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Original Research

Determining the operating range of the actuators in a turbocharged GDI engine with VVT for design of the experiments

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ABSTRACT

Growing concerns over air pollution and global warming have intensified the need for more efficient internal combustion engines with lower fuel consumption and emissions. At the same time, engine downsizing and the adoption of advanced technologies have significantly increased the complexity of modern engine systems. Under these conditions, insufficient calibration of engine control parameters can lead to substantial time and cost penalties during engine development. Therefore, calibration methodologies must evolve in parallel with engine technologies. In modern engine management systems, the increasing number of actuators has significantly expanded the calibration effort required for ECU mapping. One effective way to reduce this effort is to determine feasible operating ranges for the actuators before conducting engine-level calibration experiments. This enables the definition of practical constraints for key calibration variables, such as air-fuel ratio, spark timing, valve timing, injection timing, injection split ratio, and fuel pressure, thereby reducing the number of required test points. This study was conducted at Iran Khodro Powertrain Company (IPCO) and focused on turbocharged gasoline direct injection (GDI) engines equipped with variable valve timing (VVT). A benchmarking-based approach was used to extract suitable actuator operating ranges from several comparable engines. The engine operating map was subsequently divided into three regions in order to constrain the experimental domain and limit the number of candidate calibration states. This approach eliminated the need for exhaustive point-by-point mapping and reduced the actuator search space for calibration experiments by up to 99%.

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1- Introduction

In recent years, global challenges such as climate change, air pollution, and the depletion of fossil fuel resources have driven industries—particularly the automotive sector—to adopt advanced technologies for improving the performance and efficiency of internal combustion engines. The primary objectives are to reduce greenhouse gas emissions, harmful pollutants, and particulate matter. Consequently, technologies such as gasoline direct injection (GDI), turbocharging, and variable valve timing (VVT) have become widely utilized in modern engine design.

The integration of these technologies provides high power density and improved volumetric efficiency while enabling more precise control over combustion and emissions. However, despite their benefits in performance and thermal efficiency, they significantly increase the complexity of the engine control system, particularly the engine management system (EMS). An increased number of actuators introduces more independent variables, which imposes substantial challenges for ECU calibration. In a turbocharged GDI engine equipped with dual VVT, the fundamental calibration variables include intake and exhaust valve opening/closing timings, fuel injection pressure, number of injection events, injection split ratios, injection phasing, spark timing, and air–fuel ratio. Moreover, turbocharged engines naturally exhibit a broader operating map, which further multiplies the number of required test points. Without a structured methodology, the associated time and cost of engine development increase dramatically, and complete mapping may become impractical.

A fundamental step toward simplifying the calibration process is determining the optimal operating ranges of the actuators early in the development cycle. By constraining the calibration search space, these ranges provide the foundation for focused design-of-experiments planning, thereby reducing both development time and the extent of laboratory testing.

2- Litrature Review

As engine architectures become increasingly complex, international research regarding the optimization of ECU calibration processes has intensified. As previously discussed, a highly effective approach involves constraining actuator operating ranges prior to the initiation of the mapping process. This objective can be achieved through experimental investigation, high-fidelity simulation, or an in-depth understanding of the underlying combustion physics. Furthermore, data-driven analysis and Design of Experiments (DoE) techniques have proven instrumental in minimizing calibration effort. Additionally, benchmarking comparable engines on a dynamometer provides empirical insights into the requisite actuator operating ranges, establishing a robust baseline for ECU mapping.

Research conducted by the PSA Group (Souhaite and Mokhtari, 2014) regarding the combustion system design of the EB Turbo PureTech engine demonstrates the synergistic potential of advanced hardware integration. Their work illustrated that the application of multi-stage injection, optimized valve timing, and 200-bar high-pressure injectors resulted in a 21% reduction in fuel consumption while enhancing combustion stability at low loads [1]. Their findings underscored how strategic optimization of injector placement, piston geometry, cooling systems, and injection strategies is paramount in defining the stable operating boundaries of the engine. This study highlights the criticality of precise actuator adjustment, particularly in complex engine systems, as a primary driver of performance.

The examination of actuator ranges requires rigorous methodological approaches, as traditional calibration techniques often prove inadequate for modern engines. Isermann and Sequenz (2016) explored the model-based development of engine control and calibration [2]. Their methodology, which synthesized dynamic physical models with data-driven approaches, predicted engine behavior with a margin of error under 3%, thereby facilitating a 50% reduction in calibration time for the subject engine.

In the development of three-cylinder engines at MAHLE Powertrain, Cooper et al. (2019)

employed DoE methods to concurrently advance engine design and calibration. By rigorously analyzing the operating ranges of engine components through cycle simulations—with a particular focus on emissions—they demonstrated that characterizing operating ranges prior to DoE implementation reduces design risk and accelerates mapping development [3]. A prior study by the same group utilized an analogous strategy of intelligently limiting actuator ranges to expedite the identification of validation test points on the dynamometer [4].

Burggraf et al. (2020) proposed a semi-automated framework to extract safe actuator operating ranges based on dynamic engine performance analysis and empirical test data [5]. Their research confirms that defining the performance boundaries of EMS components is a critical initial step in the mapping phase. This approach not only curtails the test volume but also enhances calibration efficiency by systematically integrating constraints related to emissions and fuel consumption.

