Design of Necessary Safety Functions and Fault Detection in Electric Vehicle Control Unit based on Software-in-the-Loop

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Abstract: Compared to traditional vehicles, electric vehicles (EV) are designed with more complicated electrical systems which means EV has a higher failure rate. Therefore, vehicle control unit (VCU) is one of the most crucial and essential components of an electric vehicle. This paper focuses on designing a prototype of control algorithm for the electric powertrain with safety functions and fault injection technique which has been developed by using MATLAB Simulink (powertrain blockset and stateflow tool). The Simulink model includes a designed driver interface, dashboard interface that respectively provides various inputs and supports users to interact with the model before controlling their logic of operation and safety features as well as observes the feedback of vehicle model, and an electric vehicle from the MathWorks project that contains a battery management system (BMS) in battery pack, motor controller, motor and vehicle dynamics. Finally, control algorithms are conducted in safety operation and fault detection will demonstrate faults that are rationally detected from abnormal accelerator and brake pedal signals by Software-in-the-Loop test, which is beneficial before being implemented into the hardware.

Keywords: Vehicle Control Unit, Software-in-the-Loop, Control Algorithm, Safety Functions and Fault Detection.

1. Introduction

The development of control algorithms for electric powertrains and the integration of safety functions in vehicle control units have been extensively explored in the existing literature. Several researchers have focused on the design of control algorithms by Software-in-the-loop (SIL) or Hardware-in-Loop (HIL) test bench. For instance, [1] proposes the use of a SIL test bench to validate control algorithms for a driverless railway vehicle (DLRV). The SiL test bench, developed in a Simulink real-time environment, simulates the vehicle model and its subsystems, allowing for testing of various mission profiles with high time resolution, [2] discusses the development of a cost-effective and functional HIL test platform for VCU in electric racing events. It covers the design of electrical systems, selection of drive motor and battery pack, implementation of control algorithms, and validation of the VCU using joint simulations and closed-loop tests, [3] highlights the proposed fault-tolerant control strategies for various component faults in EV powertrains, validated through experiments or simulations, enabling real-time identification and mitigation of faults for safe vehicle operation.

This research seeks to bridge this gap by investigating the effectiveness and efficiency of SIL test benches in the design and validation of control algorithms for electric powertrains. Moreover, existing studies have primarily focused on specific aspects of control algorithms or safety functions, often overlooking the comprehensive integration of both within the vehicle control unit. This research aims to address this limitation by developing a holistic approach that considers the integration of safety functions within the control algorithm to enhance the overall safety and performance of electric powertrains (as illustrated in Figure 1).

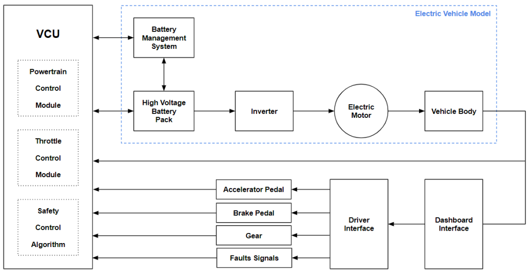

Figure 1. Diagram of the VCU and EV model.

2. System Modelling

2.1 MATLAB and Simulink

The Simulink model utilised in this research comprises three main subsystems: the driver interface, the dashboard interface, and the vehicle model (Figure 2). The "Vehicle Model" block serves as the software responsible for controlling the vehicle's operations. Within this subsystem, algorithms for battery management, motor control, and safety functions are integrated to ensure optimal performance. The "Driver Interface" component plays a crucial role in enabling user interaction with the model. It allows users to customise safety features according to their specific requirements. This interactive capability enhances the flexibility and user-friendliness of the control algorithm development process. To further support users, the "Dashboard Interface" block offers a comprehensive representation of the vehicle's performance using SIL approach. It provides signals from the VCU and displays critical performance metrics such as battery charge level, energy consumption, and other relevant parameters. This interface acts as a virtual dashboard, offering users a realistic view of the vehicle's behaviour and facilitating monitoring and analysis of its performance.

By integrating these three subsystems, the Simulink model enables the development, testing, and evaluation of control algorithms with integrated safety functions for electric powertrains. The robustness and reliability of the algorithms are

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ensured through the comprehensive representation of the vehicle's operations and visualisation of performance metrics. This approach streamlines the algorithm design process, ultimately contributing to the advancement of electric vehicle control systems.

