Virtual Button and Graphical Interface System Safety Evaluation using System Theoretic Process Analysis (STPA)

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System Theoretic Process Analysis (STPA) is an extremely valuable methodology, especially when used early in a system's concept phase, for effective and efficient development of safety requirements that address potential safety issues associated with human-machine interactions.

This paper outlines how STPA can be used to explore potential safety concerns associated with interactions between human operators and virtual buttons within graphical interfaces across the planned operational scenarios and expected system behaviors. Appropriately validated system safety requirements can be developed based on this exploratory effort.

The paper shows how STPA includes drivers and operators as system elements within the control structure where these humans are expected to interact with a "system/feature of interest" by means of virtual buttons presented in a graphical interface. The inclusion of humans as elements of the control structure enables a representation of the human as a "human controller" and, as such, enables STPA evaluation techniques to be applied to them just as these techniques would be applied to any "control" element in a control structure.

This STPA ability to include humans as system elements resulted in General Motors (GM) adopting STPA as a part of the GM System Safety Process for the evaluation of human-machine interaction applications. The existing ISO26262 process did not sufficiently address the evaluation of human behavior as part of its process as thoroughly as GM desired.

The examples in this paper build and expand upon the "human controller" context outlined by Megan France and Dr. John Thomas (et al.) in previous STPA human-machine interaction presentations. The examples examine how the "human controller" model accommodates human action selection process, use a mental model of the human understanding of the process state and behavior as well as the surrounding environment, and then how feedback may be used to update the process state and behavior models.

Finally, the paper discusses how to organize STPA generated system safety requirements and then summarizes how these requirements can be accommodated into technical requirement documents used by engineering groups responsible to execute the system design.

Virtual Control Overview

The virtualization of physical controls has become mainstream in many applications. Rather than interacting with electronic devices via buttons, switches, dials and other physical inputs, consumers are getting more and more accustomed to the idea of using virtual controls to accomplish their tasks. Virtual controls, in this context, refers to any controls that do not require the physical actuation of moving parts. Instead, touch, voice and gesture controls are used as inputs.

Virtual controls are becoming increasingly common in consumer electronics. They have become so common, in fact, that there is a very good chance you have interacted with such controls today without giving it a second thought. Smartphones have become the prime example of this method of interaction, as the buttons and dials that once adorned telephones have been replaced by touch displays. On many higher-end phones, these displays are augmented by voice and gesture controls, allowing consumers to do everything without pressing a single physical button. The ubiquity of smartphones and their move to having fewer physical controls has conditioned society to move beyond buttons, and we have seen a steady proliferation of virtual control applications.

One such application is the usage of touch screen interfaces in automobiles, the primary focus of this paper. A touch screen can now be found in the cabin of almost every new vehicle sold, with the trend growing as these displays grow larger and more numerous. While this may seem like a very recent development, the automotive industry has been on the cutting edge of virtual control adoption, with the first example of such a touch screen dating back to the 1986 Buick Riviera. The tech-

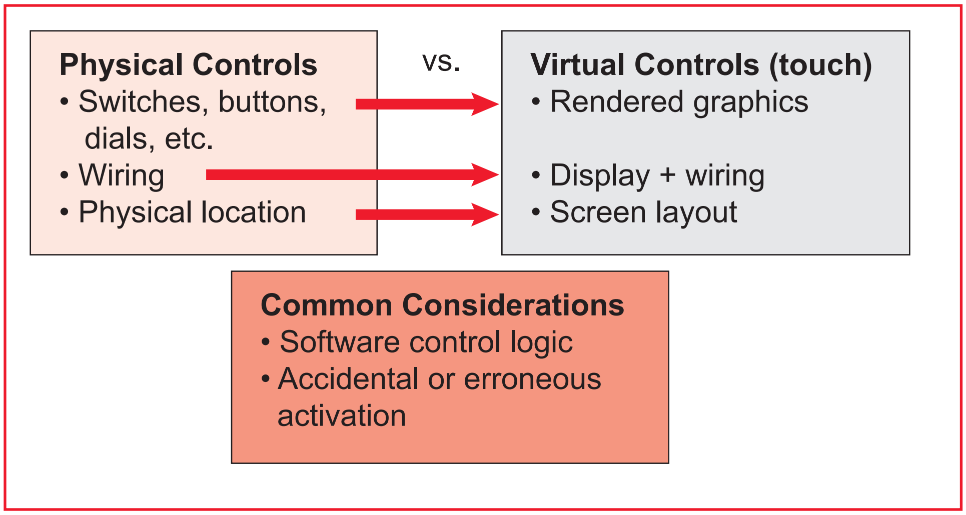

Figure 1 — Differences in Safety Considerations Between Physical and Virtual Controls.

nology has improved significantly since then, and so has our ability to safely integrate more controls into this interface. Drivers can now control features such as the radio, climate control and lighting via touch controls, with some features even controllable by voice, and the list of virtualized controls is constantly expanding. Later, we will examine how System Theoretic Process Analysis (STPA) can play a role in designing new applications of virtual controls.

