

Diagnostics Design Process for Developmental Vehicles

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ABSTRACT

In this paper a diagnostic design process is proposed for developmental vehicles where mainstream design process is not well-suited. First a review of current practice in on-board vehicle fault diagnostics design is presented with particular focus on the application of this process to the development of the Ford Escape Hybrid Electric Vehicle (HEV) program and a demonstration Fuel Cell Electric Vehicle (FCEV) program. Based on the review and evaluation of these experiences, a new tool for diagnostics design is proposed that promises to make the design more traceable, to reduce the repetition of work, and to improve understandability and reuse.

INTRODUCTION

OVERVIEW

The purpose of this paper is to evaluate the current processes employed at Ford for the design and implementation of on-board vehicle fault diagnostics. Based on this evaluation, recommendations are made as to how the process can be improved. This endeavor in particular focuses on new developmental vehicle programs that do not necessarily fit into the mainstream processes employed with a mass produced vehicle.

Many of the lessons learned and examples drawn upon in this paper come from the Ford Escape Hybrid Electric Vehicle (HEV) program and a demonstration Fuel Cell Electric Vehicle (FCEV) program. Challenges in diagnostics development, however, are not limited to developmental programs. Some representative statistics are that 32% of warranty costs are attributable to dealership visits where no identifiable problem could be found [1] and that by some estimates over 50% of electrical problems are initially diagnosed incorrectly [2].

GOALS & CHALLENGES

The primary goals of a diagnostic system are to make the vehicle system robust and to facilitate its repair. From an overall design point of view, a robust vehicle will be built to prevent or minimize the occurrence and effect of faults that adversely affect drivability, safety, or regulatory compliance. If a fault cannot be altogether prevented, then it is necessary that the fault be identified and action be taken to mitigate its effects. It is the province of the diagnostic system to perform the fault detection and isolation so that appropriate control actions can take place. The second responsibility of the diagnostic system is to issue information to help the driver and/or service technician to take action that will resolve the fault. This is accomplished by setting indicators

(like a dashboard lamp or a chime) and by storing diagnostic trouble codes (DTCs) that a service technician can read to help pinpoint the underlying fault. The actions taken to ensure that a production vehicle is serviceable by a technician also facilitate the management and resolution of vehicle problems during the development process.

One of the challenges with designing the diagnostics for a modern vehicle is that the systems are increasingly complex. The number of sensors and actuators, electronics, and lines of software code continue to increase as car manufacturers push to improve vehicle quality, performance, adaptability, and customization. This complexity makes it infeasible to consider all aspects of the system at once. The natural solution to this problem is to consider the system on a piece-by-piece basis. The difficulty that arises here is that the components of the larger vehicle system are also increasingly coupled. For example, consider the representation of a hypothetical FCEV system shown in Figure 1. Within this figure, each box represents a separate hardware module and each of the lines indicates that information from the associated physical subsystem is needed by the connected module for diagnostic and control decisions. This diagram illustrates just how coupled each of the hardware modules are. A further complication to this process is the pressure to lower system cost and shorten the overall design cycle to meet customer demands and to stay competitive in a constantly changing market. Developmental vehicle programs additionally face the problem that there isn't always a historically comparable vehicle from which to draw elements of the design.

