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DESIGN AND IMPLEMENTATION OF HARDWARE-IN-THE-LOOP (HIL) PLATAFORM FOR TURBOCHARGED STRATIFIED INJECTED (TSI) ENGINES

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Abstract. *In recent years, the automotive industry has demonstrated a heightened commitment to devising innovative strategies aimed at mitigating the contemporary environmental challenges arising from the emissions of exhaust gases and particulate matter resulting from combustion processes. Among its foremost research priorities lies the optimization of fuel efficiency and engine performance. The adoption of a model-based approach and hardware-in-the-loop to engine systems design has significantly expedited the early stages of development and facilitated rigorous performance testing of control strategies that steer engine management systems in a more environmentally conscious direction. This paper presents the design and deployment of a Hardware-In-the-Loop (HIL) platform tailored for Turbocharged Stratified Injected Engines (TSI). The proposed platform encompasses the development of an Electronic Control Unit (ECU) that interfaces with a Real-Time PC (RTPC). In terms of verification and validation, a control strategy targeting air-fuel ratio (AFR) has been created and integrated into development ECU. Additionally, a virtual engine model, rooted in the EA211 TSI, was formulated to accurately replicate the dynamics of the AFR model. Experimental results underscore the favourable outcomes obtained, thus substantiating the utility and pertinence of the HIL platform within the engine development process.*

Keywords: *Internal combustion engine, Engine management system, Control strategy, Hardware-in-the-Loop.*

1. INTRODUCTION

There is a trend in the automotive industry focusing on flex-fuel vehicles. In 2021, approximately 90.5% of passenger cars were flex-fuel, operating with both gasoline and ethanol (Anfavea, 2022). Automakers are investing in smaller engines with technologies that make them more efficient without compromising the user experience. One notable technology in this regard is direct fuel injection (BRUNETTI, 2012). The strategies enabled by direct fuel injection and the use of biofuels like ethanol are well-established in Brazil, as indicated by the annual report from Anfavea (2022), this justifies the present work and the research interest in these technologies and their impacts on the characteristic curves of a spark-ignition combustion engine. The Brazilian industry's attention to adapting direct injection technology for ethanol use, such as optimizing ethanol stratification, aligns with the policies of the "Rota 2030" initiative (Brasil, 2020).

The strategies made feasible by direct fuel injection, coupled with the utilization of biofuels such as ethanol, have firmly established themselves in Brazil's automotive landscape. This fact is substantiated by data presented in the annual report Anfavea (2022), underscoring the rationale behind the present research effort and the burgeoning interest in investigating these technologies' effects on the characteristic performance profiles of spark-ignition combustion engines (Brasil, 2020).

Research and development work on stratified charge gasoline direct injection engines dates back to the 1960s. Notable innovations have been achieved since then in control technologies, particularly those for fuel injection control and mixture formation. Direct injection engines have the potential to achieve higher specific power and improve fuel economy by minimizing knock combustion during full load operations and reducing pumping losses during partial-load conditions. They are an alternative concept that operates with a lean and homogeneous air/fuel mixture (Heywood, 2018; Duronio *et al.*, 2020; Banerjee and Kumar, 2016; Alkidas, 2007).

There are two basic approaches to stratified charge combustion: wall-guided air systems and spray-guided systems

(Zhao *et al.*, 1999). First-generation direct injection engines, proposed by Toyota, Nissan, and Volkswagen, utilize a wall-guided air combustion system and consist of a side-mounted injector, forming a rich mixture near the spark plug. According to Lee and Lee (2006); Park *et al.* (2020), this technique does not require a high-pressure injection system as it offers easier mixture development, although the mixture is significantly influenced by the flow motion in the cylinder, which varies under different operating conditions. Direct injection engines with wall-guided spark-ignition are available in Japan and Europe for years, but their sales have been limited due to small ranges of real-world fuel economy gains, and their introduction in the United States of America, according to Ando and Arcoumanis (2009), was delayed by the high sulfur content of gasoline in that country.

Two fundamental approaches to stratified charge combustion are recognized in the field, namely wall-guided air systems and spray-guided systems, as detailed by Zhao *et al.* in 1999. The initial generation of direct injection engines, introduced by manufacturers such as Toyota, Nissan, and Volkswagen, is founded upon a wall-guided air combustion system. These engines incorporate side-mounted injectors that facilitate the creation of a rich mixture in proximity to the spark plug.

