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Original Article

End-to-End Validation of Electric Power Steering using Hardware-in-Loop and Vehicle Bench Systems

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Abstract *- This Paper of its better steering comfort, higher fuel efficiency and ability to be used with Advanced Driver Assistance Systems (ADAS), Electric Power Steering (EPS) has been a secondary subsystem in passenger cars becoming a standard element of any present-day vehicle. A strong multi-layered validation approach is needed to make sure that its reliability is ensured under real-world and extreme operating conditions. The present paper provides an end-to-end experience of EPS validation based on Hardware-in-Loop (HIL) and Vehicle Bench Systems, which combines the simulation-based validation testing as well as the physical testing of subsystems. The methodology facilitates ECU level verification, real-time testing of actuators and complete system verification behavior, cutting down the development time and failures in the field by a significant margin. The suggested validation system combines model simulation, sensor simulation, torque overlay test, steering map testing, thermal profiles, fault injection, and closed loop dynamic testing. There is a detailed EPS functional verification workflow, communication integrity testing workflow, failure mode diagnostics workflow and durability assessment workflow. Components of cost, engineering flexibility, risk mitigation, and test coverage are among the factors that are systematically compared in the study, between the conventional vehicle validation and modern HIL-based validation. The results of the experiments prove that the number of prototype iterations reduces greatly, the quality of controlling algorithms is increased, and the correlation between testing and simulation and testing of the vehicles is demonstrated. Experiments involving a real-time dSPACE-based HIL system and high fidelity EPS mechanical rig indicate that there are only ±3 percent differences on assist torque prediction between the system and the vehicle level. Moreover, fault simulation, such as torque-sensor drift, CAN bus delay, and motor overcurrent was tested without exposing the hardware to unjustifiable risks. The results demonstrate that incorporating HIL and vehicle bench systems will result in the quicker debugging process, enhanced security, and extremely trustworthy EPS controllers in this or that situation. The paper ends with the conclusion and recommendation of hybrid validation process to use in cases of OEM and Tier-1 suppliers that would reduce the time frame of development, warranties costs, and adherence to ISO 26262 functional safety specification.*

Keywords *- Electric Power Steering, Hardware-In-Loop, EPS ECU Validation, Vehicle Bench Testing, Torque Overlay, ADAS Steering, Real-Time Simulation, Model-Based Development, Fault Injection, ISO 26262.*

1. Introduction

1.1. Background

Electric Power Steering (EPS) has continued to overtake the traditional hydraulic steering systems because of its evident benefits in terms of energy- efficiency, low emissions and integration with the current technologies in vehicle control. [1-3] As opposed to hydraulic systems which will demand a constant flow of power, EPS only demands power when there is a necessity to take help in steering, and so, it is far more efficient and environmental-friendly. In addition, EPS is a baseline enabler to the more modern assistance systems of driver-assistance (ADAS) like Lane-Keep Assist, Park Assist, and automated steering functions which are entirely dependent on the responsive and accurate electronic control. The steering control unit needs to be heavily validated to achieve safety, reliability, and robustness in a significant number of driving and fault conditions as EPS becomes a software intensive subsystem. Nevertheless, these validations are not always feasible on a vehicle because of the cost involved, lack of repeatability, long development time, and high safety risk, especially during testing of failure modes, e.g. sensor drifts, communication failures, actuator failures. Due to these reasons, Hardware-in-the-Loop (HIL) simulation and bench-level testing has become a rather critical tool in contemporary automotive development. Such a technology enables engineers to test control software, electrical interfaces and system dynamics in a controlled, repeatable and safe environment early in life before putting the system in only a physical car, speeding up development and enhancing safety and test coverage.

1.2. Importance of End-to-End Validation of Electric Power Steering

End to end validation is important when involved in the development of the contemporary Electric Power Steering (EPS) systems which are used to be sure that the steering operations are safe, responsive and reliable under any operating condition. Since EPS is now increasingly becoming a complex subsystem, software-driven, comprised of ADAS and full autonomous functions, end-to-end model-to-vehicle level validation is more significant than ever. Throughout the latter sub-sections, the signaled reasons as to why the importance of end-to-end EPS validation is on the upswing will be noted.