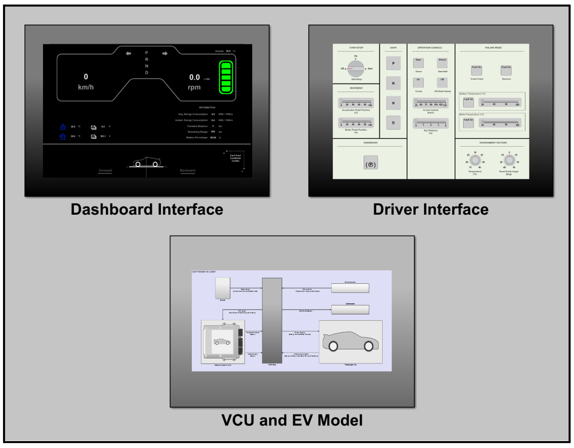


Figure 2. Simulink Model for the research.

2.2 Equation of Motion

According to MATLAB's document and Newton's second law, vehicle dynamics is established based on the "Vehicle Body 3DOF Longitudinal" block from Simulink. The total resistance forces acting on the vehicle are longitudinal force at front and rear axle, aerodynamic drag force, and grade resistance force, as demonstrated in Figure 3.

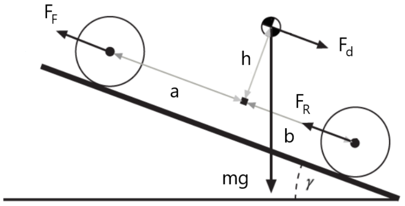


Figure 3. Forces acting on the vehicle.

Hence, the vehicle dynamic can be obtained as:

$$F_F + F_R - F_d - F_g = m\ddot{x} \qquad (1)$$

$$F_F + F_R - \frac{1}{2TR} C_d A_f P_{abs} \left(\dot{x} - w_x\right)^2 - mg\sin\gamma = m\ddot{x} \qquad (2)$$

where $\dot{x}$ and $\ddot{x}$ are respectively velocity and acceleration of the vehicle, h is the height of CG, F_F and F_R are respectively the longitudinal forces on each wheel at the front and rear, F_d is the aerodynamic drag force, F_g is the grade resistance force, T is the environmental air temperature, R is the atmosphere specific gas constant, C_d is the frontal air drag coefficient, A_f is the frontal are, P_{abs} is the environment absolute pressure, w_x is the wind velocity and γ is the road grade angle.

2.3 Electric Vehicle Model

The research makes use of the "EV Reference Application" provided by MATLAB to establish the electric vehicle model. This original model encompasses a comprehensive representation of a full electric vehicle, complete with components such as a PSMS motor, battery, direct-drive transmission, longitudinal driver and visualisation block as shown in Figure 4. In the modified version, the longitudinal driver and visualisation components have been substituted with a Driver Interface and Dashboard Interface, respectively.

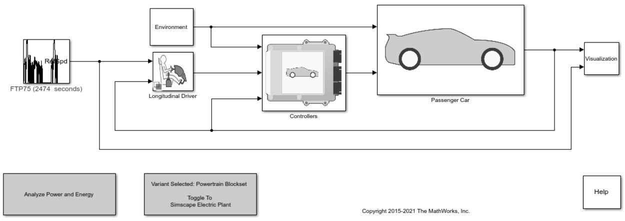


Figure 4. EV Reference Application - original vehicle model

As depicted in Figure 5, the operation of an electric vehicle relies on six essential subsystems. These subsystems, namely the driver, CAN bus, dashboard, vehicle control unit, passenger car, and environment blocks, form the foundation of the vehicle's functionality. To ensure a more realistic representation of an actual electric vehicle, these blocks have been modified from the original MATLAB vehicle model (EV Reference Application) and tailored to mimic real-world behaviour within a Software-in-Loop test bench environment.

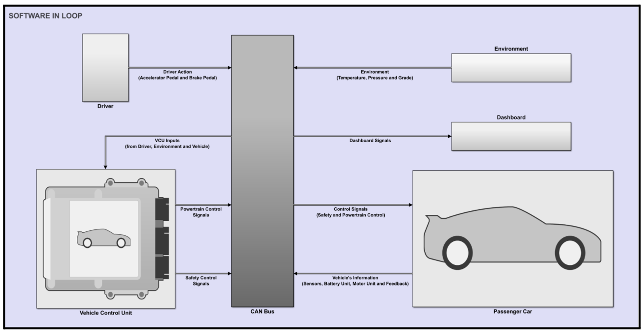


Figure 5. Combined SIL model of VCU and EV.