Recently, the spray-guided combustion system, a second-generation technique, has been developed and applied to engines. It employs a centrally mounted high-pressure injector, forming a fuel-rich mixture near the spark plug. The operational range of lean and stable combustion systems is wider than that of wall-guided air systems and port fuel injection (PFI) systems (Tan *et al.*, 2016; Yang *et al.*, 2013). This technology is the focus of this research and the most studied currently, but it is also the most expensive (Kneifel *et al.*, 2009). However, in the Brazilian and Latin American markets, direct injection stratified charge engines installed in commercial vehicles are relatively new, and the wall-guided air system was implemented due to economic and design constraints. From there, many studies and investments related to the design and development of these engines are still needed. Fuels, load conditions, and climate are some of the key parameters that differentiate previous international works.

Lean combustion mode is generally considered as a timely solution for stricter environmental regulations and global climate concerns. According to Rodrigues Filho *et al.* (2016); Tully and Heywood (2003); Jung and Iida (2018), operating with an air-fuel ratio excess $\lambda > 1$ inherently makes this type of engine more efficient and less throttled, greatly reducing pumping losses, increasing the mean effective pressure (MEP), and further enhancing engine thermal efficiency. In particular, the lower combustion temperatures provided by a lean air-fuel mixture result in a significant reduction in exhaust emissions, especially nitrogen oxides (NO_x) (Kang *et al.*, 2017). Lean operation is typically restricted, however, by the "lean limit" of combustion, measured by increased cycle-to-cycle variations, also measured by the IMEP (Indicated Mean Effective Pressure) covariance, and by the deterioration of CO and THC (total hydrocarbon) emissions (Ayala *et al.*, 2006). Much effort has been made by the scientific community to extend this limit in stratified charge engines with the aim of exploring their benefits over a wider range of air-fuel ratios, load, and engine speed.

2. MATERIALS AND METHODS

For the tests, an EA211 TSI engine was used. The manufacturer-provided data for the engine is presented in Table 1. In this study, the engine was fueled with ethanol, and the measurement conditions were adjusted in accordance with the ABNT 1585 standard. Temperature, humidity, and atmospheric pressure sensors from the Dynamite measurement system's weather station were utilized to ensure accurate measurements.

Table 1. VW EA211 200 TSI engine - technical specifications

IC Engine Characteristics	Value
Displacement	999cm ³
Cylinder diameter	74.5mm
Piston stroke	76.4mm
Number of cylinders	3 in-line
Valves per cylinder	2
Compression Ratio	10.5:1
Fuel injection system	Side-mounted Air-Guided Direct Fuel Injection
Maximum rated power	78.3kW(ethanol)@5000RPM
Maximum rated torque	168 Nm @ 1500 RPM
Injection pressure	50-250 MPa
Ignition order	1-2-3
Variable Valve Timing range	50° on intake, 40° on exhaust
Maximum Boost Pressure	100 kPa
Engine Operating Temperature	87°C at head, 105°C at block

2.1 Development of Hardware-In-the-Loop (HIL) Platform

Hardware-In-the-Loop (HIL) platforms are commonly used by companies in the automotive sector to reduce costs and accelerate automotive product development. They are designed and used to assist engineering teams that do not have physical prototypes in the early stages of development. This allows testing, verification and validation of control strategies developed for an engine to be developed and tested in a virtual environment, without the need for expensive tests on a dynamometric bench. For this reason, they have been commonly used to support the development, improvement and incorporation of control strategies in engine management systems. A HIL platform commonly consists of a development ECU and Real-Time Computing (RTPC). In an RTPC, the outcomes of certain computing depend not only on how it is done but also on when it is done (Lee, 2018). Ignition, injection, and idle speed controllers can be incorporated and run in the development ECU. The RTPC, on the other hand, has dedicated interfaces to emulate sensors, actuators and the dynamic behaviour of engine subsystems, in addition to having a strong temporal restriction on signal generation. These resources allow the electrical signals obtained to resemble those obtained from physical components.