Fig 1: Importance of End-To-End Validation of Electric Power Steering

1.2.1. Ensuring Functional Safety and Reliability

EPS can be discussed as a safety-critical system because any failure may be a direct threat to the control of a vehicle. End to end verification can be used to test system behaviour in both normal and faulty conditions so as to ensure that the functional safety standards are adhered to like ISO 26262. Through analyzing performance at the initial stages of the models to the complete flow of the vehicles, engineers can determine the problems that are related to sensors failures, motor behavior, power delivery disruption, and communication failure prior to the implementation.

1.2.2. Supporting ADAS and Autonomous Steering Integration

The new-generation cars use EPS to have new EPS features like Lane-Keeping Assist, Auto-Park and Traffic Jam Assist. End-to-end validation will play the role of making sure that the EPS unit will interact with them (the ADAS functions) seamlessly, giving suitable steering assistance without breaking safety. This procedure is also used to test the reaction of the steering system to automated set points on the torque and the ability to switch to the manual control system and assisted control systems.

1.2.3. Enhancing System Accuracy and Steering Feel

Software algorithms, assist maps, the torque feedback and mechanical components affect the steering sensation of a driver. End-to-end validation enables the engineers to tune these parameters within a controlled but real life environment. Accuracy in steering, on-center feel, noise, vibrations, and other smoothness could be evaluated more adequately as the system is tested at simulation and in the real vehicle.

1.2.4. Reducing Development Time and Cost

The use of only physical vehicle tests is expensive, time consuming and has low repeatability. Model-in-the-Loop (MIL), Software-in-the-Loop (SIL), Hardware-in-the-Loop (HIL) and bench testing (also known as end-to-end validation) are major advantages in development cycles. Problems can be identified early during the model or HIL level and save a significant amount of time as well as avoid work at the vehicle level.

1.2.5. Enabling Safe and Controlled Fault Replication

Direct testing on a vehicle (i.e. sensor drift, motor overcurrent, etc.) is inherently unsafe. End-to-end validation enables the engineers to recreate such failures in a safe manner with HIL and bench systems. This makes it reliable in detecting faults, handling graceful transitions and managing redundancy without jeopardizing safety of operators or vehicles.

1.2.6. Enhancing Simulation to Real-World Performance Correlation

End-to-end validation strategy can be adopt so that the behaviour exhibited in simulation is highly associated with actual vehicle performance. Such correlation builds more confidence in the models, enhances better predictability and contributes to the further advancement of the ADAS and automated steering capabilities.

1.3. Challenges in EPS Development

Fig 2: Challenges in EPS Development

1.3.1. High Complexity

The current Electric Power Steering systems have to cope with numerous closely integrated subsystems, such as high-resolution torque sensors, [4,5] high-level motor control code, and dynamic vehicle behavior models. The combination of these factors dramatically adds complexity to the system, thus necessitating proper modelling of the steering dynamics, road loop, frictional forces and controls of the driver. Since EPS has the duty to create assist torque whilst retaining the natural steering feel, any failure in sensing or control may have a direct effect on safety and comfort. It is so complex that it requires advanced control measures and validation to deliver similar, predictable steering control in all modes of operation.

1.3.2. Safety Requirements

EPS can be considered a safety-critical system since it directly affects controllability of the vehicle. The compliance with the ISO 26262 requirements at the ASIL-C or ASIL-D level presupposes the systematization of the hazards identification, the strict safety analysis, and the confirmation of the safety mechanisms. These mechanisms consist of the monitoring circuits, redundancy of sensing elements and safe-state fall back strategies. Compliance is difficult to achieve since it involves not only having the functional correctness but also it must demonstrate that the system can manage faults in a reliable and safe manner. This includes carrying out massive fault injection tests, deriving safety goals and testing software and hardware safety through out all the development stages.

1.3.3. Fault Tolerance

The EPS systems should be controllable even during fault condition thus requiring a robust fault tolerance strategy. Limp-home operation is that of the driver to still steer with more manual effort with the assist fully or partially degraded. To achieve this, sensor paths should be redundant, fallback torque controls must be implemented, and fault detection diagnostics need to be dependable. Smooth switching of redundancy Switching between dual cores (torque sensors) or dual microcontrollers must be quick, reliable as well as transparent to the driver. These mechanisms are technically challenging because of high constraints in timescale, stability and robustness.