2.4 VCU Model

Although the initial vehicle model adequately serves the purpose of designing and advancing the VCU, there exist several pivotal variables that necessitate meticulous determination to ensure optimal outcomes. These variables play a crucial role in influencing the efficiency and effectiveness of the VCU development process, aiming to yield outcomes of the highest calibre. Identifying and meticulously addressing these variables are essential steps in the pursuit of achieving the most favourable results possible. Due to the requirement of vehicle control unit, energy consumption, estimating range and travelled distance are consider, as shown in Figure 6, by [4], [5] and [6] before determining by these equations:

$$P = V \times I \qquad (3)$$

$$E_{cs} = \left(\frac{1}{1000}\right) \times \int_{t_1}^{t_2} P\,dt \qquad (4)$$

$$x = \int_{t_1}^{t_2} \dot{x}\,dt + x_0 \qquad (5)$$

$$E_{cs,\,avg} = \left(\frac{1}{x}\right) \times \left(\frac{E_{CS}}{3600}\right) \times 100 \tag{6}$$

$$E_{cs,\,inst} = \frac{\Delta E_{CS}}{\Delta x} = \frac{\left(\Delta E_{CS}\right)_{step\ n} - \left(\Delta E_{CS}\right)_{step\ (n-1)}}{(x)_{step\ n} - (x)_{step\ (n-1)}} \tag{7}$$

$$R_r = \frac{\left(Batt_{cap}\right)_{max}}{E_{cs}} \times Batt_{soc} \tag{8}$$

where P denotes power of battery [Watts], E_{cs} is energy consumption [kWs], x denotes travelled distance [km], $E_{cs,\,avg}$ is average energy consumption per hundred kilometres [kWh/100km], $E_{cs,\,inst}$ is instantaneous energy consumption per hundred kilometres [kWh/100km] and R_r is the remaining range [km].

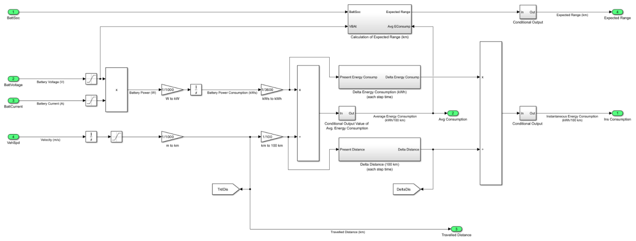


Figure 6. Calculating process of VCU

Vehicle Control Unit is a core component that stands as the linchpin of the entire endeavour. Central to its functionality are four distinct input sources, each playing a critical role in shaping its operation, alongside two essential output signals illustrated in Figure 7. Input signals encompass driver actions, vehicle model, potential vehicle failures, and environment factors. These multifaceted inputs collectively contribute to the unit's decision-making process. Conversely, the unit's two vital output signals find their purpose in interfacing with the broader system. These outputs are transmitted to both control mechanisms and display interfaces, facilitating a seamless flow of information through a meticulously simulated CAN bus protocol. The intricate orchestration of inputs and outputs underscores the significance of the Vehicle Control Unit, cementing its role as a pivotal nexus in the project's intricate web of functionalities.

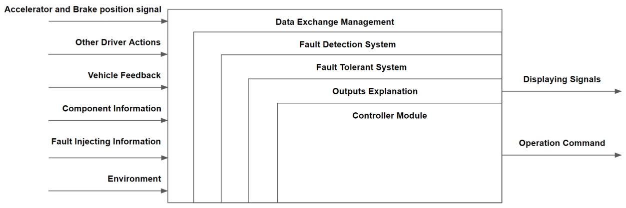
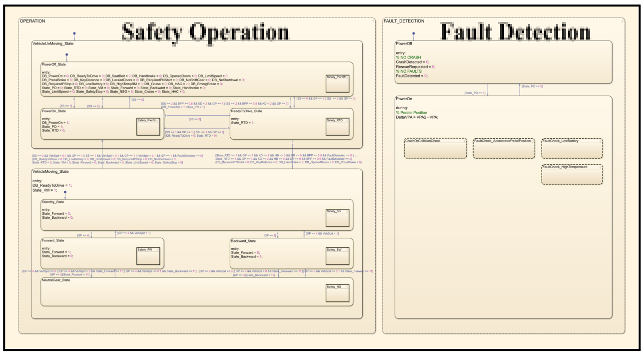


Figure 7. Operating process of Vehicle Control Unit

The control algorithm and safety procedures governing the operation of the Vehicle Control Unit, as depicted in Figure 8a or Figure 8b, are distinctly divided into two primary states: the "Operation" state and the "Fault Detection" state. Within each state lies a dedicated operation mode, along with its associated safety control algorithms and fault detection. Importantly, these states possess the flexibility to be either active or inactive throughout the simulation, depending on the occurrence of specific events and prevailing conditions. The dynamic activity of a state hinges upon the triggering influence of events and prevailing conditions, which collectively steer the execution of the state transition diagram. This orchestrates the activation or deactivation of states, allowing the VCU to adapt its operational mode in response to evolving circumstances, and ensuring a cohesive and adaptive functioning of the control and safety mechanisms.