In a HIL platform, the system to be controlled, sensors and actuators are gradually replaced by logic components or models. The models consist of a virtual representation of physical components allowing the emulation of behaviour in a computational system. When the relationships between inputs and outputs are established by physical relationships and the model parameters are known, they constitute theoretical models. On the other hand, there are components in internal combustion engines that are not known or well established and in these cases it is necessary to employ experimental modelling. In experimental modelling. They also include experimental models that are established through bench dynamometer tests in which input and output ratios are empirically established. Artificial intelligence and fuzzy logic techniques are commonly used to establish experimental models. In some cases, combinations of models are accepted (gray box) in which empirical and physical relationships are combined to represent the behaviour of the component in question. Once developed and implemented, these models are transferred to run on a real-time computer with dedicated interfaces.

The control strategies to be developed or improved are initially tested in a virtual environment (Model-In-the-Loop). Thus, it is possible to verify the functional behaviour of the control strategy without worrying, initially, with implementation aspects and details. Block diagrams, lookup tables, vectors, measurement and calibration variables are commonly defined at this stage of development. Once the control strategies have been verified in a virtual environment, the developed diagrams are converted into source code using rapid control prototyping tools. These strategies are then transferred to a development electronic control unit (ECU) to be tested on the HIL platform.

To support the development of the engine management system, we focused on integrating and developing an interface for data exchange (analog and digital inputs/outputs) between FlexECU and LABCAR. This interface allows evaluating the behaviour of embedded models and comparing them with the actual physical system. Additionally, the interface enables the generation of corresponding logical signals for the electronic control unit (FlexECU). In the INCA software, a logic was embedded for integrating interfaces to observe and validate the proper functioning of the HIL (Hardware-in-the-Loop) platform (Figure 1). Furthermore, electrical connections corresponding to the instrumentation obtained from the TSI engine were made, along with the adaptation of three mathematical models that will be compared with the real engine.

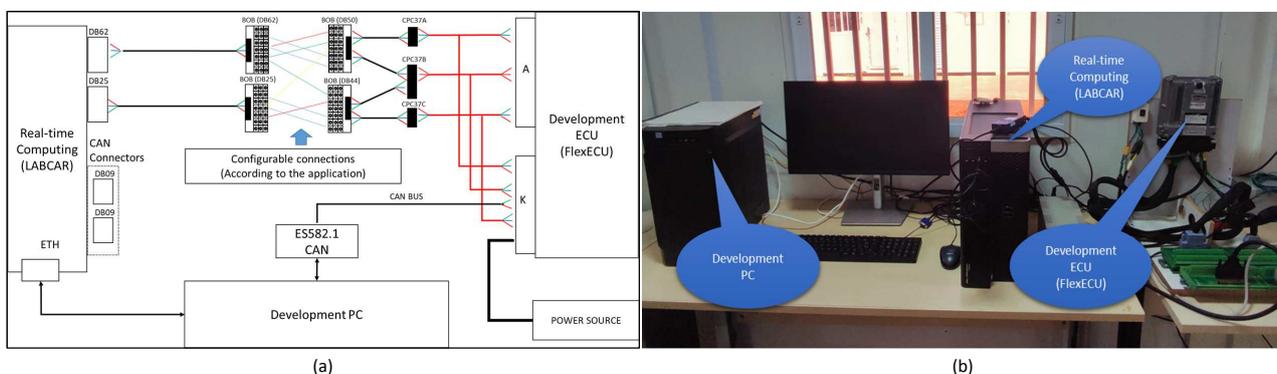


Figure 1. Design and implementation of Hardware-In-the-Loop (HIL) platform.

2.2 Sensor and actuator characterization

To carry out the development and implementation of a Hardware-In-the-Loop (HIL) Platform, we have dedicated to mapping all engine electrical connections. Thus, each sensor and actuator was tested getting sensor data for further utilization. Sensor and actuator characterisation consists to collect input and output data to establish an empirical relation between them. So far, we have mapped the following sensors: 1) mapped: 1) accelerator pedal position (APP), 2) manifold absolute pressure (MAP), 3) Throttle Position (TPS), 4) Crankshaft position (CKP) and 5) Camshaft position (CMP). Once those sensors were checked, a virtual sensor representation was developed for each sensor through Lookup Tables (LKT). Using Lookup Tables, it is possible to convert physical quantities into electrical signals (voltage/current) which is commonly performed by real sensors. Figure 2 highlights some virtual sensors built through characterization and modelling procedures.