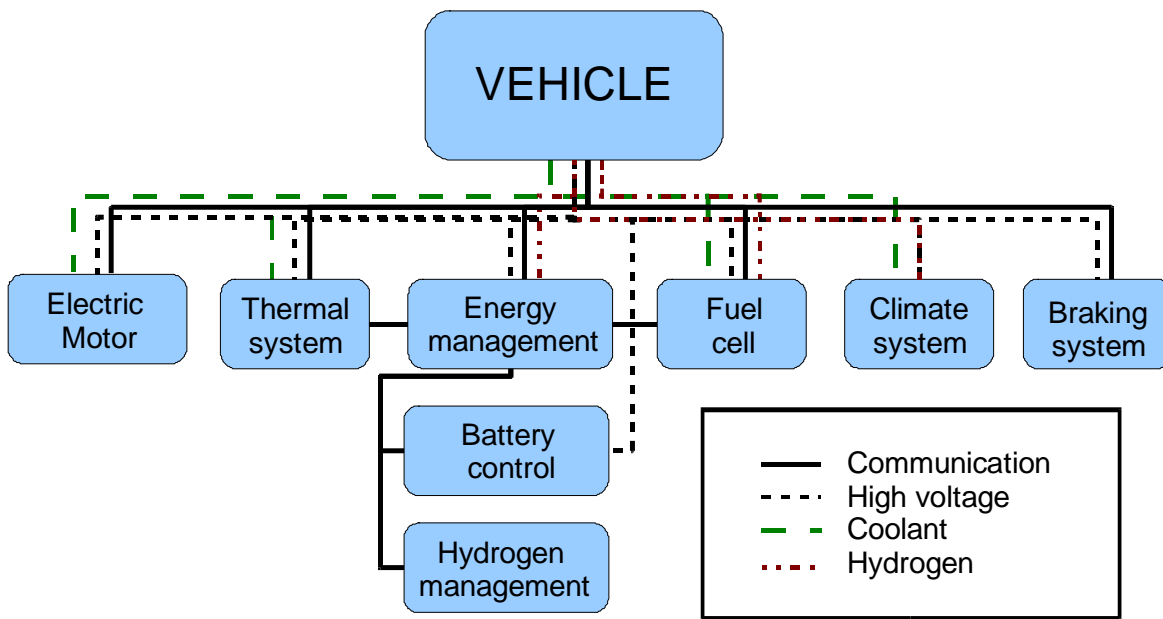


Figure 1 Fuel Cell Electric Vehicle (FCEV) Architecture

CURRENT DESIGN PROCESS

PRODUCTION VEHICLES

A focus for designing vehicle systems at Ford is the avoidance of failure modes. Specifically, a Failure Modes and Effects Analysis (FMEA) is relied upon for identifying the causes and effects of various failure modes. This information is then employed to make design and process changes to avoid or minimize the occurrence of these faults. This information is also used to develop testing plans to help validate the design. The design of the

diagnostic element of the vehicle system historically has relied on the FMEA along with in-depth fault tree analysis for the most severe faults. As evidenced by recent J.D. Power quality rankings, this approach to design has worked well for Ford.

In addition to this design process, guidelines exist for assisting engineers in the design of the Failure Modes and Effects Management (FMEM) and in the setting of DTCs. It is recommended, for example, that FMEM actions should be designed such that there are no customer discernable effects and they should prevent OBD-II faults from occurring where at all possible. OBD-II refers to those emissions faults that are covered by the current set of government regulations. Therefore, if there are no customer discernable effects and no OBD-II faults then an indicator lamp is not necessarily set along with a DTC.

This philosophy is in-line with guidelines put forth on setting DTCs. Specifically, a DTC should only be set when a customer noticeable symptom can occur; a DTC does not necessarily need to be set by a module entering a fault management strategy. In general, it is the goal that the smallest replaceable component be identified by a unique DTC. Other DTCs may identify when a subsystem is forced to take a customer noticeable back-up strategy based on interaction with another subsystem, or due to operating environment or customer actions. More specifically, each DTC should have an associated repair action or a reason that can be explained to a customer. In order to limit the logging of spurious DTCs, filtering and retry strategies should be employed. Additionally, CAN missing message DTCs should be inhibited under various conditions like start-up and low battery voltage. It is also required that DTC names be chosen from a master database that is consistent with existing SAE standards.

The architecture employed in production powertrain on-board diagnostics (OBD) is set up such that each fault is identified locally. Once identified, the fault is then announced to everyone. Individual modules can then use this information to determine whether or not some of their tests need to be inhibited. This information is then employed by a centralized diagnostic executive to determine which DTCs should be set. These diagnostic decisions can be made in a centralized manner like this since most of the information and complexity lies in a single controller unit, the powertrain control module (PCM).

