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Integrated Braking Safety System Development for Electric Formula Vehicle in NxGV Challenge 2025

Syed Muhammad Fuad Sayed Abd Rahman[1], Norazam Aliman[1]*, Mohd Afiq Murad[1]

[1] *Mechanical Engineering Department,*
Politeknik Sultan Azlan Shah, Behrang Stesyen, 35950, MALAYSIA

*Corresponding Author: syed_muhammad@psas.edu.my
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Abstract

This research presents the design and development of an advanced braking system for a high-performance electric formula vehicle engineered for the Next Generation Vehicle (NxGV) Challenge 2025. With the increasing integration of electric powertrains in motorsport applications, the demand for braking systems that ensure operational safety, energy efficiency, and optimal dynamic performance has become critically important. A prominent safety concern in fully electric vehicles is the potential for unintended acceleration caused by concurrent brake and throttle inputs. To address this issue, a Brake System Plausibility Device (BSPD) was developed to continuously monitor and evaluate input consistency. The proposed system incorporates a brake pressure sensor and a power battery sensor to monitor both input parameters. When the battery power exceeds 5 kW and the brake pressure surpasses 30 bar, the BSPD triggers an immediate disconnection of motor power to mitigate potentially hazardous conditions. An automated re-evaluation is conducted after a 10-second delay, allowing motor power to be safely restored if normal input conditions are detected. The system was prototyped on a breadboard and subjected to functional testing, confirming its responsiveness and reliability in managing safety-critical scenarios. The findings demonstrate the BSPD's effectiveness in fulfilling both performance and safety requirements for competitive electric vehicles. This work contributes to the advancement of intelligent, sensor-integrated braking solutions for next-generation electric and autonomous vehicle platforms.

1. Introduction

The Next Generation Vehicle (NxGV) Challenge 2025 is a nationwide event organised by the Malaysia Automotive, Robotics and IoT Institute (MARii), Perodua, and the Society of Automotive Engineers Malaysia (SAEM) to promote Formula-style vehicle engineering. Participants in the competition had to design and build cars that fulfil tight size rules. The cars can't be longer than 3.5 meters, taller than 1.6 meters, or wider than 1.5 to 1.8 meters as shown in Fig. 2. In addition to satisfying these technical standards, the event encourages students and teachers to put what they learn in the classroom into practice, which leads to new ideas and improvements in motorsport technology.

Fig. 1 *Next generation vehicle*

The threshold parameters governing the Brake System Plausibility Device (BSPD) are strictly codified by Formula Student and FSAE regulations, serving as a critical compromise between robust system safety and operational reliability. The 30 bar fluid pressure benchmark is derived from empirical vehicle telemetry and driver ergonomic testing; it is calibrated safely above the minor pressures seen during transient trail-braking, yet low enough to ensure instantaneous activation the moment a driver executes an emergency panic stop. Concurrently, the 5 kW electrical power threshold provides a vital engineering tolerance against electronic sensor noise and minor tractive fluctuations. This 5 kW baseline represents a minor current draw that a vehicle's mechanical braking system can easily overpower without sacrificing stopping distance, while serving as definitive proof of anomalous, continuous motor propagation. Finally, the integrated 500-millisecond time delay accounts for documented human factors in motorsport literature—specifically the momentary, harmless overlap of throttle and brake pedals during aggressive corner entry—preventing accidental power cutouts while guaranteeing that a genuine runaway fault is isolated in less than half a second.

By achieving a worst-case latency of under 50 ms, the proposed architecture operates over 90% faster than the maximum limits enforced by global rules committees. This rapid response minimizes the duration during which the mechanical brakes must contend with a runaway motor, thereby drastically reducing the thermal load on the brake rotors and preserving maximum stopping power during an emergency event. However, despite these favorable functional outcomes, several development-stage limitations must be resolved prior to track deployment. Primarily, because experimental validation was confined to a laboratory breadboard using commercial-off-the-shelf (COTS) discrete components, the assembly lacks the mechanical ruggedness required for harsh motorsport environments and introduces parasitic capacitances and inductances that can degrade signal propagation. Mitigating these structural vulnerabilities requires transitioning the architecture to an automotive-grade Printed Circuit Board (PCB) configured with dedicated ground planes.