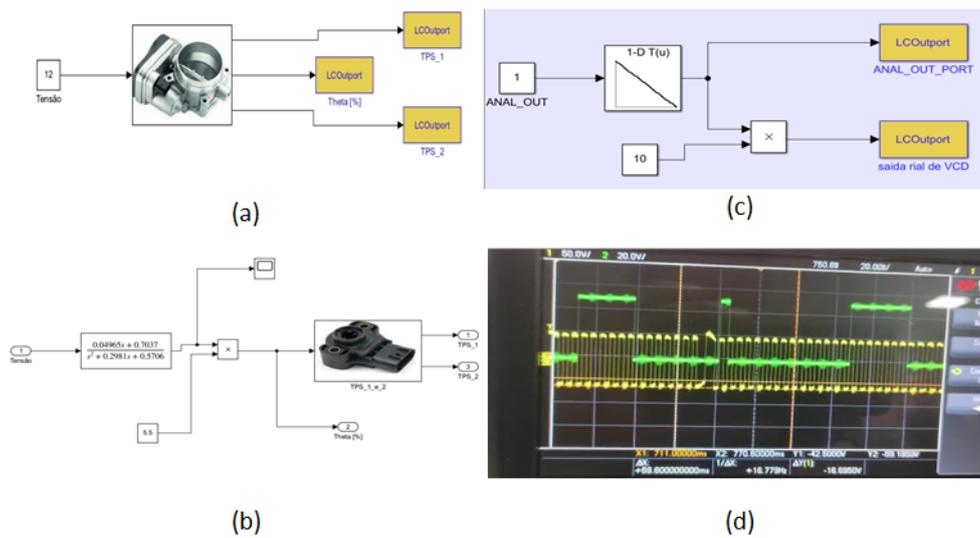


Figure 2. Sensor and Actuator characterization and modelling.

Activities related to the characterization of sensors were conducted using dynamometer tests, and the results are presented in Table 2, Table 3 and Table 4.

Table 2. Characterization of the throttle pedal position sensor

Throttle Pedal Position (%)	Throttle Pedal Position, APP1 (mV)	Throttle Pedal Position, APP2 (mV)
48.60	2520.00	1335.60
48.60	2291.60	1118.20
49.40	2495.40	1262.40
51.80	2551.80	1316.20
41.20	2056.00	1040.00
49.80	2500.60	1300.20
45.10	2242.80	1139.00

A throttle valve can be considered one of the most complex and highly non-linear ICE actuators. To characterize the engine throttle valve, we have used a system identification tool. Thus, a pseudo-random binary sequence (PRBS) signal was applied to the real throttle valve with throttle position collected in real-time. Those data were used through a fitting procedure in order to set the parameters from a generic model. The table 2 highlights the outcomes from throttle valve characterization. Characterization of engine sensors and development of component models for representing the AFR (Air-Fuel Ratio) loop.

2.3 Air-Fuel-Ratio (AFR) Engine Model

Engine control using air-fuel ratio (AFR) strategy is a critical aspect in the optimization of internal combustion engines, contributing to efficient combustion, reduced emissions, and improved performance. It involves the principles of

Table 3. Lambda Sensor Characteristics

Pumping Current (mA)	Sensor 1 (-)	B1S2 (V)	Heated B1S1, Resistance (Ω)	Heated Resistance (Ω)
128.09	1.03	0.76	73.98	0.00
127.93	1.00	0.48	73.79	0.00
127.91	0.99	0.67	73.98	0.00
127.93	1.00	0.58	73.09	0.00
127.98	1.00	0.68	73.09	246.00
127.21	0.90	0.81	73.40	148.00
127.97	1.00	0.68	73.09	304.00

Table 4. Wastegate Valve Characteristics

Wastegate (%)	Open Deviation (%)	Activation (%)	Raw Voltage (mV)
0.04	-5.49	0.44	542.60
56.79	-4.46	28.50	2972.80
39.23	-5.05	-1.31	2029.40
-0.13	-3.63	0.71	496.60
58.76	-5.05	1.88	2162.00
71.74	-5.05	1.92	2562.00
-0.37	-3.63	0.50	493.40