There are many reasons for this widespread shift towards virtual controls, including design flexibility and perceived benefits by the end customer. The removal of physical controls allows a reduction in parts complexity, which in turn reduces cost. Virtual controls also present engineers with a greater range of design options, freeing them from the familiar constraints of physical controls and allowing more unique designs. This creative approach leads to more compelling experiences for the customer. Customers have grown to appreciate sleek, minimal interfaces, and virtual controls enable such modern designs.

Safety Considerations of Virtual Controls

In addition to the benefits discussed above, virtual controls provide some key safety benefits over traditional physical controls. The aforementioned reduction in parts complexity comes with a reduction in a system's potential fault mechanisms. Fewer parts mean fewer parts that can fail, which allows us to focus greater effort on the design of the remaining parts in the system. An added benefit of this is the opportunity to reduce hardware verification testing, without as many components to test or failure modes to consider. The time and money saved here can go toward other vital safety work. By minimizing fault mechanisms, we can not only minimize the occurrence of single-point and latent faults that may lead to hazardous conditions, but also improve the overall efficiency of our safety process.

While virtual controls offer many safety benefits, care must still be taken to ensure that they are implemented in a safe manner. With greater design freedom comes greater responsibility to ensure safe operation of user interfaces, and new methods of interaction require re-examination of typical safety considerations. The inherent differences between virtual and physical controls must be understood, and the approach to designing safety mechanisms must be adjusted accordingly. Figure 1 summarizes some of these differences, using a touch screen interface as an example of virtual controls.

When designing physical controls, we are concerned with the integrity of the interface itself, the moving part that is actuated by the operator. For a touch screen, we still care about the integrity of the user interface, but instead of switches, buttons and dials, we need to consider the graphics that are rendered and displayed on the screen. These graphics are the virtual "button" that users will interact with, so we need to ensure that the graphical rendering chain is designed and monitored with sufficient integrity.

Transmission of the user's inputs to the controller that acts on the inputs plays a critical role in any human-machine interface. To ensure reliable data transmission, the integrity of wiring is the primary focus when designing physical controls. In a touch screen implementation, wiring is still important, but we must also consider the display and all of its components. In addition to wiring, the display panel, touch controller, backlighting and power source must be designed to ensure reliable transmission of user inputs. Each of these components is crucial in ensuring that the user's input is detected and transmitted to the appropriate controller.

The physical location of controls is very important to consider when designing automotive user interfaces. A user seated in the driver's seat must be able to comfortably reach all safety-critical controls, the controls must be visible without being distracting, and the input method must minimize the time in which the driver takes their hands off the wheel or eyes off the road.

This is a difficult balance to achieve when designing a physical control interface, but virtual controls simplify matters, as most vehicles are equipped only with one central touch screen interface. Instead of worrying about reach and visibility, we are concerned with the layout of controls displayed on the screen. Similar controls must be grouped together in a logical manner, safety critical controls must be readily available and stand out from other information on the screen, and the user must be able to easily navigate through different controls without interfering with their operation of the vehicle.

Despite their inherent differences, physical and virtual controls do share some common safety considerations. In any interface, the user's input will be transmitted to a controller with embedded software. This controller and its software control logic must be robust to ensure safe implementation of the human-machine interface. Accidental or erroneous activation of controls should also be considered in the interface design, regardless of the input method. If unintended activation of a feature could be hazardous, then the controls should be designed to minimize this possibility and verify user intent.

Applying STPA to Virtual Controls

When applying System Theoretic Process Analysis, it is important to begin early in the concept stage of the design. This allows an exploratory analysis of the design, before all the potential causes and effects of misbehaviors in the system are known. The anticipated operating scenarios for virtual control interfaces can be reviewed, which may lead to discussions about better use scenarios. Early usage of STPA can help identify these key elements, which can inform the design. Having an early understanding of the usage and implications of the design is invaluable, as it enables a robust design from the very beginning, rather than addressing gaps in the design with safety requirements later in the process.

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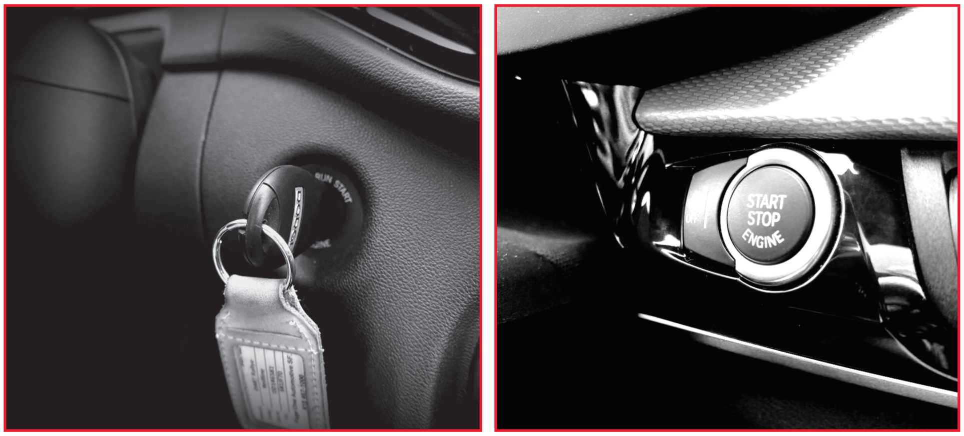
Employing STPA early in the development process also facilitates discussion between system safety engineers and system design engineers working on the project. This early collaboration builds a strong working relationship between both teams, and the STPA findings incorporated into the design will aid in safety activities performed later in the process. Early discussions between safety and design teams also allow early identification of requirements as either safety requirements or functional requirements. This is very helpful as the design goes through different iterations and requirements are modified, allowing imperative requirements to be understood before changes are pursued.