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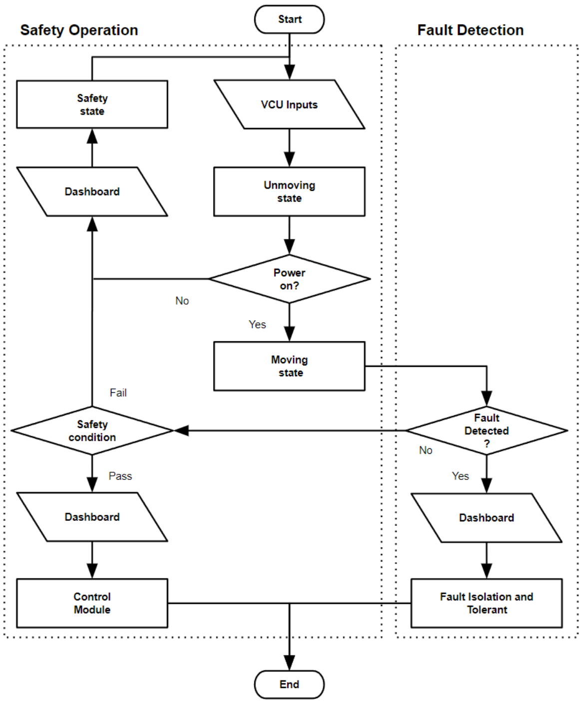


8b

Figure 8. VCU control algorithm

8a. Stateflow process in Simulink model and 8b. Flowchart

3. Software-in-the-Loop Test

Software-in-the-Loop test is deployed on MATLAB Simulink which plays a pivotal role in developing the VCU model. By subjecting the software to various scenarios and conditions before integration with physical hardware, SIL test bench supports detecting and rectifying potential issues early in the development process of safety function. This proactive approach not only minimises development costs but also enhances the overall reliability and performance of the software, making SIL testing an indispensable tool for ensuring the seamless interaction between software components and the systems they drive.

3.1 VCU Operation and Safety Functions

According to Figure 8, normal operation of VCU means faults are not detected during the simulation and the process of safety operation will be focused to prevent occupant and car's components from the damage. The control algorithm of VCU in this project has ability to:

1) Check safety conditions and control vehicle to "Start" and "Stop"
2) Control vehicle in "Moving" state:
   - Automatically activate door locker at a specific speed (moving forward and backward).
   - Synchronising gear-shift to powertrain system.
   - Cruise control
   - Hill-start Assist Control
3) Managing Failure and Acting Safely:
   - Powertrain limitation at reverse gear.
   - Powertrain limitation at low SOC (able to cancel function temporarily).
   - Battery or motor are overheated and automatically brake to stop vehicle safely (able to cancel function temporarily).
   - Implementation regenerative braking algorithm for the traction motor.
   - Limitation of regenerative braking at high SOC.
   - Generation of the dynamic discharge and charge power limits.
   - Automatically turn on hazard indicators for emergency brakes.
4) Calculating:
   - Energy consumption (average and instantaneous).
   - Remaining range.
   - Travelling distance.
5) Displaying to Dashboard:
   - Multi-information display.
   - Vehicle information (speed, current, voltage, gear, etc.)
   - Common warning lights.

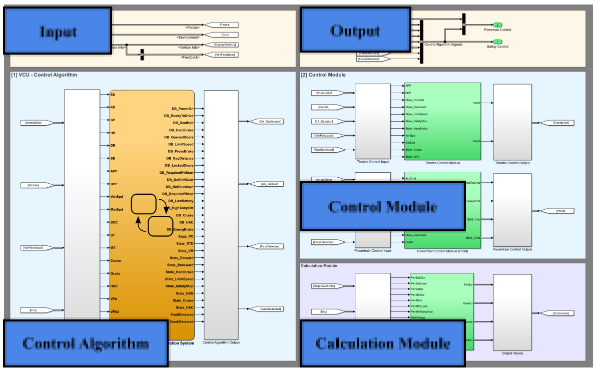


Figure 9. Design of VCU model by Simulink

The designed VCU in Figure 9 will receive input data (pedals, driver actions, environment, vehicle information and feedback) from CAN bus protocol, which users are able to interact with the Simulink model through GUI is called Driver Interface. All of those data will be transmitted to the Control Algorithm of VCU for concerning safety factors before moving to Control Module which is consist of: throttle control module and powertrain control module and all inputs will be also used for calculating energy consumption, remaining range, travelling distance and heat loss of the battery and motor unit by Calculation Module. Finally, all data for controlling and displaying will be transmitted back to CAN Bus.