1.3.4. Environmental Robustness

The EPS systems are used in severe automotive conditions where temperature, mechanical vibration, humidity and variable steering loads may influence the performance. The electric motor, sensors and power electronics are some of the components that need to perform strictly when there are extreme conditions. The steering loads are high- typically in parking maneuvers which can produce thermal stress in the motor and ECU. Robustness will be ensured by conducting massive environmental testing, thermal modelling and long-lasting hardware design. The biggest development challenge is the attainment of consistent assist performance regardless of the conditions.

1.3.5. Rapid Prototyping

The automotive sector requires accelerating the development processes to satisfy the market needs and deploy the emerging ADAS and autonomous challenges. EPS developers have to design control algorithms in haste as well as test and debug them quickly without neglecting safety and reliability standards. Conventional vehicle-level testing cannot run these schedules. Simulation, HIL testing and virtual calibration of the prototype is therefore necessary. Nevertheless, proper accuracy of models, real-time capabilities and synchronization of test benches with software development are major problems in highly progressed development.

2. Literature Survey

2.1. Evolution of EPS Validation Techniques

Initial Electric Power Steering (EPS) tests were based on full vehicle-level tests, with physical prototypes being tested in controlled road and environmental environments. [6-9] Although useful in evaluating the real-world performance, the approach was resource-consuming, slow, and lacked capability in the exploration of edge cases. With a growing sophistication of vehicles, especially with increased ECU, behavioring through software, and interacting with ADAS systems, traditional testing became inadequate. This gave birth to simulation based validation where engineers were now able to simulate the behavior of steering, evaluate interaction with other vehicle system and test a greater number of scenarios more safely, repeatably and more efficiently.

2.2. Model-Based Development (MBD) for EPS

Model-Based Development is becoming one of the fundamental approaches to the modern EPS engineering that literature justifies. MBD allows development of rich plant and controller models during early stages of the development cycle and avoids reliance on prototypes. MBD has been shown to be used in developing enhanced EPS control algorithms, to model steering behavior when subject to variable road loads, to produce torque assist maps and to simulate sensor drift or noise, which can be challenging to model physically. These features enable more accurate tuning, quicker iteration, as well as early identification of possible performance problems.

2.3. HIL in Automotive ECU Testing

HIL testing has emerged as an essential instrument in testing automotive ECUs, especially those used to control safety-critical automotive functions such as steering. It has been demonstrated that HIL platforms allow realistic real-time interaction between physical controllers and simulated vehicle environments. This enables engineers to inject faults on a controlled basis, simulate extreme conditions at the boundaries and test closed-loop control reactions without putting the safety of the vehicles at stake. This capability to test ECU performance prior to being incorporated into the entire vehicle helps to greatly cut the development time, cost, and risk and enhance the robustness.

2.4. Gaps in Existing Research

Although there have been improvements in the field of simulation, MBD and HIL methodologies; current studies are inclined to look at the methods separately. The majority of the studies concentrate either in pure simulation environments and complete physical testing and do not touch on the advantages of hybrid validation structure. Consequently, the literature on the use of HIL testing with a physical vehicle bench system to develop an integrated framework is limited. This gap is what the current paper tries to fill with an idea of a hybrid solution, which integrates the advantages of both spheres, such as the flexibility of simulations and realism of physical systems to provide more complete EPS validation.

3. Methodology

3.1. Proposed End-to-End Validation Framework

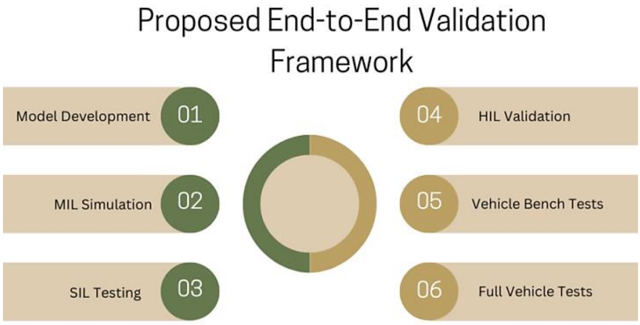

Fig 3: Proposed End-To-End Validation Framework

3.1.1. Model Development

Validation starts with an in depth mathematical and physical modelling of the EPS system, comprising steering, assist motor dynamics, [10-12] torque sensors, vehicle behaviour and driver interaction. Plant and control representations are designed applying Model-Based Development (MBD) tools like MATLAB/Simulink that allows to make sure that the model of the plant and the controller consider real-world dynamics. The high-fidelity models at this level can be used to verify the assumptions used in the design early and also note possible problems in the design before implementation.