Before going through the rigor of STPA to ensure a proposed virtual control is implemented safely, it should be determined whether that virtual control is

Figure 2 — Examples of Virtual Graphic Implementations [Refs. 3 & 4].



(Images by M. Sheehan)

Figure 3 — Physical Ignition Devices [Ref. 5 & 6].

safety critical. Since this is an automotive example, ISO 26262 — the international standard for functional safety in road vehicles — should be referenced [Ref. 1]. This standard provides guidance to determine requirements that prevent or manage potential hazards so that the system can be considered free from unreasonable risk. It focuses on harm to humans, which would be understood as "losses" in STPA terms.

In addition to the ISO standard, two analysis tools will help with the identification of a virtual control as safety critical. The HAZOP, short for Hazard and Operability, helps us identify potential hazards that could lead to accidents or harm. The output of this exercise feeds into the HARA, or Hazard Analysis and Risk Assessment. The HARA examines the severity, exposure and controllability of hazards, and allows safety engineers to assign an Automotive Safety Integrity Level, or ASIL, to the hazard. This ASIL rating provides a measure of the risk of the hazards associated with a given virtual control and allows us to determine whether the virtual control is safety critical.

Human Controller Aspects of STPA Evaluations

As we begin to frame our STPA approach to virtual controls, it will be useful for us to consider the impact humans can have on our system. Referencing work by Megan France and John Thomas [Ref. 2], we can apply the "Human Controller Model" construct to our analysis. This allows us to consider the hu-

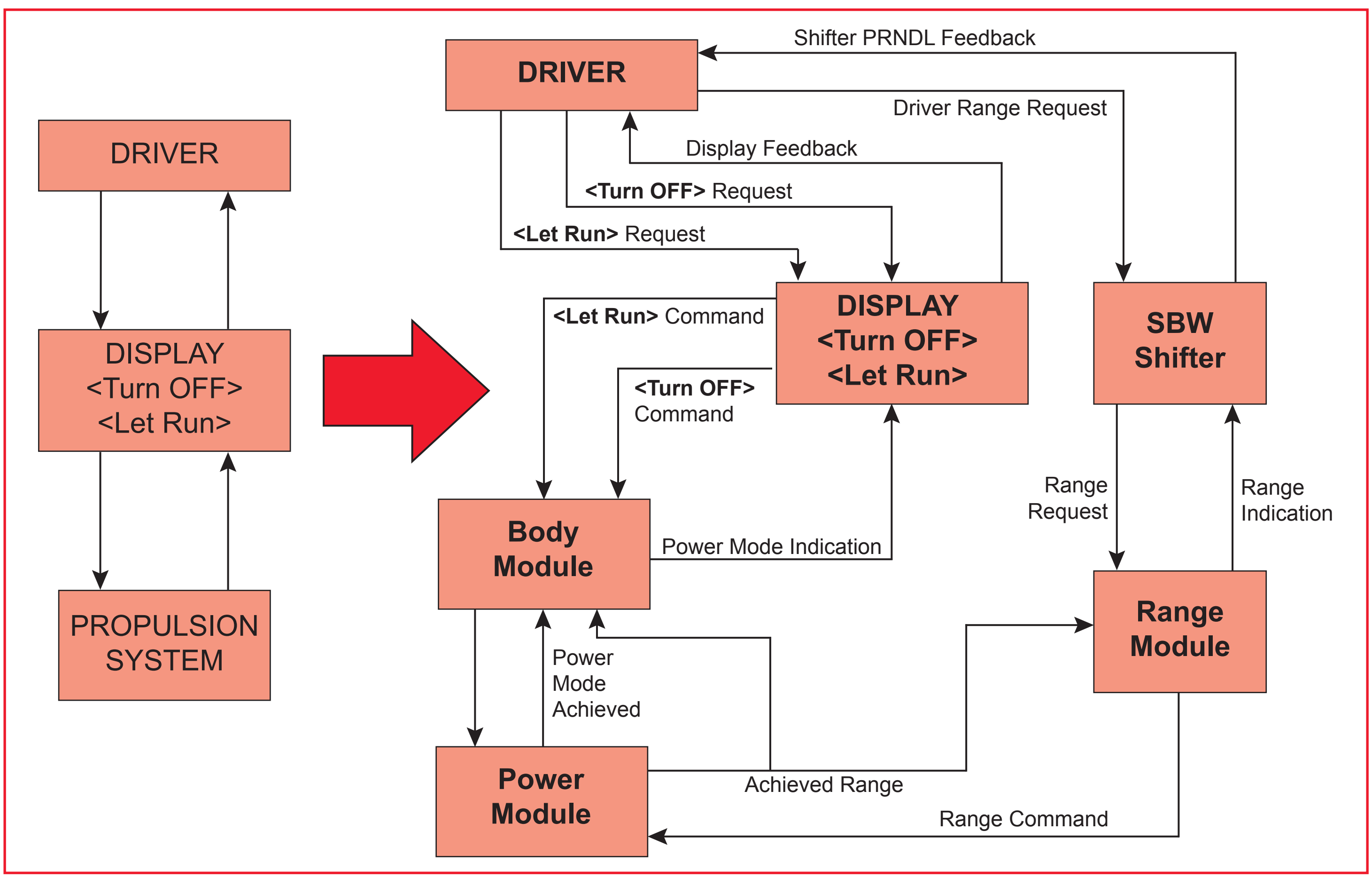


Figure 4 — High-Level to More Detailed Control Structure Representation.

