain which identifies through state flow analysis the Main Functions required to convert systems inputs to outputs along with the design elements needed to generate these functions. The system Boundary Diagram and Function Tree are derived directly from the SSFD (6).

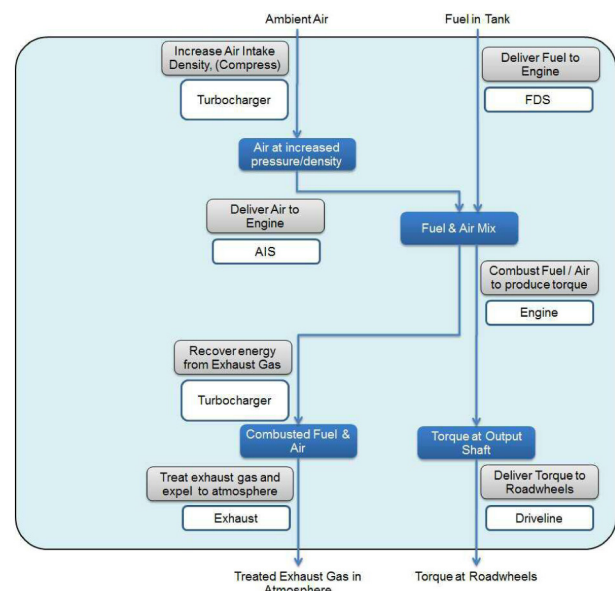


Figure 2. Powertrain System State Flow Diagram for simplified system (For larger version of graphics see [Appendix](#))

Interface analysis is conducted on the basis of the Boundary Diagram; [Table 2](#) is an extract from the Powertrain Internal Interface Table for a single interface. In developing an Interface Table all

interface exchanges of energy (E), material (M) and information (I) as well as any physical requirements (P) that occur at an interface are identified. The table documents the Main Function each exchange is associated with, along with the effect the exchange has on the Main Function rated 2 to -2 depending on whether the effect is beneficial or detrimental to the Main Function. Importantly a description of the exchange and the Interface Function required to manage the exchange are also included (6). Metrics for the interface exchanges are documented, although these are not included in the table extract for reasons of confidentiality. This analysis is repeated for all interfaces, both those internal to a system, and those between the internal elements and the elements external to the system (6).

Table 2. Powertrain Internal Interface Table extract for a single interface (not all interface exchanges listed)

Interface	Type	Effect	Description of Exchange	Interface Function	Main Function
Turbocharger to Exhaust	P	2	Exhaust is connected to the Turbocharger	Connect and seal Exhaust to Turbocharger	Recover energy from Exhaust Gas
	E	0	EBP at Rated Speed	Transmit back pressure from Exhaust system to Turbocharger	Recover energy from Exhaust Gas
	E	-1	Heat transferred from Turbocharger to Exhaust	Operate over range of operating temperatures	Recover energy from Exhaust Gas
	E	-1	Engine Rock	Manage engine rock transmitted from turbocharger to Exhaust	Recover energy from Exhaust Gas
	E	-1	Vibrational Input from Turbocharger to Exhaust	Manage vibration transmitted from Turbocharger to Exhaust	Recover energy from Exhaust Gas
	M	2	Exhaust Gas flow from Turbocharger to Exhaust	Transport exhaust gas from Turbocharger to Exhaust	Recover energy from Exhaust Gas

Figure 3 and table 3 show the equivalent documents for a simplified Exhaust Aftertreatment (AT) system at subsystem level to those shown for the system level (Powertrain) analysis.

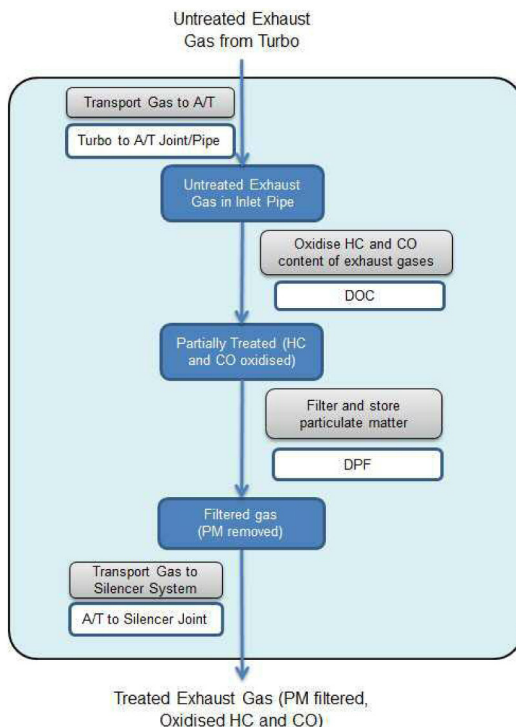


Figure 3. Exhaust Aftertreatment System State Flow Diagram

Table 3. Exhaust Aftertreatment External Interface Table extract for a single interface (not all interface exchanges listed)