AFR control, including stoichiometric ratios, lean and rich mixtures, and their impact on combustion efficiency and emissions. Various control methods and technologies, such as sensor-based feedback systems, closed-loop control strategies, and real-time adaptive algorithms, are employed to regulate AFR based on engine operating conditions. The benefits of precise AFR control encompass enhanced fuel efficiency, reduced emissions of NO_x, PM, and GHGs, as well as improved engine performance and durability. Advanced AFR control strategies integrate technologies like variable valve timing, direct injection, and turbocharging, aiming for optimal performance and efficiency. Additionally, AFR control plays a vital role in hybrid and electric powertrains, enabling strategies such as engine start-stop, regenerative braking, and powertrain optimization with electric motors. Looking ahead, future directions include advanced sensors, machine learning algorithms, and integration with emerging technologies like fuel cells and hydrogen combustion. Overall, AFR control remains crucial in achieving sustainable and efficient engine operation, continually driving advancements in the field of engine control systems.

The calculation of fuel consumption involves determining the volume of air ingested by the engine. In this study, the original electronic control unit of the tested vehicles provided the necessary parameters, including intake manifold temperature, intake manifold pressure, and the lambda value set by the control unit. These parameters were utilized to establish a consumption curve for each engine speed range. Additionally, data from the engine's power and torque graphs were analyzed to derive the specific fuel consumption curve. The adapted equation (Eq.1) incorporates the direct rotation per second (*rps*) value to calculate the air consumption (\dot{m}_{ar}).

$$\dot{m}_{ar} = rps \cdot \frac{p_1 \cdot V_d}{R \cdot T_1} \quad (1)$$

The displacement volume of engine is represented by V_d in m^3 ; The density of air $\rho(T)$ is a function of temperature and it can be defined by $\frac{p_0}{RT}$ in $[kg/m^3]$.

To calculate the time of injection (T_i) was used the follow equation (Eq.2)

$$T_i = \frac{\rho_0 \left(\frac{p_1}{p_0} \right) \left(\frac{T_0}{T_1} \right) V_d \cdot e_v}{\dot{V}_i n_i (A/F)} \quad (2)$$

where the volumetric efficiency e_v (Eq.3) we used \dot{m}_e to mass flow of mixture, N to engine rotation and x to number of engine strokes divided for 2.

$$e_v = \frac{\dot{m}_e}{\rho_m \cdot V_d \cdot N \cdot x} \quad (3)$$

The test conditions are described in the.Tab.5.

Table 5. Test Conditions

Test Condition	Value	Description
Temperatura do motor	90 °C	Motor heated
Wastegate	0%	Open, no compression
VVT admissão	25 °apms	Position without actuation, where it starts to open
VVT escape	-25 °apms	Position without actuation, where it fully closes

3. RESULTS

The injection time mapping, illustrated in Figure 3, represents the configuration of injection time (Eq. 2) based on the pressure within the intake manifold and engine speed. This control is essential for optimizing engine performance and environmental outcomes.

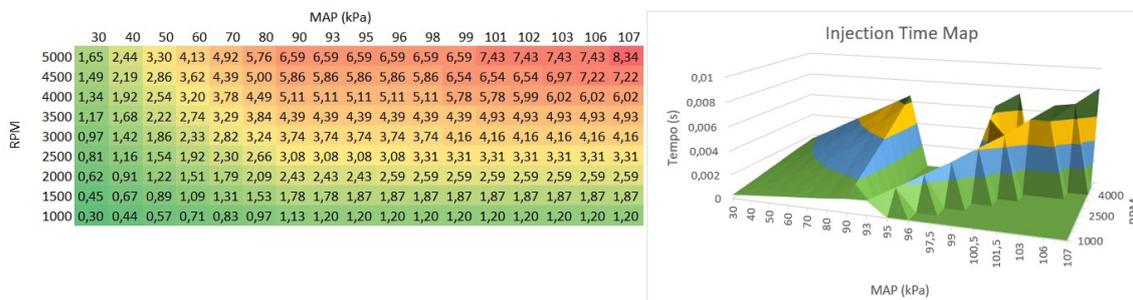


Figure 3. Injection time mapping: Configuration of the EA211 TSI engine using the FLEX ECU by Bosch.