man operators who interact with our system as part of the system. This is a valuable understanding to have when performing the analysis, as it can uncover unsafe actions and misuse that could result from human interaction.

There are three main aspects to the Human Controller Model. The first is the controller's goals and how the controller makes decisions based on expectations, with the controller in this case being the driver or occupant of the vehicle. Another key aspect is how the human controller thinks about the system and its environment, including potential flaws in this understanding. The final consideration is the influence of human experiences and the expectations related to processing sensory inputs and feedback. We will further explore the Human Controller Model in an example application of STPA to virtual controls.

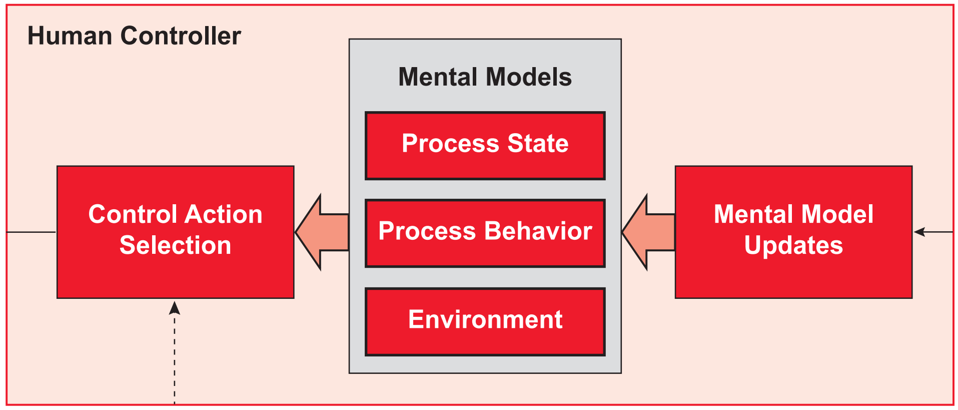


Figure 5 — Human Controller Extension Model [Ref. 2].

Virtual Control Application Examples

As alluded to earlier, there are already countless examples of virtual control applications in automobiles. The automotive industry has become one of the leaders in interface innovation, with manufacturers around the world inventing new controls and features that reshape how people drive and interact with their cars. Figure 2 shows some examples of virtual control interfaces in existing vehicles, which illustrates the prominence ascribed to these interfaces. In a modern, minimalist vehicle interior, virtual controls take center stage.

We will now look at an example in which a new virtual control application is under study. This example will examine the virtualization of the vehicle's ignition interface, by replacing the physical keyed ignition or start/stop push button switch with a virtual control interface. This new ignition interface will use a combination of manual touch screen inputs and automatic behavior based on vehicle conditions. STPA will be applied to uncover shortcomings in the design and potential unsafe control actions within the system.

STPA Application: Understanding Operating Contexts and Conditions

The first question to ask, before beginning the STPA evaluation, is whether this proposed virtual control is critical to safety. By employing the HAZOP analysis mentioned previously, hazards can be identified, showing that failures of the ignition interface could lead to potential accidents or harm. HARA can then be applied to assess the severity, risk of exposure and operator controllability for each of the hazards identified in the HAZOP. After going through each of these exercises, we can confirm that this interface is indeed safety critical. It controls the propulsion state of the vehicle, which has an impact on many other safety critical systems, and failure of which could lead to harm.

To begin application of STPA, the operating contexts and conditions in which the interface is used must be understood. Using this new virtual control interface, how does the driver turn the ignition on? How does the driver turn the ignition off? If the driver leaves the vehicle unattended, what is the impact on living things left behind in the vehicle? All of these are important questions to ask in order to understand the usage of virtual controls for an ignition interface. The various vehicle states in which the system will be used must also be considered, such as entering the vehicle, driving the vehicle, exiting the vehicle and post-crash scenarios.

STPA Application: Control Structure and the Human Controller Model

One of the first steps in any application of STPA is to define the control structure of the system. Ideally, the control structure should include all components in the system, with all critical inputs and outputs clearly illustrated. The components of the control structure should be organized such that all inputs flow downward into the system, and outputs flow back up. Since the system in this example is a human-machine interface, the operator or driver is the initial source of inputs into the system. The driver should then be placed at the very top of the control structure, with their inputs flowing down to the other components of the system.