Additionally, the existing analog filtering network was validated under clean laboratory power conditions, which overlooks the severe Electromagnetic Interference (EMI) characteristically induced by an electric vehicle's tractive system switching hundreds of amperes. In a deployment environment, this high-frequency inverter noise risks causing severe signal degradation or inadvertent trips unless suppressed via differential signaling or optimized RC low-pass networks. Finally, the reliance on standard component tolerances (e.g., ±5% resistors and capacitors) injects unwanted variability into the RC time constants governing the critical 500 ms fault-detection delay and the 10 s re-evaluation windows. Given that thermal drifting under sustained racing conditions could shift these safety-critical thresholds, the subsequent design iteration must integrate high-precision, automotive-grade (AEC-Q100 compliant, ±0.1% tolerance) components to guarantee deterministic resilience.

1.1 System Overview

Figure 2 illustrates the electrical and safety architecture of the electric formula vehicle. The system is partitioned into a high-voltage (HV) traction domain comprising the HV battery pack, Accumulator Management System (AMS), Insulation Monitoring Device (IMD), pre-charge and discharge circuitry, DC–DC converter, motor controller, and motor and a grounded low-voltage (GLV) domain that supplies the Vehicle Control Unit (VCU), the Brake System Plausibility Device (BSPD), sensors, indicators, and auxiliary loads. This segregation reduces fault propagation, simplifies protection coordination, and enables clear safety boundaries during operation and service.

Central to the architecture is a safety loop that links the cockpit and external emergency-stop buttons, the inertia switch, the Brake Over-Travel Switch (BOTS), the GLV master switch, and the BSPD. Activation of any device in this chain or detection by the BSPD of implausible driver inputs (simultaneously high brake pressure and high traction power) opens the loop and commands the Tractive System switches (TSS) and contactors to isolate the HV bus and de-energize the motor controller. Service and diagnostic features, including tractive-system measurement points (TSMP), an energy meter, and status indicators (TSAL), provide observability for safe commissioning and trackside operation.

