

Failure Mode Avoidance Approach for Hybrid Electric Vehicle Systems

Allen Dobryden
 Ford Motor Company, Retired

Brian Rutter, Derek Hartl, and Eric Bramson
 Ford Motor Company

ABSTRACT

Adoption of new technology with ever increasing complexity challenges organizational structures and processes as subsystem ownership crosses several powertrain subsystem boundaries (and thereby involves multiple departments). Integrating such technology without introducing inadvertent failure modes can be a difficult task. This paper illustrates an upfront approach to understanding the potential system impact of using an example new technology.

In product development activities involving primarily reuse of known technologies, organizational and subsystem boundaries are generally clear. Interfaces are well established and responsibilities for managing failure mode avoidance are generally known. Implementation of new technology which does not naturally fit the well-established organizational definitions and boundaries presents distinctive challenges to system design, system integration, and verification using failure mode avoidance (FMA).

The example technology primarily impacts the exhaust system, the powertrain cooling system, and the powertrain control system. The reconciliation of the various system functions, interfaces and potential error states need to be communicated and understood by the areas affected. The numerous interfaces need to be identified, characterized, and must be managed systematically to ensure compatibility and integration of the design elements at all levels to avoid potential failure modes. In a large, distributed product development organization, this can be a major effort and requires a greater degree of collaboration and system work than in previous projects to ensure success. This paper is a case study of a project to explore the potential impacts on the organization and powertrain system of adopting a new technology.

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INTRODUCTION

A rigorous failure mode avoidance (FMA) process as an integral part of product development has been previously documented [1] [2] [3] [4]. The difficulty in accomplishing one of these projects, however, increases greatly when multiple, interacting disciplines or organizations are involved with a technology that is new to the organization. In product development activities involving primarily reuse of known technologies, perhaps with minor improvements, organizational and subsystem boundaries are generally clear. Interfaces are well established and responsibility for failure mode avoidance is known.

As companies strive for greater energy efficiency, cost reduction, or other goals, one approach is the adoption of increasingly complex technologies which may integrate several functions, and cross traditional system boundaries. An example of this is an exhaust gas heat recovery (EGHR) system. A device of this type directly involves the exhaust system, the powertrain cooling system, and the powertrain control system. EGHR operation affects several other systems and a

number of attributes (e.g. climate control, fuel economy).

Implementation of EGHR on a hybrid electric vehicle provides several benefits and a number of challenges. Hybrid vehicle systems already add a layer of complexity to conventional product development.

The implementation of such a highly-integrated technology which is new to the organization (hereafter referred to as a "newly established technology") may present challenges for failure mode avoidance. Engineering integration and system boundaries may be unclear initially. There may be lack of understanding of the operation or characteristics of the system. These issues may lead to unrecognized failure effects or causes. Severity of failure modes at the powertrain or vehicle level may be incorrectly assigned.

In an effort to better understand the potential organizational and system impacts to adoption of an EGHR system, an investigation was undertaken applying an FMA approach. The goal of this paper is to address in more detail how a systems engineering framework can be used effectively on complex failure mode avoidance projects involving multiple groups. It outlines an approach for the upfront

work which can enable all the required component-level failure mode detection and prevention if the decision is made to proceed with adoption of the technology

FAILURE MODE AVOIDANCE PROCESS AND TOOL SET

The 4-Step Failure Mode Avoidance process has been previously well documented by Henshall, Campean, Rutter, and Souch [1] [2] [3] [4]. For review, it is based around a systems engineering framework using an inter-related set of tools which are traceable and auditable. Working through the tool set provides a comprehensive analysis of system functions, how those functions might fail, and how those potential failures can be detected and prevented. The four steps of the process, with corresponding tools used, are shown in [Table 1](#) (from [1]).

Table 1. 4-Step FMA Process

FMA Process Step	Tools
1. Gain understanding of how the system functions	System Boundary Diagram Interface Matrix and List System State Flow Diagram Function Tree
2. Identify system failure modes and effects	FMEA
3. Analyze potential causes of system failure	Function Fault Tree P-Diagram
4. Develop countermeasures to failure, and methods of verification	Robustness Worksheet Design Verification Plan

When dealing with a newly established technology which involves multiple parts of the organization, it can be unclear how to draw system boundaries. Using the 4-Step FMA process facilitates this discussion among the groups involved.

EXHAUST GAS HEAT RECOVERY SYSTEM

The concept of using exhaust waste heat for cabin heating has been known for some time [5]. Efficient devices for this purpose have more recently been introduced [6]. An EGHR system is especially useful on a hybrid electric vehicle (HEV). An HEV can improve fuel economy by shutting off the engine when sufficient battery power is available for propulsion. On a cold day, however, the engine may have to be run solely for the purpose of providing cabin heating.

Using an EGHR system on a HEV allows faster engine shutdowns on cold ambient startups, when engine thermal energy would normally be required to heat the cabin. As depicted in [Figure 1](#), heat from the exhaust stream is captured and transferred to the engine coolant system, which decreases the time required to run the engine to heat the cabin (referred to as “active” mode). This results in better fuel economy on cold days. When raising the engine coolant temperature is not desired however, there must be a means to bypass this function and not transfer exhaust heat to the coolant (“bypass” mode). This

requires some kind of control system, either mechanical or electro-mechanical, to change the mode of operation automatically. For purposes of discussion in this paper, the EGHR ‘system’ refers to the device itself, the exhaust and coolant connections and material flowing through it, and the controls necessary to operate and diagnose it.

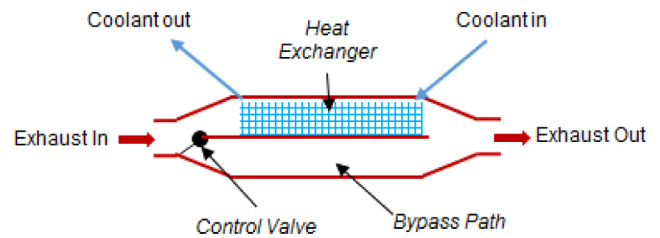


Figure 1. EGHR Schematic

There are a number of system interactions which must be considered for implementation of EGHR, requiring the involvement of multiple vehicle systems teams. Integration of EGHR with an already complex HEV powertrain increases the number of potential interactions. The FMA approach described below was used to understand and capture the scope of these interactions.

EARLY STAGE FMA ACTIVITY

Approach and Deliverables

In a large, distributed engineering organization, the prevention of failure mode causes or mechanisms in a complex technology may require the input of dozens of individuals in different departments over time. Involving all those people from the beginning of the project is not practical, considering the time commitments involved and scheduling conflicts. Further, while each part of the organization may generally adhere to the recommended FMA process, their process mental model and application may vary. Each group has its own background in dealing with their unique issues. They may have a standardized set of FMA documents, into which considerations of the newly established technology must be added. They may also have their own design rules which apply, for prevention of known issues.

The approach taken for understanding potential failure modes and causes in the EGHR project was to form a team of stakeholders for the purpose of essentially completing the first two steps of the 4-Step FMA process described above, at a system level. The team consisted of systems engineering experts, and gathered occasional input from relevant technical specialists. Their task was to sort out the various EGHR functions, potential failure modes, and potential effects. In the event that the technology was to be implemented each group could continue later with failure mode detection and prevention as appropriate. Primary stakeholder groups for this exercise were determined to be:

- Hybrid Systems team, who wanted the benefits of the technology for the vehicle programs
- Exhaust group, who would have primary responsibility for design & release of the EGHR device
- Powertrain Cooling group
- Controls group



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