The control of the injection valve timing in internal combustion engines is a critical aspect of optimizing engine performance and emissions. One effective approach involves the utilization of a lambda sensor and manifold pressure feedback for precise control. The lambda sensor provides real-time measurements of the air-fuel ratio, allowing the engine control unit (ECU) to adjust the injection timing accordingly. By monitoring the lambda value, the ECU can ensure that the engine operates at the stoichiometric ratio for optimal combustion efficiency. Additionally, incorporating manifold pressure feedback allows the ECU to fine-tune the injection timing based on the engine load conditions. By continuously monitoring and adjusting the injection timing with inputs from the lambda sensor and manifold pressure, this control strategy enables improved fuel efficiency, reduced emissions, and enhanced overall engine performance.

One effective method of charge control involves the use of Throttle Position Sensor (TPS) control. The TPS measures the position of the throttle valve, providing valuable information to the engine control unit (ECU) for precise control of the air-fuel mixture. By monitoring the TPS, the ECU can accurately regulate the amount of air entering the combustion chamber. This allows for precise control of the engine’s power output and torque characteristics. The TPS control strategy enables the engine to adapt to different operating conditions, such as varying load and throttle positions. By adjusting the throttle opening based on the TPS input, the engine can achieve optimal combustion efficiency, responsiveness, and drivability. Furthermore, TPS control plays a crucial role in emission control by ensuring the engine operates within the required air-fuel ratio range. Overall, TPS control is an integral part of charge control in internal combustion engines, enabling precise control over the air intake and contributing to enhanced engine performance and efficiency. The figure 4 represents the throttle opening map as a function of intake manifold pressure and engine speed demonstrates the obtained results for the engine state in order to ensure optimal engine performance.

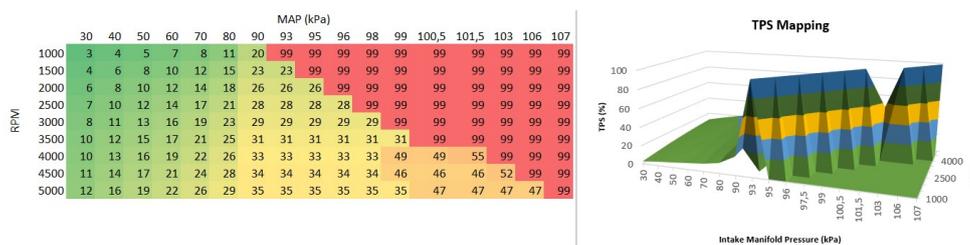


Figure 4. Throttle Position Sensor (TPS) mapping: Configuration of the EA211 TSI engine using the FLEX ECU by Bosch.

With the implementation of the HIL testing platform and the development of optimized operating maps, it is now possible to conduct virtual engine operation tests. This involves inputting the gathered data into the LABCAR platform and running computational scenarios without risking the integrity of the actual engine. This approach enables accelerated maturity in engine control while minimizing risks.

4. CONCLUSION

In conclusion, the findings presented in this paper highlight the importance of injection time mapping and throttle position sensor (TPS) control in optimizing engine performance, fuel efficiency, and emissions. The injection time mapping, based on intake manifold pressure and engine speed, allows for precise control of injection timing, ensuring optimal combustion efficiency and environmental outcomes. Incorporating a lambda sensor and manifold pressure feedback further enhances control accuracy, enabling adjustments to maintain the stoichiometric ratio and fine-tune injection timing based on engine load conditions. Additionally, TPS control plays a crucial role in regulating the air-fuel mixture, adapting the engine to varying operating conditions and achieving optimal combustion efficiency, responsiveness, and emissions control. The successful implementation of a Hardware-in-the-Loop (HIL) testing platform, coupled with optimized operating maps, facilitates virtual engine operation tests, minimizing risks to the actual engine while accelerating the maturity of engine control. This integrated approach contributes to improved fuel efficiency, reduced emissions, and enhanced overall engine performance. The advancements and insights presented in this study pave the way for further advancements in engine control technology, ultimately benefiting the automotive industry and the environment.

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