Additionally, the communication between subsystems for powertrain OBD is done as directly as possible. A disadvantage of this approach is that the relationships between the subsystems can be confusing, tightly coupled, and not very reconfigurable. The advantages of this approach are that there is less CAN traffic and the communication is more reliable since it does not have to pass through any intermediate subsystems. One of the primary motivations for employing this communication architecture is that it minimizes the number of subsystems that can directly affect vehicle emissions and thus would have to be covered under related warranty as regulated by OBD-II.

FORD ESCAPE HEV PROGRAM

The Ford Escape HEV program basically followed the typical production vehicle development process; though the process was spread out over a longer time period to allow for the design and test of new HEV specific technologies. The aforementioned production vehicle diagnostic guidelines were also adhered to. One difference was that the architecture employed on the Escape HEV for setting DTCs was decentralized, as opposed to the OBD diagnostics for most production vehicles where diagnostic decisions are made by a centralized executive. The Escape HEV program originally tried to send all diagnostic information to a high-level supervisor in this manner, but the amount of CAN traffic proved to be too great.

Following the launch of the developmental vehicle fleet, the HEV systems group commenced evaluating vehicle data to improve the on-board software and diagnostic systems. A challenge experienced by the group was that an inordinately large amount of DTCs were being pulled from each of the vehicles in the fleet. The large number of DTCs was due in part to the fact that a single underlying fault could lead to a cascade of other DTCs. One mechanism for this was that a fault in one subsystem would interact with another subsystem, degrading its performance and causing another DTC to be triggered. Another mechanism for this cascade was that the originating fault would cause a mitigating action to be taken which would then lead to other DTCs being set. The number of DTCs being produced made managing the information and resolving the underlying causes of the DTCs difficult. Another factor that made identifying the causes difficult was that multiple faults could map to the same DTC, this was due in part to the decentralized implementation of the diagnostics.

In order to manage all of this data, a considerable amount of energy was invested in generating tools and processes to track and resolve problems. In particular, a comprehensive Vehicle Information Database was generated that mapped underlying causes to indications like DTCs, lamps, chimes, integrated circuit text messages, and user observed effects. Additional information such as the action taken and how the DTC is cleared were also included. This database was used to try to identify patterns of observations that could be mapped to a single underlying fault. A web-based tracking tool was also developed to follow and share information on unresolved DTCs. Prior to the introduction of this tool each scan averaged 10 DTCs, after the tool 0.15 DTCs were averaged per pull. Previously existing tools were also used for tracking other software and system issues. The knowledge gained from these tools and processes was then used to improve the vehicle software and diagnostics.

Some reasons why the Escape HEV program experienced more difficulty in tracking and resolving diagnostic information than with a conventional production program was because there were more hardware modules which were distributed but tightly coupled, and much of the technology had not been implemented on a Ford vehicle before. Some lessons taken away from the development process of the Escape HEV program were that the interaction between modules and the vehicle-level diagnostics must be modeled, a database of vehicle diagnostic information is helpful, early analysis of DTCs will reduce defects and cost, shared processes and templates should be employed, and IT support should be provided to developmental programs. Subsequent generations of HEVs have tried to learn from and improve upon the diagnostics and processes of the Escape HEV developmental vehicles.

DEVELOPMENTAL FCEV PROGRAM

The developmental FCEV fleet was a technology demonstration program, in contrast to the Escape HEV, which was eventually destined for production. In part because of this, the FCEV program had fewer resources and some process guidelines were not followed in order to get the vehicles on the road in a timely manner. Another reason for the deviations was the large number of suppliers operating on the program. Additionally, for some suppliers the demonstration FCEV program was the first automotive program they had ever participated in.

The diagnostic system design was performed primarily on a component basis and DTCs were assigned to many items that are not customer noticeable or safety critical. The motivation for this approach to DTCs was that the 30 vehicle fleet would be geographically distributed and the DTCs would provide engineers information about the performance and use of the vehicles. The FMEM actions were again designed in much the same manner as a production vehicle.

The FCEV program ran primarily concurrently with the Escape HEV program and had an experience that was similar to that of the Escape HEV program. Specifically, the FCEV program experienced a proliferation of

confusing diagnostic information that made it difficult to identify and resolve vehicle problems. Towards the end of the FCEV development, some members of the Escape HEV team that had helped to manage and investigate the proliferation of diagnostic information on that program came over to help with a similar effort.