3.2 VCU Fault Detection and Isolation

Next process of building an electric vehicle control unit in the research is to create faults that users has ability to control by using Fault Injection Method (as illustrated in Figure 10) on these aspects: failures signal occurring on accelerator pedal position (APP), low battery situation, component at high temperature and crash or collision event, respectively. Then, the main goal of VCU is for detecting exact faults, providing proper action and isolating them for each situation.

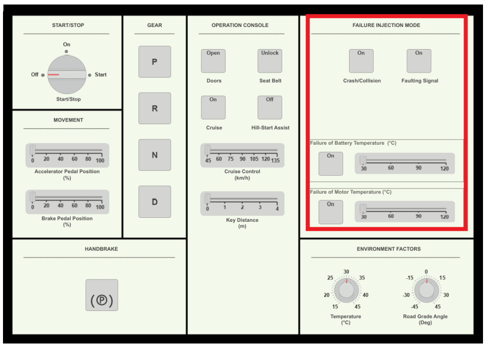


Figure 10. Failure Mode in Driver Interface

3.2.1 Fault Triggering Mechanism of accelerator position

Accelerator position faults are divided into: undetected, stuck and delayed signals that will be automatically chosen by turn Faulting Signal in driver interface (Figure 10) through the triggering mechanisms as designed in Figure 11 by Simulink.

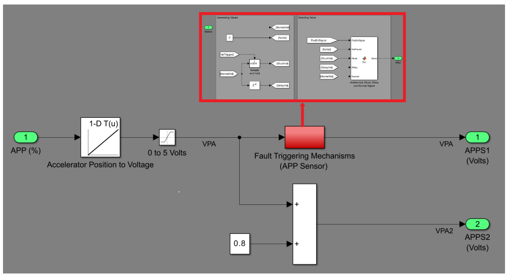


Figure 11. Conversion system and Fault Injection system of accelerator pedal signal

According to research [7], the accelerator position sensor contains two separate non-contact Hall Effect sensors acting in series which are VPA and VPA2 signals. Both of them require a supply voltage of 5V with the normal range of operation for the VPA signal is 0.8V to 3.188V and 1.6V to 3.988V for VPA2 signal (as described in Table 1). By adapting simulation results from [7], APP in percent can be converted into two output voltage signals (VPA and VPA2 where their difference equals 0.8V) by a linear look-up table as shown in Figure 11.

Sensors	Lower limit	Upper limit	Difference
APP Sensor 1 (VPA)	0.8 Volts	3.188 Volts	$\Delta VPA = VPA2 - VPA = 0.8$
APP Sensor 2 (VPA2)	1.6 Volts	3.988 Volts	
Fault Condition			
$0.8 \leq VPA \leq 3.188$ and $\Delta VPA \neq 0.8$			
VCU Action			
Case 1 (v = 0): vehicle is not moving → Warning and activating Limp-home mode Case 2 (v > 0): vehicle is moving → Warning and replacing signal of APP sensor			

Table 1. Fail-safe control strategy for accelerator pedal simulator failure

3.2.2 Crash Triggering Mechanism

Similar to Faults Triggering Mechanisms, crash event is also created by turning on the "Crash/Collision" button, which enables the triggering mechanisms for simulation of the crash event, occurring on the electric vehicle model, in order to verify and validate the control algorithms of VCU. Solution of VCU for crashing tests is designed to shut down the high voltage battery of the vehicle. Based on research [8] and [9], VCU is also programmed for automatically releasing seatbelts and unlocking doors that increase the opportunity of occupants to survive after the collision.