Interface	Type	Effect	Description of Exchange	Interface Function	Main Function
Turbocharger to Turbo/AT Joint	P	2	Turbo/AT Joint is connected to the Turbocharger	Connect and seal Turbo/AT Joint to Turbocharger	Transport Gas to AT
	E	0	EBP at Rated Speed	Transmit back pressure from exhaust system to Turbocharger	Transport Gas to AT
	E	-1	Heat transferred from Turbocharger to Turbo/AT Joint	Operate over range of operating temperatures	Transport Gas to AT
	E	-1	Engine Rock	Manage engine rock transmitted from turbocharger to Turbo AT Joint	Transport Gas to AT
	E	-1	Vibrational Input from Turbocharger to Turbo/AT Joint	Manage vibration transmitted from Turbocharger to Turbo/AT Joint	Transport Gas to AT
	M	2	Exhaust Gas flow from Turbocharger to Turbo/AT Joint	Transport exhaust gas from Turbocharger to Turbo/AT Joint	Transport Gas to AT

The system and subsystem level interface analysis facilitates the development of a system and subsystem level DFMEAs (10). Subsystem DFMEAs included those for the Turbocharger and the Exhaust Aftertreatment system both of which identified the Turbocharger to Exhaust Aftertreatment interface as a high risk item reinforcing the high priority set on this item by the Quality History for the previous models.

Component Level Analysis

Application of the 4-Step FMA process at component level to the Turbocharger to the Exhaust Aftertreatment joint (henceforth termed “Turbo/AT Joint” for simplicity) follows similar analysis to that conducted at system and subsystem levels with the exception that the robustness improvement aspects of the process are not only planned but are implemented. While the manner in which robust countermeasures are identified and implemented as a part of the *Step 3: Robust Countermeasure Development* of the 4-Step FMA process is the main focus of this paper it is important that this step is seen in the context of the 4-Step FMA process as a whole due to the coherent information flow that occurs throughout the process (6).

In conducting *Step 1: Function Analysis* at the component level of analysis with a comparatively straight forward component design it is the authors' experience that development of a SSFD is often unnecessary and a Boundary Diagram can be developed directly if the engineering of the component is well understood from previous experience.

It was believed that one reason for the Turbo/AT Joint being identified as a high priority in the Quality History was that historically the design responsibility for this design element was not clearly agreed by those designing the interfacing subsystems. To help ensure one responsible owner for the joint the interfacing design elements for both subsystems were included in the Turbo/AT Joint Boundary Diagram (figure 4) with the Exhaust design team taking responsibility for all design elements within the boundary.

The functions that each of the design elements included in the Boundary Diagram generate were defined directly (figure 5).

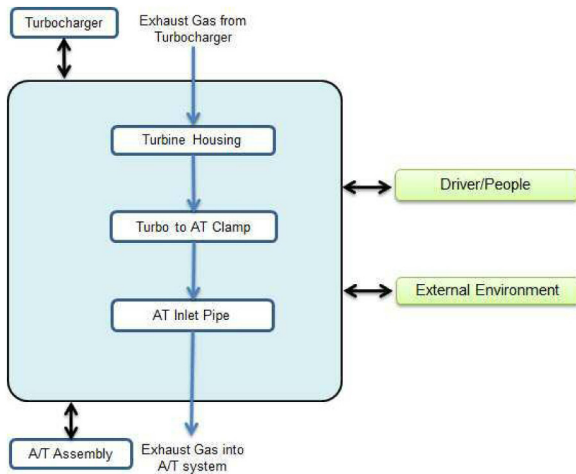


Figure 4. Turbo/AT Joint Boundary Diagram

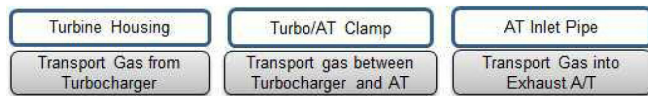


Figure 5. Main functions generated by Turbo/AT Joint design elements

The results of interface analysis conducted on the basis of the Turbo/AT Joint Boundary Diagram are illustrated in table 4 by the extract from the Turbo/AT Joint Internal Interface Table for selected interfaces.

Table 4. Turbo/AT Joint Internal Interface Table extract showing selected interfaces and interface exchanges

Interface	Type	Effect	Description of Exchange	Interface Function	Main Function
Turbine Housing to Turbo/AT Clamp	P	2	Clamp is in contact with Turbine Housing	Clamp Exhaust AT Inlet Pipe to Turbine Housing	Transport Gas between Turbocharger and AT
	E	-1	Heat from Turbine Housing transmitted to Clamp	Clamp over range of operating temperatures	Transport Gas between Turbocharger and AT
	E	-1	Vibration from Turbocharger transmitted to Clamp	Manage vibration transmitted from Turbine Housing to Clamp	Transport Gas between Turbocharger and AT
AT Inlet Pipe to Turbo/AT Clamp	P	2	Clamp is in contact with AT Inlet Pipe	Clamp Exhaust AT Inlet Pipe to Turbine Housing	Transport Gas between Turbocharger and AT
	E	-1	Heat from AT Inlet Pipe transmitted to Clamp	Clamp over range of operating temperatures	Transport Gas between Turbocharger and AT
	E	-1	Vibration from AT Inlet Pipe transmitted to Clamp	Manage vibration transmitted from AT Pipe to Clamp	Transport Gas between Turbocharger and AT
Exhaust Gases to Turbo/AT Clamp	M	-1	Exhaust Gas content deposited on Turbo/AT clamp	Resist corrosion due to soot, fuel, and corrosives in the exhaust gas.	Transport Gas between Turbocharger and AT