The lessons learned from the Escape HEV program apply equally well to the experiences of the FCEV program. Some additional lessons learned include maintaining tighter controls on subsystem suppliers. This could be facilitated by consolidating the number of suppliers. For example, it might be possible that multiple subsystems could be supplied by the same company.

ASSESSMENT

The current Ford development process has evolved to improve the reliability of a given vehicle design. The process is formalized and well-implemented and has been very successful, yet still it does not emphasize an integrated vehicle controls and diagnostics design. An effort in the controls group of the Sustainable Mobility Technologies Laboratory (SMTL) at Ford that was inspired in part by the experiences of the Escape HEV and demonstration FCEV programs is now underway to help formalize a Controls Development Process (CDP) [3]. This effort aims to improve traceability, coordinate various workstreams, and catch design flaws earlier in the development process. It is proposed that diagnostics development could be more formally integrated into the overall design process as part of the CDP.

As vehicles have become more complex and individualized, development of a good diagnostic system has become increasingly difficult. This position is illustrated by the statistics on repair and diagnosis quoted in the introduction, as well as by the experiences of the Escape HEV and demonstration FCEV programs.

Out of necessity, these programs developed strategies for managing large amounts of confusing diagnostic information. This information was fed back to significantly improve upon the original software and diagnostic systems. These improvements were also documented to help facilitate the design of future HEVs. These processes and guidelines are very useful and should be carried over to other programs. The overall process, however, took a lot of time and effort. Furthermore, the guidelines developed from the lessons learned might not be applicable to a new vehicle technology. The efficiency and applicability of the development process could be improved if the diagnostic system could be designed better in the first place, rather than relying on vehicle data to identify complex cascades and errors in diagnostic strategy. Additionally, relying on vehicle data will likely lead problems to fall through the cracks since a relatively small number of vehicles are tracked over a relatively short time duration during the development process. On the Escape HEV program, strategy changes were made on the basis of DTCs that were observed only a single time during the entire development process.

PROPOSED PROCESS CHANGES

In order to improve the diagnostic systems being designed for today's complex vehicles, standardized processes must be employed that more explicitly include diagnostics from an early stage. These diagnostics development processes can be included as part of the larger CDP effort. Formalized processes help engineers to employ good practices that have been learned from experience, they help all current and future members of a team to understand the work that has been done, they help make sure nothing is overlooked, and they facilitate different activities occurring concurrently. Ford currently has a well-defined process in place for providing vehicle reliability. Additionally, Ford is standardizing the development of technologies and products across all parts of the company to capture best practices and to facilitate the hand-off between the technology development process and the product development process. Diagnostics and controls design, however, are just beginning to be emphasized within this overall process.

In what is to follow, those elements of the current development process that can be leveraged in the development of a vehicle diagnostic system will be described. Within this description, some best practices that facilitate traceability, concurrency, and understandability will be mentioned. Some of these best practices are being addressed by the CDP effort. Additionally, a new design tool will be described that can be added to the current product development process to more explicitly address diagnostics. This tool will be referred to as a Diagnostics Design Matrix (DDM) and its purpose is to facilitate the assignment of indicators (lamps, chimes, DTCs, etc.) and to identify actions to be taken in response to the identification of a fault. Throughout the entire chain, it will be attempted to decouple the design process for the individual subsystems while still capturing relevant interactions.

EXECUTE CURRENT PROCESSES EFFECTIVELY

The current Ford development process is standardized and well-implemented to improve vehicle reliability. In this section, those elements of the process that can be leveraged to facilitate the design of the diagnostic system will be examined. As a part of this exercise, some advantages of using a formalized process will be mentioned as well as some best practices that can be employed throughout the design process.