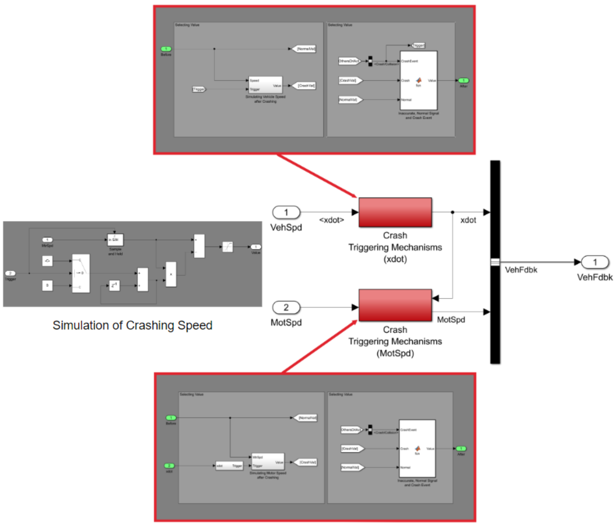


Figure 12. Crash Triggering Mechanisms

4. Simulation Results

4.1 VCU Action for Normal Operation

VCU has the responsibility to operate the vehicle safely, simulation results below are an example of controlling vehicle to start, then enable cruise control at 105 km/h and stop vehicle after travelling 2.5 km that can be observed in Figure 13. Cruise control is activated after 27 seconds, the vehicle speed is controlled to maintain its speed at 105 km/h until the second of 92rd. By observing Figure 14, APP is operated by VCU for holding vehicle speed without depress action of the driver on accelerator pedal.

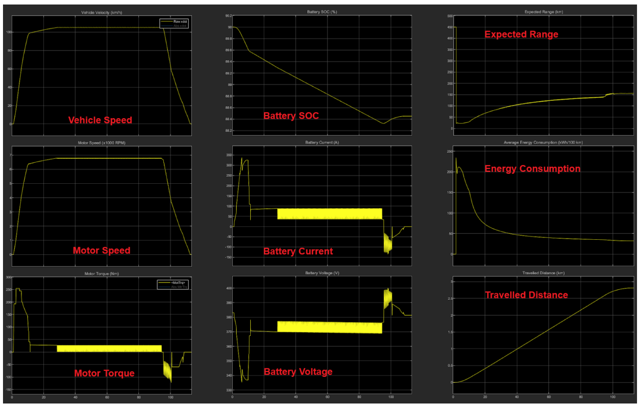


Figure 13. Vehicle information of normal operation

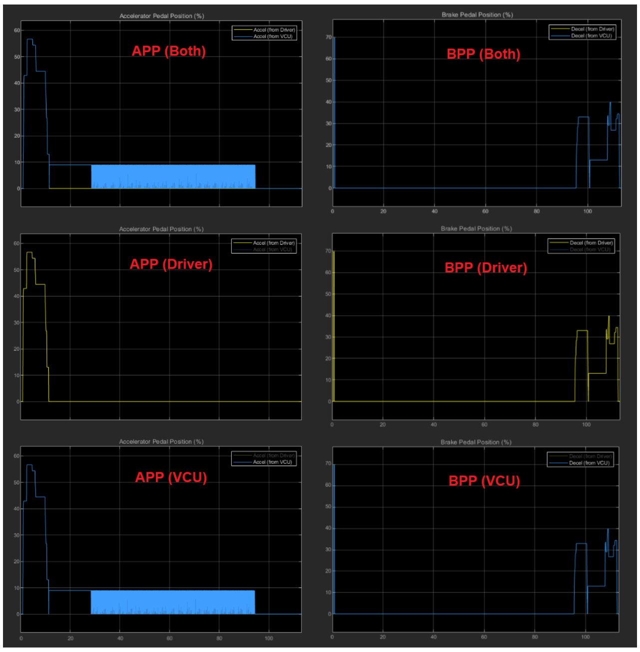


Figure 14. Accelerator and brake pedal signal of normal operation

4.2 VCU Action for Fault Detection

Figure 15 below illustrates the process of fault detection, fault condition is set according to Table 1. The simulation starts with a moving car and VCU receiving a stuck signal of accelerator pedal. Therefore, the action of VCU is to effort warning indicator light and replacing VPA signal by VPA2 signal mentioned in the previous heading.