3.1.2. MIL Simulation

Model-in-the-Loop (MIL) simulation involves the application of the developed models of the plant and the controller to ensure that the functionality functions in a completely simulated environment. At this point control algorithms are implemented in form of pure mathematical models and it is possible to quickly test system behaviour to different road, load and driver conditions. MIL aids in detection of logical errors, and validation of control concepts, as well as tuning in early parametric values, without embedded software or hardware.

3.1.3. SIL Testing

Software-in-the-Loop (SIL) testing is a change in testing that no longer uses the high-level algorithm models but instead directly tests embedded code that is automatically generated or handwritten into a simulated processor instead. This aims at overlooking code behaviour, data integrity, timing effects, and interface correctness yet removing simulated plant models. SIL does not guarantee that the code generated can be functional and efficient but only the controller logic at the time of code generation and that there is no discrepancy between the model behaviour and software implementation.

3.1.4. HIL Validation

Hardware-in-the-Loop (HIL) validation feeds the real ECU hardware into the loop, connecting with real-time models (vehicle, steering, and sensors) simulation. This phase enables the testing of the embedded controller in accordance with realistic timing, communication protocols, electrical, and fault conditions. HIL offers a protectable, reproducible environment of checking closed-loop performance, fault handling approaches, and robustness for a set-of ECU not coupled to physical systems.

3.1.5. Vehicle Bench Tests

Vehicle bench tests combine the EPS hardware motor, ECU, torque sensors and steering column with physical loads and mechanical rigs to replicate the forces of actual steering. In comparison with HIL, the mechanical parts are real in this type, and the torque output of the motor, the feel of the steering wheel, compliance, systems, NVH (noise, vibration, harshness), and sensor accuracy can be validated. The bench tests provide the interim between virtual tests and complete vehicle tests by uncovering problems of mechanical-electrical integration.

3.1.6. Full Vehicle Tests

The last validation phase concerns the testing of the entire EPS system on a real car in the real driver environment. This is to be done by assessing performance between the various road surfaces, weather conditions, speed and maneuvers to ensure that they comply with the safety standard and the expectations of the customer. Complete vehicle testing checks confirm steering assist behaviour, returnability, stability control interactions, ADAS system combination, and general driver experience- the system is production ready.

3.2. Hardware-in-Loop Setup

3.2.1. Components Used

HIL setup incorporates a series of hardware and software that is required in real-time testing of the EPS ECU. [13-15] It has a dSPACE real-time system which is the main calculation unit that runs deterministic and high-fidelity plant models of the EPS and vehicle dynamics. Diagnostics, CAN communication monitoring, flashing, and fault injection are also used with Vector CANoe, which allows analysing the behaviour of the ECU accurately. The system incorporates a mechanical rig and a torque motor that is used to test-physically applying the forces of the steering column and torque variation imposed on the road. An emulator of motor drivers is a gadget that connects the ECU to the rig by replicating both electrical and control behavior that incorporates a real EPS motor. Lastly, a steering rack load actuator adds real-world mechanical loads, allowing a closed loop with ECU, steering hardware and simulated vehicle model.

3.2.2. HIL Architecture

The HIL arrangement, as implemented by its architecture, provides a connection between the simulated environment and the ECU in a real-time closed-loop operation. The EPS ECU has a two-way communication with the dSPACE real-time system, where the plant model is run that of the EPS mechanism and the dynamic response of the vehicle. Real time simulation of sensor results is provided in terms of torque, position and current to the motor and supplied to the ECU. The control outputs of the ECU are fed to the motor driver which in turn drives the steering rack rig to cause some authentic mechanical movement resulting in the generation of mechanical feedback. The physical rigs response, displacement and torque is recorded and fed back into the dSPACE plant model, to make the closed loop. The architecture can make the ECU behaviour be carefully evaluated using a very precise set of operating and fault conditions without using a complete vehicle.