The primary existing document that will be relied upon in the diagnostics development process is the FMEA. The FMEA is useful to diagnostics development in that it helps to identify the causes of failures and how the resulting effects cascade through the system. Additionally, the FMEA provides a link to the rest of the design process. This link to the overall design process facilitates traceability of the diagnostic system design. More specifically, the FMEA is generated in two stages; the first stage being the broad Concept FMEA, and the second stage being the more detailed Design FMEA. When constructed correctly, the FMEA employs vehicle requirements as an input.

One best practice is to start constructing FMEA documents early in the design process. A Concept FMEA comes first and has the same format as a Design FMEA as shown in Figure 2, just with less detail. Specifically, a Concept FMEA should focus on identifying the function, potential failure modes, potential effects, their severity, and first-level causes. Possible design and process changes can begin to be thought about, especially for critical failures, but they are not necessarily the focus. As the development process continues the Concept FMEA becomes the starting point for the Design FMEA and it should become more filled in as the process continues. Another best practice associated with the development process is to hit the critical or easy items first. Iteration is a natural part of the design process; in order for the FMEA process to be completed multiple times, an engineer needs to avoid getting stuck on the details at first. This facilitates concurrency in that information can be shared between groups multiple times before the design is finalized. Having a well-defined process in place can also assist with concurrency. This way an individual engineer knows how his/her piece fits into the larger process and, therefore, can temporarily employ placeholders knowing that he/she will be able to fill in the blanks at a later point.

Figure 2 shows the format of an FMEA document. The items in the Function column of the FMEA should come directly from a vehicle requirement. Making sure that every requirement is captured by an FMEA helps to ensure that no failures are overlooked. The Potential Failure Mode column then identifies how the corresponding requirement in the Function column is not met. The next column identifies the effects of the given failure mode. This column is one of the places that helps to identify how problems cascade through the system. A best practice that can be employed here is to maintain the focus on the particular physical subsystem or function that is the subject of the given FMEA. Specifically, if an effect cascades to another FMEA, identify only how it cascades, not what the impact is in the other FMEA. For example, if the hydrogen subsystem of a fuel cell vehicle is failing to supply hydrogen to the fuel cell at the correct pressure, that should be the effect

listed. The responsible engineer should not go on to list how the high pressure hydrogen causes problems in the fuel cell. Those details will be addressed in the fuel cell FMEA. Another best practice in constructing these documents is to limit the number of categories an engineer must consider for each column. By doing this, it helps to guide the engineer's thinking so that the document is completed accurately and quickly. Categories of failure effects are 1) no function, 2) partial function, 3) intermittent function, and 4) unintended function. The next column identifies the severity of the effects, while the Class column is employed to identify any critical effects that may need special attention. The Causes/Mechanisms column identifies how the associated failure mode may have arisen. Again in order to narrow the focus of the engineer generating the FMEA, the causes considered should be classified as those noise factors identified in the related P-diagram document. These noise factors are specifically categorized as 1) deterioration over time, 2) manufacturing variation, 3) customer usage, 4) external environment, and 5) system interaction. Causes due to system interaction provide another element of the FMEA that helps to identify cascades through the system. Again it is important here to not look beyond the scope of the subsystem being considered. In other words, the system interaction should only identify the cause as seen in that subsystem, not what happened in the other system that led to this cause. For example, if performing an FMEA for the fuel cell, a cause should be something like, "the hydrogen was fed to the fuel cell at too high of a pressure," rather than, "the pressure regulator in the hydrogen subsystem had failed." The remaining columns of the FMEA relate to identifying and enacting changes to design, process, and requirements to prevent or reduce the occurrence of a given failure mode.

Some other best practices related to FMEA construction include that an FMEA should be written at the vehicle level first, and then information and requirements should be flowed down to the component level. For example, an effect of a failure mode in a given FMEA could become a cause in some other FMEA. This approach helps to improve traceability, which is one of the primary goals of the CDP. Here each requirement is a function in an FMEA that can be traced through all the different levels of the vehicle system. This traceability helps everyone understand where different elements of the document came from and helps facilitate capturing how a requirement or design change flows through the entire system.