As a part of *Step 2: Function Failure Analysis* the structure and initial content of the Pipe Joint DFMEA is derived from information obtained from interface analysis as is illustrated by figure 6 (10). In developing the DFMEA the Main Functions documented in the corresponding Interface Table are transferred directly to the first column of the DFMEA. Causes of failure of each Main Function are then established by considering failure modes of the Interface Functions associated with the Main Function since failure to manage an interface exchange is a potential cause of failure of the Main Function (6).

Also within *Step 2* the P-Diagram is derived from information established during Function Analysis (10). Since Noise Factors can only affect a system through its interfaces the Noise Factors shown in the P-Diagram extract illustrated in figure 7 are determined by considering each interface exchange in table 4. Since table 4 is an

Internal Interface Table the P-Diagram extract does not include information on External Environment Noise Factors. Also since the customer does not have any direct interface with the Turbo/AT Joint component the effect of any customer usage Noises will be included as system interactions. For example, vibration caused through the use of the vehicle off-road will be transmitted to the joint by the Turbocharger and/or AT Assembly.

Item Function	Failure Mode		Severity Class	Potential Cause(s)/ Mechanism(s) of Failure
	Potential Failure Mode	Potential Effects		
Transport gas between Turbocharger and AT	Not all exhaust gas transported between Turbocharger and AT (Gas leak)	Untreated exhaust gas emitted to atmosphere resulting in emission requirements violation	10 YC	Exhaust AT inlet pipe not fully clamped to Turbine Housing Differential thermal expansion of Turbine Housing and clamp resulting in decrease in clamping Vibration transmitted from Turbine Housing to Clamp causes degradation in clamping force Differential thermal expansion of AT Inlet Pipe and clamp resulting in decrease in clamping Soot, fuel, corrosives in exhaust cause degrading of clamp sealing

Figure 6. Extract from Turbo/AT Joint DFMEA

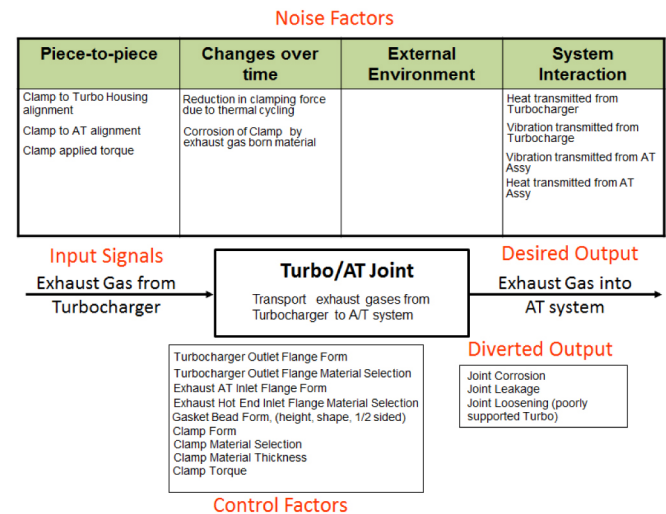


Figure 7. Turbo/AT Joint P-Diagram

A comparison of table 4 and figures 7 illustrates that information in the Interface Tables facilitates the identification of Noise Factors on the P-diagram. As a part of the *Step 3: Robust Countermeasure Development* Control Factors are then established in the conventional manner through engineering knowledge and experience (11) and listed on the P-Diagram. A Robustness Checklist (RCL) (figure 8) is subsequently developed in the conventional manner (12) as a part of *Step 3* and includes information on Noise Factors, Control Factors and Diverted Output transferred from the P-Diagram.

The RCL details the countermeasure actions to be taken to ensure that the component is robust to particular Noise Factors both in terms of the Noise Factor Management Strategy to be adopted and the Control Factors that can potentially be used within that strategy. Information documented in the RCL in terms of robust countermeasure implementation is fed into the DFMEA as Recommended Actions. The analysis summarised by the RCL is a result of the coherent flow of information through the first three steps of the 4-Step FMA process and equally importantly the information cascaded through the systems levels centred on interface analysis (figure 9).

Diversed Output / Errors States				NOISE FACTOR MANAGEMENT STRATEGY				Current Controls				
				Cat	Strategy							
						Error States	Turbocharger Outlet Flange Form	Turbocharger Outlet Flange Material Selection	Exhaust AT Inlet Flange Form	Exhaust AT Inlet Flange Material Selection	Gasket Bead Form (height, shape, 1/2 adoo)	
							A	x	x	x	x	x
							A					
				HIGH IMPACT								