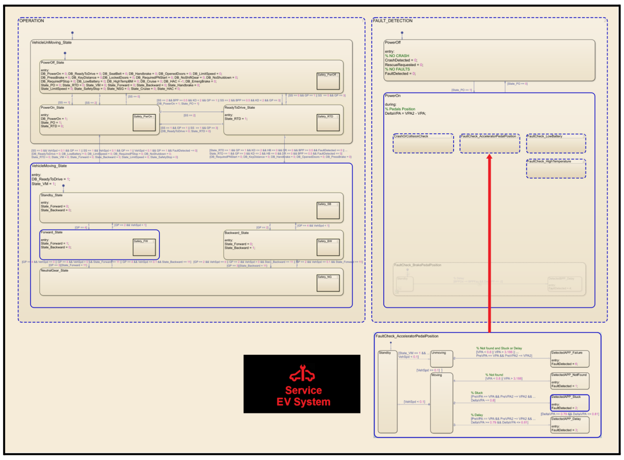
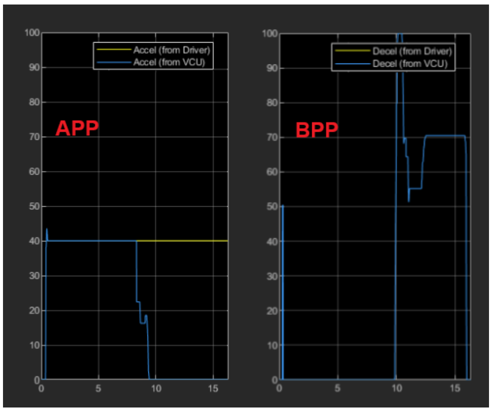


Figure 15. VCU Stateflow of fault detection

Figure 16a shows that the accelerator pedal position is stuck at 40% after 8.5 seconds by fault injection module; the control algorithm already detected exact failure immediately when comparing APP signals from driver and VCU. When a failure signal is detected, the fault detection module in the control algorithm basically uses the backup signal from VPA2 instead of VPA as normal operation. Therefore, the vehicle is able to continue operating with a warning indicator on the car's dashboard (Figure 16b) and stop the vehicle safely at the end.



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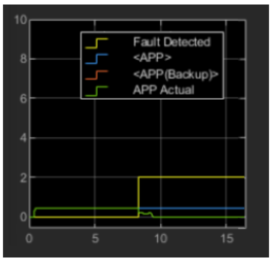

16b

Figure 16. Simulation results of fault detection in VCU
16a. APP stucking signal and BPP signal, and
16b. Replacement of APP signal when fault is detected

4.3 VCU Action after Crashing

In this case, the simulation starts with a car collision occurring at 85 km/h that can be observed in Figure 19. The vehicle speed immediately drops from 85 to 0 km/h similar to the motor speed. Thus, control algorithm detected collision occurring in this situation as depicted as "CrashDetected" signal in Figure 20

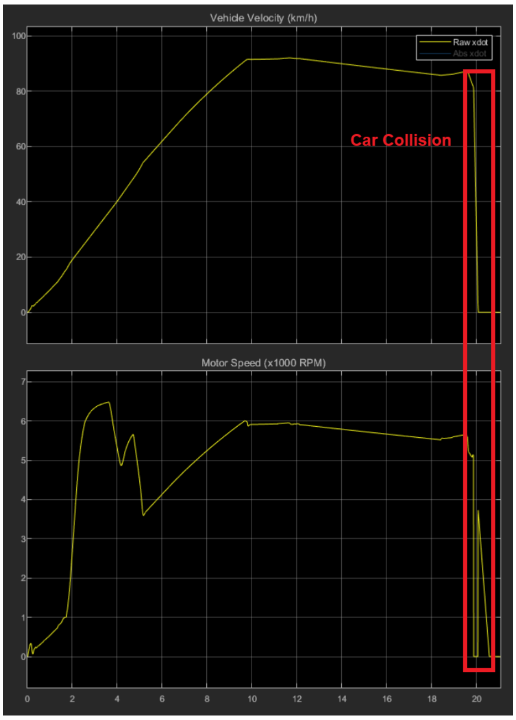

Figure 19. Vehicle speed and motor speed of crashing simulation

The VCU excels in crash simulations, boasting rapid and precise crash detection capabilities. Upon confirming a crash event, the VCU springs into action, automatically releasing seat belts and unlocking door locks as the vehicle comes to an immediate halt. This automated response enhances post-crash support, allowing occupants to exit the vehicle swiftly and facilitating prompt access for first responders (Figure 20).

The VCU's swift and automated release of seat belts ensures that occupants can escape the vehicle without delay, potentially saving lives and reducing injury risks. Simultaneously, its quick unlocking of door locks expedites the arrival of assistance, further enhancing safety and well-being after a collision. In essence, the VCU's crash response is a testament to its dedication to safety, providing crucial support when it's needed most in the aftermath of a crash scenario.