Function	Potential Failure Mode	Potential Effect(s) of Failure	Class	Potential Cause(s) / Mechanism(s) of Failure	Occur	Current Control		D e t e c t e d	R e p a r e d	Recomm. Action(s)	Respons. & Target Date	Action Results					
						Prevent.	Detect.					A c t i o n s T a k e n	S e v e r i t y	O c c u r r e n c e	D e t e c t e d	R e p a r e d	

Figure 2 Format of an FMEA document

INCLUDE DIAGNOSTICS MORE EXPLICITLY

In order to better formalize the diagnostics design process it is proposed that a new Diagnostics Design Matrix (DDM) tool be included in the development process. The DDM is meant to standardize those varied informal techniques that individual engineers and individual programs typically employ. Using a standardized tool will help capture best practices, will make the design more traceable by tying it into the larger process, will make the design more understandable and more likely to be reused, and will help engineers arrive at their design, rather than just being a document to record the results of their design.

DDM definition

An example DDM is shown in Figure 3. It is proposed that there be a DDM for each FMEA, therefore, there would be DDMs at a higher functional level as well at the lower subsystem levels. In this process of flowing requirements down from high-level functions to subsystems, it is desirable that each functional requirement be allocated to a single subsystem; this will help to decouple the design process. The construction and application of the DDM will address those instances where a functional requirement cannot be allocated to a single subsystem. The left indices of a DDM are causes that come directly from the corresponding FMEA. Aligning the DDM with an FMEA assists in accounting for all of the possible causes and allows each cause being diagnosed to be traced all the way back to the originating requirement. The top indices of the DDM are the observable effects of the causes. These effects also come directly from the corresponding FMEA. The x's in a given row indicate those effects that correspond to the cause associated with that row. If a row is independent from all other rows, then that cause can be uniquely distinguished and the engineer can make decisions about what indicators to set and what mitigating actions to take. Multiple x's in a given row indicate that that cause produces both effects together. Numerical entries in a row indicate a temporal relation between the effects, first effect f occurs, and then effect g occurs. Causes are distinguished on-board the vehicle based only on the x's and the numerical entries. The r's indicate that the given cause is related to that effect, but it does not necessarily trigger it. For example, a failed fan may result in a temperature rising, without necessarily crossing the threshold that indicates the pump has failed. An r can also indicate a customer observable effect that cannot necessarily be measured on-board the vehicle for diagnostic purposes. These r's can assist in making the on-board diagnostics more robust, and can be employed to help troubleshoot a problem off-line.

location		EMM	EMM	EMM	EMM	EMM	FMM	EMM	EMM	FCU	..					
observable effects	underlying causes	cn	gr	sc	cn	cn	sc	sc		sc	cn	DTC	Caution lamp	Warning lamp	Chime	Action
		effect a	effect b	effect c	effect d	effect e	effect f	effect g	effect h	effect i	effect j					
d/m	cause 1	x								r		1234				local LOS 1
d/m	cause 2		x									2345	x			request vehicle QOR
d/m	cause 3		x													
e/c	cause 4			x	x					r		S: 3456 D: 4567			x	No restart
si	cause 5					x					r	←				local LOS 2
d/m	cause 6						1	2				1: 5678 2: 6789	1	2		2: request vehicle LOS
e/c	cause 7									x						
d/m	cause 8					x						8901	x			
d/m	cause 9										x					

Figure 3 Example Diagnostics Design Matrix (DDM)