When defining the control structure, it is acceptable to start with a very high-level sketch if the full system design is not known. As

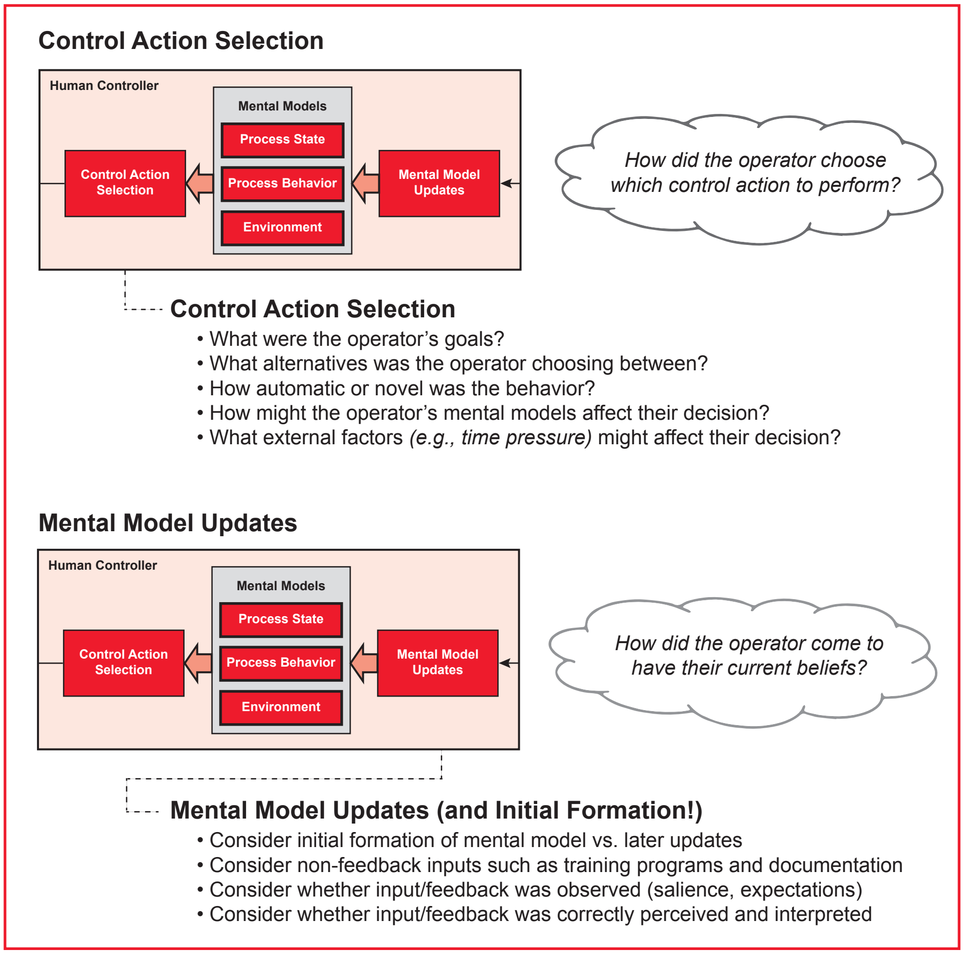


Figure 6 — Human Controller Model Example Questions to Organize Thoughts.

the design matures and interactions within the system are understood, the control structure should be expanded to include the full detail of the system. Figure 4 provides an illustration of this control structure evolution for the example of a virtual control ignition interface. On the left, a rudimentary control structure shows the most basic operation of the system, in which the driver uses the touch screen display to tell the propulsion system to either turn on or remain running. On the right, the system is fully understood, as this expanded control structure details the interactions of all components in the system to achieve the desired function.

From the control structure diagram, it is clear that the driver plays a vital role in this system. The driver's interactions with the system will determine the propulsion state of the vehicle, which has safety implications as highlighted in the preliminary analysis. This is where the value of the Human Controller Model [Ref. 2] is evident. By modeling the driver as a controller in the system, and understanding the expected behavior of this human controller, the operation of the system in different scenarios can be accurately predicted and real-world use cases can be developed.

Figure 5 illustrates the three main aspects of the Human Controller Model. These three areas offer a glimpse into the operator's thought processes as they interact with the system. By understanding each of these sections, the human controller and their interactions can be accurately modeled as part of the overall system.

The first section, Control Action Selection, covers how and why the operator decides to perform a given control action. This takes things such as the operator's goals, what options they have to choose from and external factors into account. By understanding the process by which the human controller makes decisions that impact the system, we can make realistic predictions as to the behavior of the system under different circumstances.

The Mental Model comprises the operator's understanding of the overall system. This is further divided into three areas: Process State, Process Behavior and Environment. Process State outlines the operator's comprehension of the state of the system. This includes everything the human controller knows about the current state, the states that are available to them and the current status of system variables. Process Behavior describes the human controller's understanding of what the system can do, how the behavior changes during operation and how the system reacts to certain inputs. Environment details the operator's concept of the environment in which the system exists. This could include the impact of environmental conditions external to the vehicle, as well as the impact of other systems within the vehicle, all of which make up the system's environment.