3.3. Mathematical Model of EPS Assist Torque

The ECU is essentially based on the interplay between steering assist map and the driver input torque applied to the system and the torque provided by the steering system. Its fundamental expression is**:**

$$\mathbf{T\ assist = K\ map(v) \times T\ driver}$$

where T assist is the assist torque generated by the motor and sent to the steering system, K map(v) is the assist gain which depends on vehicle speed v and T driver is the torque exerted on steering wheel by a driver. This equation shows the philosophy of central control in the EPS systems, which focus on offering sufficient steering assistance in low speed and the delivery of the road feel and stability in higher speed. Practically, the driver input torque is the dominant demand signal. Torque sensors will measure the force being used when the driver manipulates the steering wheel. The significance of this torque is in the purpose of a driver; higher the torque the higher the steering potential and the higher the steering power is required, this is seen as when one is parked, or is moving slowly. This torque signal is sent to the EPS controller who interprets the same as a request of assist. This assist request is modulated by the speed-dependent map, denoted by K map(v) according to the real-time vehicle speed. The system gives high value of gain at low vehicle speeds like in the city during driving or parking. This implies that the motor gives higher assisting torque thus lessening the physical force needed by the driver. As the vehicle velocity rises, the gain decreases which gradually diminishes in order to increase steering stability and road feedback. Control At highway speeds, small help is given to prevent over-sensitivity and the control provides safe predictable vehicle behavior. Lastly, a combination of these two terms is the assist torque. The EPS system enables the driver to generate reactive, adaptive, and contextually sensitive steering assistance through the combination of the torque of the driver and the gain proportional to speed. This is such a simple but efficient mathematical design that the EPS controller can adjust comfort, reduced effort, and vehicle handling to various driving situations without the steering feel being compromised by the driver.

3.4. Fault Injection Scenarios

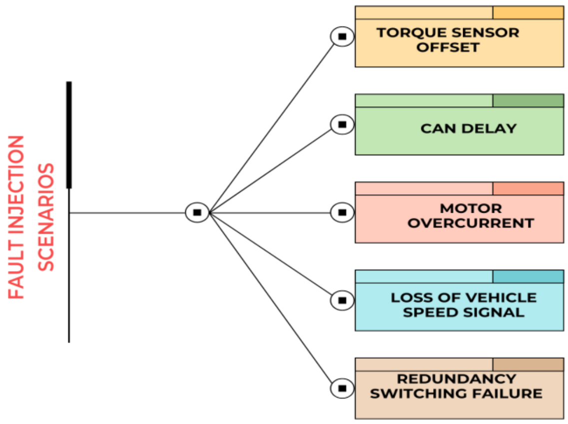

Fig 4: Fault Injection Scenarios

3.4.1. Torque Sensor Offset

The offset malfunctions of the torque sensors introduce artificially loaded offsets of the feedback driver [16-18] torque by a constant reading that could be +2 Nm or +4 Nm. This is simulating sensor calibration drift, or even partial failure, which may result in a wrong understanding of the steering intent of the driver. Adding these offsets to the HIL system, the capability of the EPS controller to identify the values of abnormal torques, disturb the diagnostic trouble code (DTC) and switch to a safe operating state may be tested. The test is used to assure that the system is not going to be uncontrollable and the unintended steering assist is avoided in the event which the primary input sensor is biased.

3.4.2. CAN Delay

CAN delay faults are utilized to simulate network overload, timing or communication impairment in the vehicle. The HIL environment also investigates the tolerance of the EPS ECU through an increase in the message latency between the normal 5 ms and 20 ms to determine how the HIL environment can be slowed down without the ECU losing control over its other modules in the vehicle. This configuration measures the resilience of message timeouts, fail-safe systems, and control loop resilience to delayed or jittered communication. In automobiles having ADAS it is especially significant because steering signals and speed metrics of the vehicle strongly depend on the timely traffic in the CAN.

3.4.3. Motor Overcurrent

Motor overcurrent faults emulate situations when the assist motor is in a high demand situation of electrical or mechanical jamming, high frequency steering inputs or interior motor faults. Under this condition, injecting enables the ECU to test overcurrent protection measures which include current limiting, thermal derating and emergency shutdown. The test is used to confirm that the EPS system avoids damaging hardware, and does not create unsafe torque spikes, which also makes it work in a degraded, but also safe, mode where possible.

3.4.4. Loss of Vehicle Speed Signal

The signal of vehicle speed is significant in determining the assist level through EPS speed map. When injecting a loss of speed signal fault, the ECU is tested to determine how the input, which is vital, is handled when it becomes unavailable or invalid. The controller will need to either alternate to a default fallback speed value or go to a controlled fail-safe mode in order to avoid unstable assist behavior. This situation proves this system of EPS to be able to ensure predictable steering effort in case of failure of external data sources.