In addition to the individual causes and effects, the DDM also includes some other information to help the engineer produce a diagnostic system that is complete while avoiding a proliferation of confusing or redundant information. Those causes that we are interested in from the FMEA specifically trace back to the five noise factors from the P-diagram: deterioration over time (d), manufacturing variation (m), customer usage (c), external environment (e), and system interaction (si). Deterioration and manufacturing variation both pertain to a problem with a part local to this given subsystem. We do not, however, care about the mechanism of a failure, only its cause. Therefore, we do not care that the cause of the failure is that the part was old or that it was manufactured out of tolerance, we only care that the cause is that particular part. Since the given part is local to this system, if its effects also can be observed locally, we will take responsibility for determining its indications and the resulting mitigating actions within this DDM. A system interaction, however, by definition is a cascade from another system. In order to avoid setting cascading or confusing indicators, we want to avoid assigning anything to this cause. Therefore, we indicate by the symbol ← that this is a secondary cause and we will try to assign the indicators in the DDM from which this cause cascaded. We may, however, want to take some action locally to mitigate the effect of this cascaded cause. Using an example from before, if hydrogen is received by the fuel cell at too high of a pressure, we do not want to set a DTC for it, we want to set the DTC in the hydrogen subsystem indicating what caused the pressure to be too high. We may, however, want to take some action to avoid the high pressure hydrogen from causing damage to the fuel cell. The three noise factors we have considered so far are causes that are in general unique to a single DDM. External environment and customer usage, however, are noise factors that can directly cause a failure in multiple subsystems. With this in mind, if there are multiple instances of one of these causes in multiple DDMs, responsibility for that cause must be assigned to a single DDM to avoid redundant or conflicting indications.

Another piece of information included in each DDM is associated with the effects. Specifically, each effect is marked as 'sc', 'cn', or 'gr' if it is respectively safety critical, customer noticeable, or a government regulated effect (like emissions). This information is included to help the engineer adhere to corporate guidelines that

specify that a failure does not need to be indicated if it has no effect on the performance of the vehicle and it does not compromise the customer's safety or regulatory compliance. The purpose of this guideline is to minimize the proliferation of unnecessary indications. A determination of safety criticality can be made directly based on the Severity column of the FMEA. Whether or not an effect is customer noticeable or government regulated is a decision that must be made by the engineer. If an action taken in response to a cause is customer noticeable then a DTC would also need to be issued even if the original effects were not customer noticeable.

A final piece of information accompanying each effect is the subsystem where the effect is observed. In the case that the effect cannot be observed on-board the vehicle, the location of the effect is indicated '---'. Ideally, each engineer would be able to make all diagnostics design decisions using only a single DDM. However, there may be instances where an effect of a primary cause is found in a different DDM. In these cases, decisions must be made by sharing information between engineers. The vast majority of causes, however, can be distinguished locally, thereby greatly decoupling the design process. Another way that an engineer can decouple the design process is to try to implement mitigating actions whose effects are not observable to other subsystems.

In the case that two different causes cannot be distinguished by the available observable effects, a DTC can be set that reflects that one of the two causes is present. It would then be up to the service technician to pinpoint which of the two causes is actually at fault. In terms of determining the mitigating action, a design must be provided that is possibly conservative in order to address both cases. If this situation is unacceptable, then the DDM has helped to identify the problem. The engineer can then add another sensor or identification algorithm to distinguish between the two causes. Conversely, the DDM can also help identify a situation where a single cause can be independently identified by two different effects. This situation could allow the removal of a redundant sensor or algorithm, as long as that information was not also needed for control purposes.

DDM Construction

As can be seen by the definition of the DDM above, a DDM can be constructed in part on the basis of its associated FMEA. In the following, a formalized procedure for constructing the DDM will be presented along with a discussion of best practices and a discussion of how some of this work could be automated to decrease the amount of re-entry required of the responsible engineers.

DDM Construction Procedure

1. Begin with an FMEA in some degree of completion.
2. The causes from FMEA column (Potential Causes/Mechanism(s) of Failure) become the left indices of the DDM (ignoring mechanism(s) of failure).
3. Identify for each cause its noise factor type (d/m, c/e, si).
4. Potential effects of failure modes become the top indices of the DDM.
5. Identify whether each effect is safety critical, customer noticeable, or government regulated.
6. Determine the subsystem where each effect is observed.
7. If a cause has type d/m and it can be distinguished based on local effects, assign indications and actions.
8. Find all causes of type c/e. If found in multiple DDMs, assign the cause to a single DDM. Assign indications if distinguishable in the assigned DDM.
9. Assign actions to causes of type si without assigning indications.
10. Confer with other engineers regarding causes that cannot be identified locally, that cascade from another DDM, or that are found in multiple DDMs. Make decisions regarding indications and actions.
11. Indistinguishable causes can share a DTC, their effects can be assigned DTCs, or extra sensors and algorithms can be added to help distinguish the causes.