The final aspect to consider for the Human Controller Model is the Mental Model Update. It is important to remember that the Mental Model is not static; as the human controller gathers data about the system, the understanding of the system and decision-making process will be updated accordingly. To put in other words, the operator will learn more about the system through usage, which in turn will change how they use the system. Instructions and training, observed cause and effect,

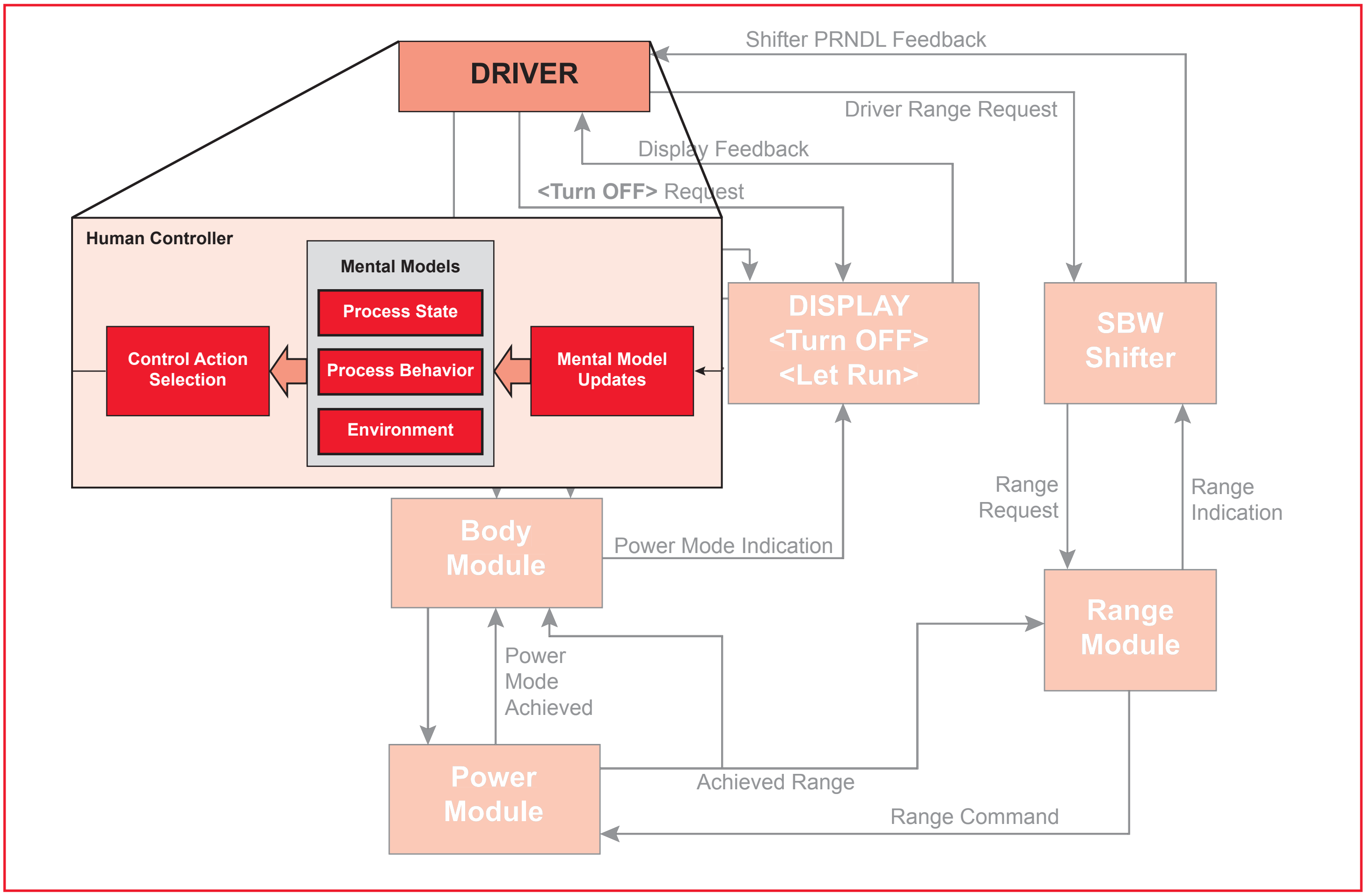


Figure 7 — Initial Driver Element Replaced with Human Controller Extension.

and feedback provided to the operator will all effect how the human controller updates their Mental Model.

Megan France's work on the Human Controller Model provides questions to guide engineers through formulation of each of the three aspects. By answering these questions, the human controller can be fully understood as part of the system. Figure 6 shows some of the questions that help in understanding Control Action Selection and Mental Model Updates.

Application of the Human Controller Model greatly enhances understanding of the driver within the overall system. By inserting a fully developed model of the driver into the control structure, the control structure now paints a realistic picture of the system's usage. No longer an unknown variable within the system, the driver is now defined and understood as well as any other component in the control structure. We now have a useful human-machine extension

"NOT Providing" Cause Hazard	"Providing" Cause Hazard	Incorrect Timing Incorrect Order	Stopped Too Soon Applied Too Long
Missing Not Followed	Providing When Not Expected	Provided Too Early/Late When Required	Providing Unstable or Oscillating Content
	Provided More/Less Than Required	Provided Before/After When Required	Providing Truncated Content
	Provided Content Results in Control Conflict	Provided Content in Wrong Order	Providing Stuck Content
		Provided Opposite of What Expected	

Figure 8 — UCA Columns with Helpful Sub-Phrases.

model to aid in our STPA evaluation of a virtual control ignition interface.