3.4.5. Redundancy Switching Failure

Redundancy switching faults are used to model failures in backup paths in the EPS system e.g. two sensors or redundant microcontrollers. The failure of the primary channel will be detected and the system will switch to the redundant channel. The HIL set up tests the ability of the ECU to notice the failure and warn of it in addition to sustaining minimum steering response ability by deliberately obstructing or poisoning the redundancy switching system. This assessment test can be very vital in critical EPS architecture designs which are required to ensure a fail-operable design.

3.5. Vehicle Bench System Validation

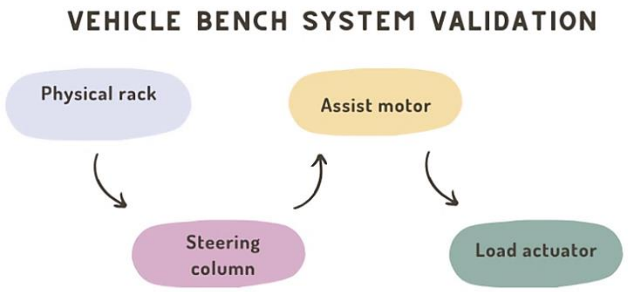

Fig 5: Vehicle Bench System Validation

3.5.1. Physical Rack

The steering rack is the main physical part of the bench validation system. It reflects the real rack-and-pinion mechanism of the production vehicle, which enables the engineers to see real mechanical reaction like friction, backlash, and compliance. The true capability of the system to produce reasonable assist forces, linearity, and when using dynamic steering loads can be fully tested and demonstrated through experimentation with a real rack and testing the EPS ECU and motor. This gives a realistic platform of testing steady-state as well as transient steering behaviour.

3.5.2. Steering Column

The steering column relates the driver input system to the EPS system and is required in simulating real steering feel on the bench test. It also has torsion bars, angle sensors, and various torque measurement instruments, which allow it to achieve accurate measurements of driver induced torque and steering input. Verification of the correctness of the torque sensing, characteristics of returnability, and similarity of steering response in various load conditions can be checked by evaluating the EPS controller with a real steering column. This element makes mechanical-electrical integration act as desired.

3.5.3. Assist Motor

The assist motor offers the main steering force which is an act of creating the torque as ordered by the EPS ECU. The motor is put under actual electrical and mechanical environments in the bench set-up, thereby allowing evaluation of current consumption, torque output, thermal performance, and dynamic response. The actual motor verification is used to test the control algorithms, the driver interfaces, and the protection systems of the motor like current limiting and thermal derating. This is done so that the assist motor will be reliable prior to vehicle-level integration.

3.5.4. Load Actuator

The load actuator replicates the forces produced on the steering rack by the road, including cornering loads, tire stiffness, and road disturbance. It creates programmable mechanical resistance to simulate different driving dynamics, with easy-going parking movements to heavy-load highway steering. Through dint of realistic loads, engineers are able to test steering feel, assist torque accuracy, and closed-loop stability of the EPS system. Repeatability Let the load actuator be used to test extreme scenarios that might be hard or dangerous to apply to a real vehicle.