In generating the DDM, it is important to remember one of the best practices of FMEA construction mentioned earlier: address the identification of those causes that are easily determined or are critical first. In particular, steps 1 through 9 pertain to those elements of the DDM that can be addressed primarily using available information and without input from another DDM. Therefore, these elements should be addressed first. Furthermore, it is recommended that DDMs be constructed for intermediate versions of the FMEAs, rather than waiting for the FMEAs to be finalized first. This notion of concurrency and iteration is critical to identifying problems in the design of the overall system early in the development process. For example, a DDM could help identify the need for an extra sensor to pinpoint the cause of a critical failure mode.

Since so many elements of the DDM come directly from an FMEA, it would be advantageous if those portions of the DDM could be populated automatically, thereby saving the responsible engineer the time necessary for re-entering the redundant information. Perhaps a program could be written to do this, or some extra functionality could be added to an existing software program. An additional advantage of this would be the possible ability to link the FMEA to the DDM, thereby facilitating traceability. The particular elements of a DDM that could be taken from an FMEA are the causes and their noise type, the effects and their safety criticality, and the location where the effects are observed. One issue with this would be achieving consistency in naming. In particular, the identification of just the cause itself without the mechanism, as well as its associated noise type may require that the FMEA be written in a particular way. A helpful trait is that, aside from customer usage and external environment noise types, each cause is found in only a single FMEA, thereby making the maintenance of consistency between names easier. If the effects of one FMEA are linked to the causes of another FMEA, that also assists consistency in naming between subsystems. Similarly, if causes from multiple subsystems produce similar effects in a different subsystem, there may be issues with generating a consistent description of the effects in each of the originating subsystems. One solution would be to automate the population of the DDM with two different entries for essentially the same effect, then rely on the responsible engineer to resolve the inconsistency. Safety criticality of an effect could be determined from the Severity column of the FMEA using a threshold. In order to automatically include the location of an effect, the FMEA writer would need to make sure to include that explicitly.

Another way in which re-entry effort could be saved would be to use the DDM to automatically generate other documents. One example would be to compile the individual DDMs together to create essentially the Vehicle Information Database that the Escape HEV program had used to help resolve issues during development. Since the DDMs themselves are relatively small and are explicitly tied to other elements of the development process, their maintenance is much more manageable than the original Vehicle Information Database.

CONCLUSION AND FUTURE WORK

In this paper the development processes for production vehicles and of two developmental vehicle programs have been examined. The experiences of these programs demonstrated the challenges of developing diagnostic systems for modern vehicles employing substantial new technology. In particular, the diagnostic systems on the developmental Escape HEV and demonstration FCEV programs led to the generation of large amounts of diagnostic information during the early stages of development that was difficult to evaluate. In order to manage this information, these programs developed some effective tools and processes for managing the information in order to improve the overall vehicle design. These programs also generated some program specific guidelines for the improved design of the vehicles' diagnostic systems. Another consequence of the experiences of these programs was the initiation of the CDP effort whose aim is to improve the vehicle control system development process.

Within this paper some recommendations were provided to improve vehicle diagnostics. Specifically, it was recommended that current and proposed formalized development processes be adhered to. In particular, those guidelines put forth by Ford regarding FMEA construction and diagnostics, and put forth by the CDP effort should be executed. Additionally, it has been recommended that a new diagnostics tool, the Diagnostics Design Matrix (DDM), be explicitly included in the design process. This tool formalizes the design of diagnostics across programs and groups, thereby improving understanding and facilitating reuse. Including this tool in the overall design process also improves traceability by linking the resulting diagnostics design to other elements of the design process all the way back to the fundamental vehicle requirements. The tool itself assists engineers in determining indicators and mitigating actions for faults, rather than just serving as a place to document the results of the diagnostics design. The DDM can also help reduce the amount of re-entry work required of responsible engineers by assisting the automatic generation of documents.

For future work it is necessary that the recommendations of this paper be implemented as part of a developmental vehicle program. During this process there would likely need to be some modifications made to address practical issues as they arose.

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