STPA Application: Evaluation Using Human-Machine Extension Model

With the control structure diagramed and the driver in the system now comprehended as a human controller, evaluation of the system can begin. The approach taken for this example is to evaluate the system's functions and key inputs to identify Unsafe Control Actions, or UCAs. Figure 8 shows how this evaluation is set up. UCAs can result from a function or input not being provided when expected, being provided when not expected, being provided in the wrong order or at the wrong time, or being provided for too long or not long enough. This approach is modeled after the HAZOP and is good for identifying all faults and misuse that could occur.

Our understanding of the control structure and the human controller allows us to predict the behavior of the system in the scenarios outlined above. The insight gained from development of the Human Controller Model is crucial in this evaluation.

In this example, some of the things learned from modeling Control Action Selection were that replacement of mechanical ignition devices is a very novel idea, and that instruction and guidance cues would likely need to be provided to operators of this system.

When forming the Mental Model, the Process State area was first considered. From their understanding of similar systems in the past, it can be assumed that the driver believes that there will be a mechanical means to turn the vehicle on or off, and that there is a method to turn propulsion off in an emergency. Regarding Process Behavior, through experience in using this virtual control ignition interface, the driver will assume that the system turns the vehicle on and off automatically. Finally, through development of the Environment portion of the Mental Model, we know that it is important to consider how the system behaves when the driver enters or exits the vehicle. It is also important to note that other vehicle systems, such as braking and shift by wire, are not changing and will still behave as expected.

The Mental Model Updates aspect of this Human Controller Model informs us that feedback of propulsion state must be clear in order for the driver to learn correct operation. Additionally, feedback mechanisms should be evaluated for effectiveness.

With the lessons learned from development of the Human Controller Model in mind, the functions and inputs of the system, or control actions, can be evaluated. By analyzing each control action against the scenarios outlined in Figure 8, Unsafe Control Actions can be uncovered. UCAs reflect undesired operation of the system and will often directly lead to the hazards identified previously. Some UCAs may not lead to hazards, but they should still be noted as they may reveal functional shortcomings of the design. While not safety related, this is very useful information for the design team.

For each identified UCA, the Causal Scenarios that could potentially lead to the occurrence of the UCA should be understood. The Causal Scenario is the system event that triggered the unsafe condition described by the UCA. This could be a failure of a component in the system, but since the driver has been modeled

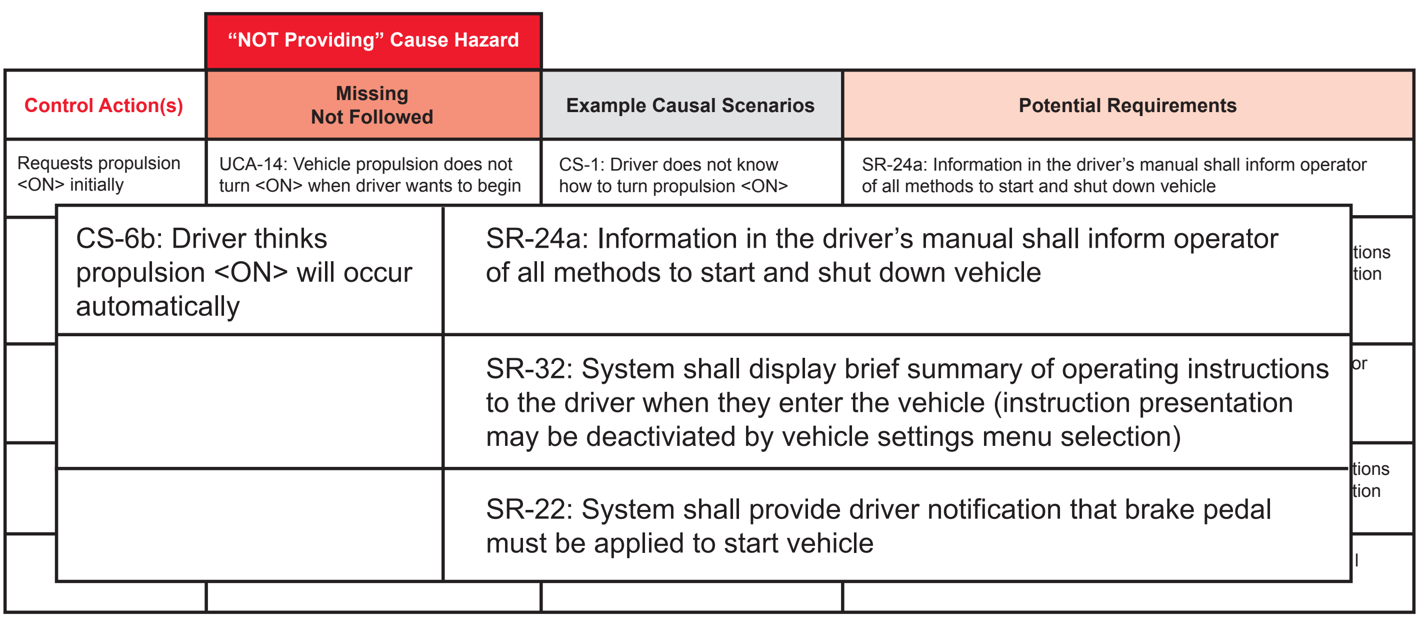


Figure 9 — Causal Scenario and Safety Requirement Example.

as part of the system, this could also include driver error. The findings from the development of the Human Controller Model should be considered when identifying Causal Scenarios. Decision making in unfamiliar circumstances, incomplete knowledge and incorrect assumptions about the system's behavior are all potential sources of driver error. By understanding the driver as a human controller, faults in the driver's judgment can be identified as potential causes of unsafe states.