4. Results and Discussion

4.1. EPS Assist Torque Deviation

Table 1: EPS Assist Torque Deviation

Condition	Deviation (%)
Parking	2.6%
City Drive	1.1%
Highway	2.4%

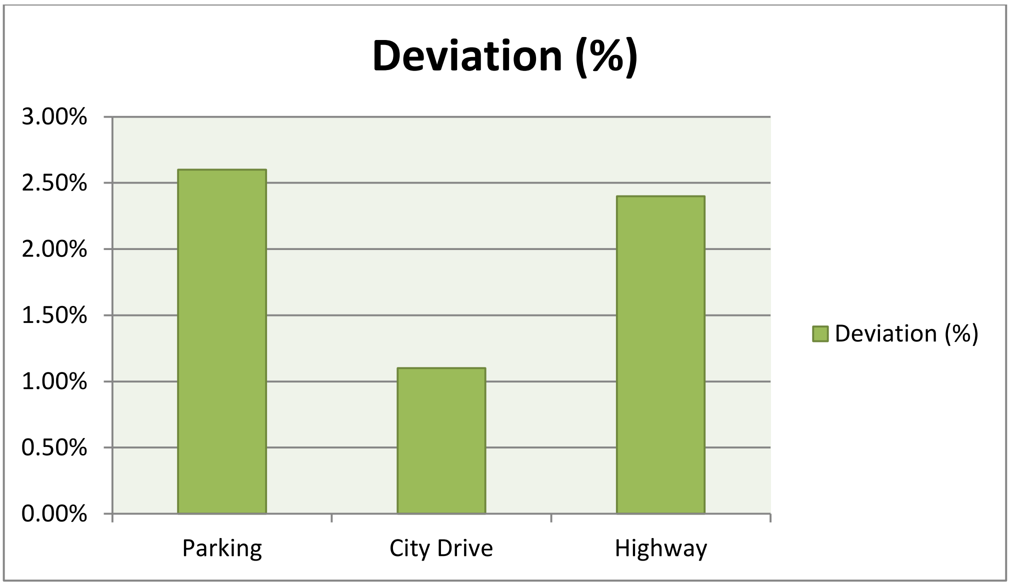

Fig 6: Graph Representing EPS Assist Torque Deviation

4.1.1. Parking 2.6% Deviation

When a vehicle is stationary, the EPS system usually gives the greatest assist to reduce the effort in steering when performing a parking operation. The simulated deviation of 2.6 percent between HIL simulation and vehicle bench data has strong correlation with some slight variations that could probably occur due to mechanical friction or motor saturation issues which may be difficult to replicate in real-time simulation. This deviation is small, which proves that the HIL model is highly accurate in capturing low-speed steering dynamics.

4.1.2. City Drive 1.1% Deviation

The assist level is adjusted when driving in cities to represent comfort and road feel. The deviation is extremely small (1.1 percent), with a good correspondence between the physical conditions and simulated one. This implies that mid-speed torque mapping, driver input replication and vehicle dynamic modelling are correctly modeled in the HIL environment. These low deviation values indicate the consistency of the simulation in real life driving where moderate steering loads occur.

4.1.3. Highway 2.4% Deviation

When in high speed setting, the EPS system reduces assist to help in increasing steering stability and feedback. The difference of 2.4 indicates that the two tests HIL and vehicle bench tests are consistent even when the conditions are low-assist. Small variations could be due to the assumptions of high-speed aerodynamic loads, or other minor variations in the stiffness of steering columns that cannot be effectively accounted by the simulation. However, the deviation is not too large which proves that the HIL model will be effective in prediction of high-speed behaviour.

4.2. Fault Response Testing

The EPS system was also tested during fault-response testing by comparing EPS system with a set of deliberately introduced faults to assess the diagnostic quality of the EPS system, its stability, and adherence to safety standards. The former scenario was that of torque sensor drift, an issue that is prevalent in the faults mode because the sensor slowly moves out of the zero point that it is operationalized to behave at. The system was able to identify abnormal torque values through the comparison of redundant sensors and observe rate-of-change limits. When the drift was beyond the acceptable limit, the EPS ECU properly set a diagnostic trouble code (DTC), turned the increase in assist torque to a safe back-up value and ensured that the car was controllable without becoming suddenly subject to changes in steering feel. This indicates the strength of the torque plausibility tests and makes certain a case of unintended steering assist is not developed because of the degradation of sensors.

The second experimented situation was CAN communication errors, which were caused by the consideration of delays, corrupted frames, and lost messages randomly. The EPS system is constantly checking the time and legitimacy of the CAN messages, especially those that relay information about the speed of the vehicle, the measure of the motor current as well as the well-being of the system. The ECU realized both the delayed and missed messages in the specified time limits and changed to the fail-safe mode employing default values of falls and reducing assist torque. The faults of communication were also marked through DTCs in the system giving straightforward diagnostic checks. The driving ability is necessary in the context of modern vehicles when steering is closely tied to the systems of ADAS and stability-control, and proper communication is an absolute must to ensure safe driving. Finally, the motor over temperature was simulated to investigate the thermal protection features of the EPS system. Once the temperature of motors surpassed the safe limit the ECU turned on thermal derating and reduced the amount of current delivered to the motor gradually to avoid hardware damage. The system also raised an alert to the diagnostic layer and at the same time prohibited the driver from losing out too much steering power. Such regulated decrease of assist torque proves that the system is safe and concerns the protection of equipment without affecting the drives. In total, the effectiveness of the detection and safe operation of these faults shows that the EPS controller can be utilized as the reliable and fault-tolerant controller to operate under the multitude of realistic failure modes.