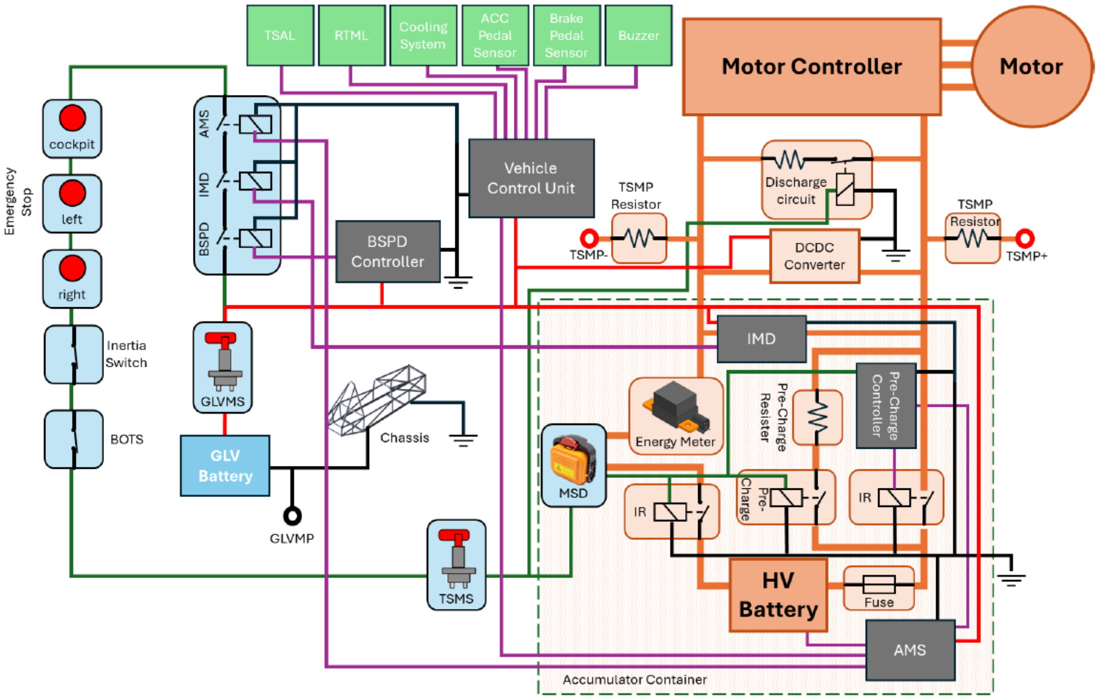

Fig. 2 *Electrical and safety architecture of the electric formula vehicle*

2. Literature Review

The integration of advanced braking systems is essential for enhancing safety and performance in electric formula vehicles participating in high-stakes competitive events like the NxGV Challenge 2025. In these high-performance environments, the implementation of robust safety circuitry, such as a Brake System Plausibility Device (BSPD), is crucial to mitigate severe risks like unintended acceleration [1]. While widespread automotive research investigates active safety features within autonomous and semi-autonomous driving systems [2], the core engineering objective remains identical: establishing rapid, reliable, and physically consistent operation to eliminate risks associated with sensor anomalies or unexpected environmental conditions. The technological evolution from traditional hydraulic architectures to complex electro-pneumatic, brake-by-wire, and steer-by-wire technologies highlights a industry-wide shift where independent plausibility checks have become foundational to safe operational logic [3]. Consequently, specialized safety mechanisms are no longer localized components but are critical tools for enhancing active vehicle safety, mitigating collision risks, and preserving dynamic stability under extreme transient conditions [4].

In commercial and industrial automotive design, a plausibility framework often translates to sophisticated control algorithms, automated slack adjustments, real-time adherence estimation [6], and active collision avoidance strategies [7] embedded within complex Advanced Driver Assistance Systems (ADAS) [5, 8]. However, for formula-style electric race cars, this high-level logic must be distilled into a dedicated, hardware-defined safety node [9]. Unlike software-reliant ADAS applications, a motorsport safety loop is a closed, hardware-serialized shutdown path containing critical trip switches (such as emergency stops, brake-over-travel switches, and insulation monitoring devices). Within this framework, the BSPD serves as a non-programmable logic gate tasked with identifying physically impossible driver inputs—specifically concurrent high brake pressure and high tractive power—and breaking the safety loop in a purely deterministic manner.

By evaluating commercial literature regarding electronic torque management during unexpected braking events [10], specific functional parameters can be established for motorsport applications. The need to suppress dangerous, persistent torque while a driver is actively braking directly justifies the implementation of a 500-millisecond persistence window, a latching fault state, and a timed 10-second re-evaluation window. From an ISO 26262 functional safety perspective, this architecture operates as an isolated, independent, and high-integrity safety layer. It achieves millisecond-scale latency and autonomous fault management entirely decoupled from the main vehicle control unit, establishing a direct link between broad commercial safety standards and the rigorous, vibration-resistant, 30 bar / 5 kW threshold architecture developed for the NxGV 2025 competitive landscape.

3. Methodology

The Brake System Plausibility Device (BSPD) controller shown in Figure 3 was developed as a dedicated, hardware-based safety circuit in line with FSAE safety requirements. Its primary function is to detect abnormal driving conditions that may compromise vehicle stability and initiate an immediate shutdown of the tractive system.

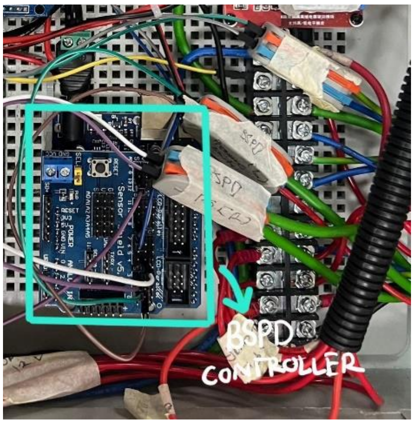

Fig. 3 *BSPD controller*

The device functions by monitoring two critical operating parameters simultaneously as shown in Fig. 4:

- Traction power output from the battery to the motor, which must exceed 5 kW.
- Brake line pressure, which is considered a hard-braking event when the measured pressure surpasses 30 bar.