Once the Causal Scenarios for a given Unsafe Control Action have been identified, Safety Requirements can be defined to address each Causal Scenario. By writing Safety Requirements for Causal Scenarios, we are going after the root of the problem by preventing the conditions that lead to UCAs and safety hazards. This enables a robust system design that focuses on prevention of hazards through avoidance of events that may cause them, rather than focusing on mitigating the hazards after they have already occurred.

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STPA Application: Example Development of Safety Requirements

Take, for example, the development of a set of Safety Requirements for the virtual control ignition interface. For the control action in question, the operator initially requests the propulsion system to turn on, prior to beginning their drive. This control action is then evaluated against the four scenarios in Figure 8.

Focusing on just one of these scenarios for this example, if this propulsion request is not provided, the result is an Unsafe Control Action defined as "vehicle propulsion does not turn <ON> when driver wants to begin propulsion." This was assigned the identifier UCA-14, as the 14th overall Unsafe Control Action defined in the STPA evaluation.

Referencing the lessons learned from the Human Controller Model development, Causal Scenarios can be defined with an understanding of the driver's thought processes. It is known from analysis of Control Action Selection that a virtual control ignition interface is very novel to the driver, and the driver's past experience with ignition interfaces was considered in the Process State portion of the Mental Model. With this in mind, it can be reasoned that a possible Causal Scenario is "Driver does not know how to turn propulsion <ON>," identified as CS-1. Further consideration of the Process Behavior section of the Mental Model reveals that through experience in using the new virtual control ignition interface, the driver will observe that the vehicle starts automatically in most cases. This leads to another potential Causal Scenario, CS-6b, which states "Driver thinks propulsion <ON> will occur automatically." Either of these Causal Scenarios, CS- 1 or CS-6b, could feasibly lead to UCA-14 "vehicle propulsion does not turn <ON> when driver wants to begin propulsion."

Safety Requirements can now be defined for the identified Causal Scenarios. In the scenario CS-6b "Driver thinks propulsion <ON> will occur automatically," there are a few different ways to address this scenario. Instructions can be provided to the driver on usage of the virtual control ignition interface, either in the vehicle owner's manual or presented on the vehicle's display. More specific instruction can even be provided depending on the state of the vehicle, such as a display of "press brake to start" when the brake is a necessary input.

The requirements developed for this particular Unsafe Control Action, UCA-14, are a good example of functional requirements that can result from STPA. Being unable to turn propulsion on when requested isn't desirable behavior, but this does not lead to any identifiable hazards. As a result, the associated requirements aren't safety critical, but they are useful to the design team in their efforts to optimize system performance. Figure 9 shows excerpts from the spreadsheet in which the full evaluation of this UCA was performed.

Lessons Learned

This collaborative STPA exercise between system safety engineers and system design engineers revealed many useful lessons learned. As shown in the example development of requirements, STPA is helpful for discovering improvements to the overall design, not just the safety elements. As a result, early usage of STPA can lead to redesign of the initial proposal. In the case of the virtual control ignition interface, the original plan was to wait until the driver performs some initiating action before displaying instructions on the screen. The evaluation revealed that this might not be helpful if the driver does not think to perform an initiating action, so the design was changed to present instructions earlier in the process. This helped the design team develop a user interface that guides the driver through their various propulsion state options.

Another lesson from this evaluation is that the control structure should be assessed and possibly updated and expanded if shortcomings are discovered. The control structure should not be considered final until the evaluation is complete, because through the STPA exercise, changes may be necessary to address issues. One issue identified early on was the potential for hazardous states caused by erroneous or inadvertent driver action, particularly the vehicle rolling away upon exit. To address this, inputs from the shift-by-wire and braking system were added to the system to ensure the vehicle is secured upon driver exit. By identifying this shortcoming and enhancing the control structure early in the STPA process, requirements for these external systems were able to be defined early, reducing the churn caused by late changes had the problem gone unnoticed.

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Finally, joint use of STPA between system safety engineers and system design groups provides several benefits for both groups. It allows both groups to think beyond a failed component perspective, as is the approach with tools such as FMEA or FTA. This is often the standard approach to safety, but STPA brings a controls-focused perspective, revealing Unsafe Control Actions that may otherwise go unnoticed. The method of applying requirements to the Causal Scenarios that enable these UCAs is also helpful in preventing the scenarios from ever occurring. This is more effective than the failed components approach, as that is more akin to managing potential hazards through mitigation, rather than preventing the hazards from happening in the first place. In summary, STPA provides a more thorough analysis that results in more robust, integrated requirements.

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