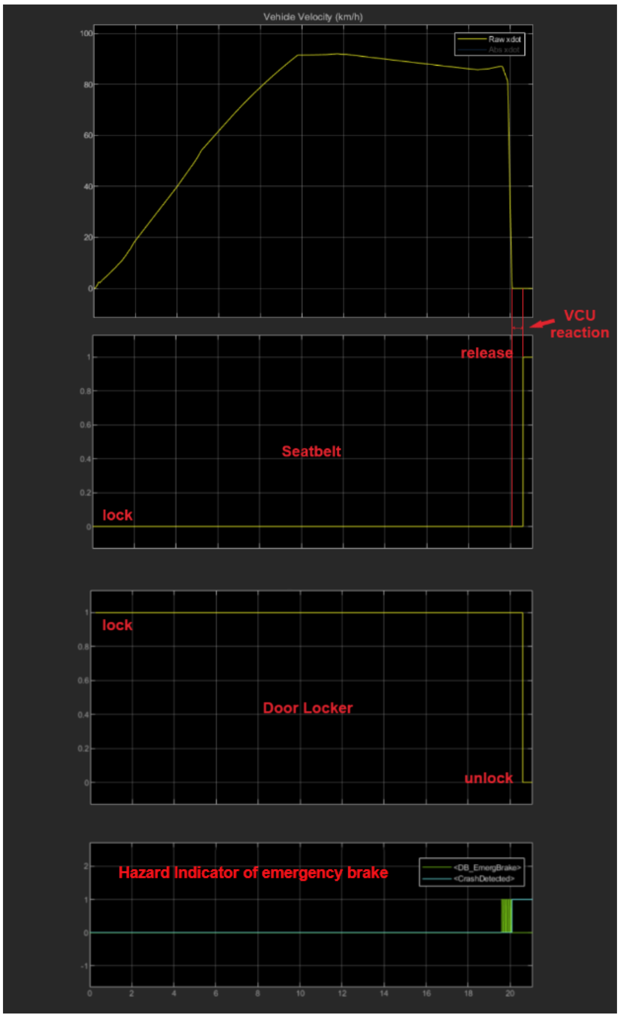

Figure 20. VCU action during crashing simulation

5. Conclusions

It is essential to note that the focus of the research is on the Software-in-Loop test bench without real-time simulation, which means that hardware components will not be directly tested or analysed. Instead, the research will focus on developing and testing the safety algorithms that control the powertrain and energy management systems of the vehicle. Beside that, the absence of a charging system and thermal management system in the electric vehicle model is also a consideration.

VCU is the core in this Software-in-the-Loop test, all algorithms are tested and simulated right after modifying. This research is expected to be a good prototype for the development of necessary functions and fault detection on electric vehicle control units. The results of simulation provide good outputs to validate the operating control algorithm in VCU in terms of safety functions and fault detection.

Overall, this research followed all processes as expected for enhancing the safety, efficiency, and performance of pure electric vehicles by developing control algorithms with integrated safety functions using Software-in-the-Loop test bench.

Reference

[1] Vignati, Michele, et al. "A software-in-the-loop simulation of vehicle control unit algorithms for a driverless railway vehicle." *Applied Sciences* 11.15 (2021): 6730.

[2] Zhang, Ji, Xiangjie Lv, and Yu Lv. "Research on vehicle control strategy and hardware in loop for pure electric FSAE vehicle." *Journal of Physics: Conference Series*. Vol. 1732. No. 1. IOP Publishing, 2021.

[3] Wu, Chenyun, et al. "Fault diagnosis methods and Fault tolerant control strategies for the electric vehicle powertrains." *Energies* 15.13 (2022): 4840.

[4] Chen, Yuche, et al. "A review and outlook of energy consumption estimation models for electric vehicles." *arXiv preprint arXiv:2003.12873* (2020).

[5] Zhang, Yuhe, et al. "Remaining driving range estimation of electric vehicle." *2012 IEEE International Electric Vehicle Conference*. IEEE, 2012.

[6] Sonalikar, Shailesh S., and Sushama D. Shelke. "Estimation of remaining range of electric vehicle using Kalman filter." *2018 International Conference on Inventive Research in Computing Applications (ICIRCA)*. IEEE, 2018.

[7] Rahal, Mohamad. "Innovative circuits to detect faults in accelerator pedal sensor wires in modern vehicles." 2013 25th International Conference on Microelectronics (ICM). IEEE, 2013.

[8] Ahmad, Mohamad Khairi, et al. "Analysis of Auto Release Seatbelt System for Multipurpose Vehicle." Journal of Automotive Powertrain and Transportation Technology 2.2 (2022): 30-41.

[9] Ahmad, Mohamad Khairi, et al. "Analysis of Auto Release Seatbelt System for Multipurpose Vehicle." *Journal of Automotive Powertrain and Transportation Technology* 2.2 (2022): 30-41.

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