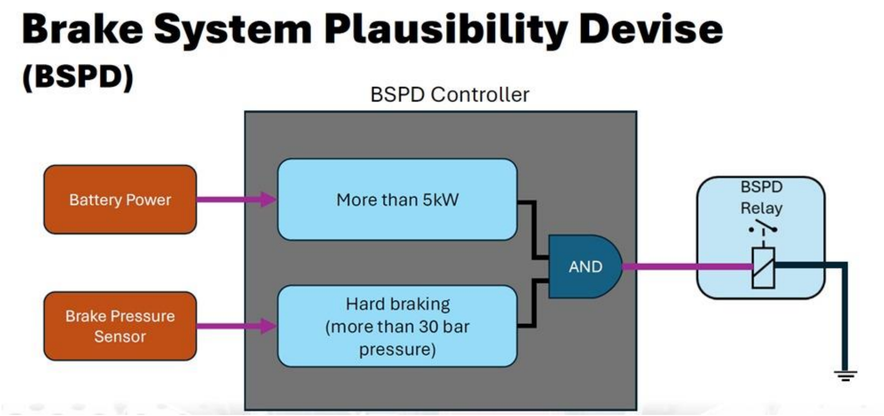

Fig. 4 *BSPD block diagram*

When both conditions occur at the same time and persist for longer than 500 milliseconds, the BSPD interprets the situation as implausible and activates the shutdown circuit. This command interrupts motor power through a relay switch, preventing unintended acceleration and ensuring driver safety. Once the cutoff is engaged, the system remains in a locked state until an automatic re-evaluation is carried out after 10 seconds. At this stage, the BSPD reassesses sensor signals, if the values have returned to normal ranges, traction power is restored, otherwise, the cutoff remains engaged until the subsequent evaluation cycle. Two main sensors were integrated into the system:

- Brake Pressure Sensor: Installed at the master cylinder to provide real-time measurements of hydraulic pressure in the brake line.
- Current/Power Sensor: Positioned ahead of the motor controller to continuously track electrical power delivered to the motor.

Table 1 *BSPD logic truth table*

Throttle (TP)	Brake (BP)	Condition	BSPD Output (Tractive Power)
0	0	No throttle, no brake	1 (Enable)
0	1	Brake only	1 (Enable, motor cut via brake logic)
1	0	Throttle only	1 (Enable)
1	1	Throttle + Brake (implausible)	0 (Disable / Motor Cut)

Based on table 1, the outputs from both sensors are transmitted to BSPD's comparator-based control circuit. Using logic operations, the circuit evaluates whether the predefined thresholds are exceeded. Upon detection of unsafe conditions, the relay mechanism disconnects the motor power within milliseconds, offering a fast and dependable response. For verification, a breadboard prototype was constructed to test the system's logic and sensor integration. Simulated trials were carried out under both normal and abnormal operating conditions. These tests measured detection accuracy, response time, and re-evaluation behavior.

4. Result & Analysis

The experimental assessment revealed that the BSPD reliably identified implausible operating conditions and executed a swift cessation of motor power. In every case where the established thresholds were surpassed, the system reacted within milliseconds, averting the risk of accidental acceleration. Subsequent to disconnection, the device commenced its designated verification phase. Ten seconds after the initial cutoff, the BSPD reassessed the brake pressure and traction power metrics. Traction power was restored just when sensor data confirmed that the vehicle had reverted to safe operational conditions. In instances when anomalous values persisted, the cutoff remained operational, preventing the system from allowing risky power restoration.

In forty simulated trials with implausible inputs, the BSPD demonstrated absolute reliability, achieving a 100% activation rate. The mean delay from fault detection to shutdown circuit cut-out was approximately 32 milliseconds, with no individual response exceeding 50 milliseconds.

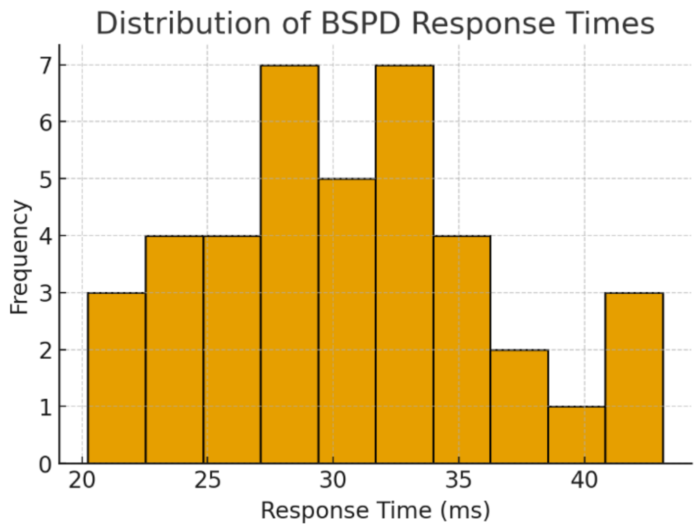

Fig. 5 *Distribution of BSPD response times*

The prototype BSPD underwent functional testing on a breadboard, with trials conducted under both safe and implausible input conditions. The results are summarized in Table 2.