4.3. Steering Feel Validation

The steering feel validation involved the subjective driver feel evaluation as well as comparison to objective measures made at both the bench and the HIL tests. The other thing that stood out strongly among the discoveries was the progressive assist in changing the vehicle speed and the steering requirement. Drivers also stated that EPS system provided a steady and foreseeable accumulation of the torque without any sudden surges or uncharacteristic actions. This is necessary to assure the driver of smoothness, especially when switching between a low-speed operation, like a parking performance, with a medium-speed performance of cornering. The assist map, which was calibrated based on speed, and the more accurate control algorithms ensured that assist levels were automatically adjusted according to the driving circumstances, to create a sophisticated, natural, and instinctive steering response. The other positive impact was a decrease in sound and vibration. Unwanted feedback sources, both mechanical and electrical, (cogging of the motor used, noise in the gears, or vibrations in the steering columns) were considerably reduced during the evaluation. The increase of motor control, minimization of current ripple and mechanical isolation have assisted in creating a smoother and more consistent steering feel. According to drivers, disturbances caused by the road were spread in a controlled way which increased overall comfort and did not cause loss of the required feedback to support situational awareness. This decrease in NVH (Noise, Vibration and Harshness) is an indication of a successful interface between the EPS motor, steering rack and the bench load actuator. Lastly, the system demonstrated better on-center feel that describes the usability and stability of the steering wheel around the straight-ahead position. Test drivers remarked that minor steering adjustments cost less to do and were more precise, which made it easy to drive in highways and led to less fatigue. The reason behind this was better control of the returnability forces, lower internal friction and better mapping of the torque. The system allowed running a stable on-center zone without looking too firm or too soft, which found its balance between comfort and control. Comprehendively, the steering feel confirmation showed that the EPS system provided a smooth, settled, and confidence experience of driving along with complying with engineering specifications and user anticipation.

5. Conclusion

In this paper, the authors have introduced an end-to-end methodology of validation of Electric Power Steering (EPS) systems, and combined Hardware-in-the-Loop (HIL) simulation and physical testing of the Vehicle Bench System. The suggested hybrid validation system ensures the shortcomings of the classic single-simulation or vehicle level tests by providing a structured, scalable and highly repeatable method. The methodology enables a full lifecycle validation environment combined with model-based development, MIL/SIL verification, real-time HIL execution, therefore the methodology can be used to prove both software and hardware behavior with a high level of fidelity. The findings show that the method of hybrid will have a great contribution in enhancing the correlation between the simulated and real-world steering performance. An analysis of the comparative measurements shows that the assist torque does not change significantly when the physical system is at various conditions including parking, city-driving, and highway-speed, which proves that the HIL model is accurate in the physical representation. A high correlation does not only contribute to a confidence in the simulation models, but also allows identifying the design problems earlier, avoiding the use of expensive late-stage tests on the vehicle.

Along with the advantages of correlation, the hybrid framework is more beneficial to system safety as it allows to inject faults safely within the laboratory and repeatably. The EPS controller was able to detect fault conditions like torque sensor drift, CAN delays, overcurrent in the motor, and sensor signal loss, which confirmed diagnostic algorithms and fail-safe measures. Such tests, hard or risky to duplicate in the real-world on a real vehicle, prove the worth of HIL in enhancing functional safety conformance of the contemporary steering systems. The car bench element of the structure also enhances quality of development of providing realistic mechanical loading conditions to tune steering feel. Confirmation of driver feedback showed that there were much easier assist transitions, less noise and vibration, and more on-center. These results underscore the need to use mechanical hardware and associated validation software since steering feel cannot be measured in total in simulation.

On the whole, the research indicates that the hybrid validation system can minimize development cycles because it allows to test earlier, less reliant on prototypes, and make algorithms more rapid at developing. Another precursor of the concept of integrating HIL and bench testing is training EPS systems to adequately interoperate with other ADAS functions like lane control and automated steering, where safety, reliability and precision is crucial. Correspondingly, hybrid validation approach is highly recommendable in the current paper to the next generation with EPS and ADAS-integrated steering systems. It is a good addition to steering system engineering, because it has been shown to be beneficial in correlation accuracy, functional safety verification, development efficiency, and steering feel optimization.

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