Table 2 *Implausible input test*

Parameter	Experimental Value
Number of trials (implausible conditions)	40
Activation success rate	100% (40/40)
Average response time	32 ms
Maximum response time	< 50 ms
False activations (control trials)	0 (10/10 safe trials)
Re-evaluation interval	10.0 Â± 0.1 s
Safe power restoration rate	100% under normalized conditions

While the system consistently stayed well below the safety-critical thresholds, a deterministic analysis reveals a slight variance in response times ~ 5.8 ms. This variation was primarily driven by two factors:

- **Asynchronous Signal Propagation:** The simulated step-inputs for brake pressure and tractive power were asynchronous relative to the internal RC timing networks of the analog comparators. Depending on exactly where the input stepped within the capacitor charging cycle, minor millisecond-scale variations occurred.
- **Mechanical Relay Latency:** The physical actuation of the safety relay contacts introduces an inherent mechanical bounce and propagation delay (typically 2 to 8 ms) that varies slightly depending on ambient coil temperature and mechanical wear.

To contextualize these results within the domain of high-performance motorsport, the experimental data was benchmarked against official Formula SAE (FSAE) and Formula Student (FS) rules, as shown in Table 3.

Table 3 *Comparative benchmarking against competition standards*

Metric	FSAE / FS Rulebook Mandate	Proposed BSPD Performance	Margin of Safety
Max Worst-Case Delay	≤ 500ms (FSG) / ≤ 1000 ms (FSAE)	48 ms (Worst case)	> 90% faster than mandated limit
False Activation Rate	0% (Implied operational requirement)	0% (10/10 control trials)	Fully compliant
Latching/Re-evaluation	Must latch fault until power cycle or safe state	10.0 ± 0.1 s hold before auto-reset	Fully compliant for NxGV specifications

The suggested design performs more than 90% quicker than the maximum restrictions set by global rules committees, with a worst-case latency of less than 50 ms. This quick reaction reduces the amount of time that the mechanical brakes have to deal with a runaway engine, which significantly lowers the thermal load on the brake rotors and maintains maximum stopping force in an emergency. Despite these positive functional results, a number of development-stage issues need to be fixed before the track is deployed. The assembly lacks the mechanical robustness needed for challenging motorsport environments and introduces parasitic capacitances and inductances that can impair signal propagation, primarily because experimental validation was limited to a laboratory breadboard using commercial-off-the-shelf (COTS) discrete components.

Furthermore, the current analog filtering network was verified under clean laboratory power conditions, which ignores the severe Electromagnetic Interference (EMI) that is typically caused by the tractive system switching hundreds of amperes in an electric vehicle. If differential signaling or tailored RC low-pass networks aren't used to minimize this high-frequency inverter noise, it could lead to significant signal loss or unintentional trips in a deployment setting. Lastly, the RC time constants controlling the important 500 ms fault-detection delay and the 10 s re-evaluation windows are introduced with undesired unpredictability due to the dependence on standard component tolerances (such as ±5% resistors and capacitors). The next design iteration must use high-precision, automotive-grade (AEC-Q100 compliance, ±0.1% tolerance) components to provide deterministic robustness since thermal drifting during prolonged racing circumstances could change these safety-critical thresholds.

5. Conclusion

This work presented the design and development of an advanced, hardware-level Brake System Plausibility Device (BSPD) safety architecture for a high-performance electric formula vehicle. The primary scientific contribution of this research is the demonstration of a lightweight, deterministic, and sensor-integrated logic layer that effectively mitigates unintended acceleration hazards without requiring complex computing overhead or interfering with energy-recovery strategies. By cross-checking concurrent driver brake and throttle inputs, the system ensures a reliable power cut and safe restoration sequence under normalized conditions. Functional verification confirmed that this simple yet robust safety layer satisfies the stringent performance needs of competitive electric vehicles, offering a scalable blueprint for both student and professional motorsport platforms. Future work will focus on transitioning this architecture to an automotive-grade printed circuit board, conducting formal ISO 26262-aligned safety validation, and evaluating its performance during on-track testing.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***introduction:*** *Syed Muhammad Fuad, Norazam;* ***literature review:*** *Syed Muhammad Fuad, Mohd 'Afiq;* ***methodology:*** *Norazam, Mohd 'Afiq;* ***result and analysis:*** *Syed Muhammad Fuad, Norazam, Mohd 'Afiq;* ***Conclusion:*** *Norazam, Mohd 'Afiq;* ***draft manuscript preparation:*** *Syed Muhammad Fuad, Norazam, Mohd 'Afiq. All authors reviewed the results and approved the final version of the manuscript.*

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