More advanced research has increasingly leveraged large-scale simulations and machine learning to address the challenges of extracting operating zones for transient driving cycles. Aithal and Balaprakash (2019) utilized extensive simulated data to train a neural network surrogate model, which accurately predicted engine performance and emissions across various operating points [6]. Crucially, this model minimized the reliance on intensive experimental testing. However, a prerequisite for such simulations is a precise, a priori knowledge of the engine’s feasible operating spaces.

Furthermore, industry-standard tools such as AVL’s CAMEO software offer a structured mapping approach that utilizes DoE algorithms and zone-based structures [7]. This methodology integrates experimental laboratory data with numerical models, enabling engineers to select test points purposefully and evaluate actuator performance within a consistent, constrained range.

In addition to system-level calibration, fundamental physical limitations—such as injection spray dynamics—impose strict boundaries on actuator ranges. Studies on GDI injector spray behavior confirm that injection pressure and spray development directly govern fuel-air mixture preparation and combustion efficiency. Asef et al. analyzed the mixture formation of a six-hole GDI injector using optical measurements in a constant volume chamber coupled with CFD simulations. Their results indicated that spray development is non-symmetrical and accelerates as chamber pressure decreases, showing high correlation between simulated spray velocities and experimental data [8]. Such findings emphasize the necessity of precise injector characterization to define appropriate injection parameters during ECU calibration.

Despite these advancements, existing literature—particularly in the domestic context—has predominantly focused on localized flow simulations, the impact of isolated variables (e.g., injection angle), or field performance analysis. The extraction of practical, benchmarking-based actuator ranges derived from comprehensive experimental data remains under-addressed. Iran Khodro Powertrain Company (IPCO), as a pioneer in internal combustion engine development in Iran, addresses this gap by utilizing standardized, high-performance engine test cells equipped with advanced dynamometers. The present study leverages experimental benchmarking data from both proprietary and commercialized engines, coupled with a comparative analysis of their performance characteristics. Drawing upon years of expertise in engine development and ECU calibration within the Iran Khodro Industrial Group, this research seeks to establish a localized, robust model for optimizing the calibration of turbocharged GDI engines equipped with Continuously Variable Valve Timing (CVVT).

3- Research Methodology

To determine the suitable operating ranges for the base actuators of a GDI engine, four commercialized engines and three developmental engines at IPCO were examined and benchmarked. The dataset used in this study was obtained from steady-state combustion tests performed on an engine dynamometer, where boundary conditions were kept as consistent as possible across all tests. Because the ECU software of these engines was already finalized, the recorded target values during testing provide a realistic representation of the feasible operating limits for actuators such as the VVT system, the high-pressure fuel pump, and the GDI injectors. Table 1 summarizes the general specifications of the engines evaluated in this work.

Table 1 Technical specifications of the benchmarked engines utilized to determine actuator operating ranges

	Engine 1	Engine 2	Engine 3	Engine 4	Engine 5	Engine 6	Engine 7
Engine type	3-cyl inline	3-cyl inline	4-cyl inline	4-cyl inline	4-cyl inline	4-cyl inline	3-cyl inline
Engine displacement	1000 cc	1200 cc	1600 cc	1500 cc	1600 cc	1600 cc	1300 cc
Fuel system	GDI	GDI	GDI	GDI	PFI	PFI	PFI
Induction type	TC	TC	TC	TC	NA	TC	TC
Valve timing	Dual CVVT	Dual CVVT	Dual CVVT	Dual CVVT	Dual CVVT	Dual CVVT	Dual CVVT

In a typical GDI engine, up to three injection events may be employed. Assuming the presence of two valve timing control actuators, a total of ten calibration variables must be defined at each engine operating point to ensure combustion stability while optimizing emissions and fuel consumption. These base mapping variables include spark timing, equivalence air–fuel ratio, injection mass split ratio between the first and second injection events, start or end of injection for the first, second, and third injection stages, fuel rail pressure, intake cam phasing, and exhaust cam phasing.

A major factor contributing to the time-consuming and costly nature of the mapping process is the number of variables that must be swept in order to identify the optimum calibration point. However, among the ten variables listed above, spark timing and equivalence air–fuel ratio are not fully independent. For a given operating point and any specific combination of the remaining variables, their values are effectively constrained. Spark timing must be adjusted either to achieve maximum brake torque (MBT) or to remain within the knock borderline (KBL). Similarly, except under special operating conditions, the equivalence air–fuel ratio is primarily dictated by exhaust gas temperature constraints; in practice, mixture enrichment is mainly applied to reduce exhaust gas temperatures and protect exhaust system components. Consequently, for a turbocharged GDI engine equipped with dual VVT, the calibration problem can be reduced to eight effectively independent variables.

An effective strategy for reducing the dimensionality of the mapping process is to divide the engine operating range into distinct operating zones. This approach eliminates the need to sweep certain independent variables in specific zones, or at minimum allows their variation ranges to be narrowed according to the prevailing engine operating conditions. Figure 1 illustrates the proposed zoning concept together with the associated engine performance characteristics in terms of injection pressure, injection strategy, and valve timing. The same framework was subsequently used to classify the experimental test data and determine the appropriate actuator operating ranges.

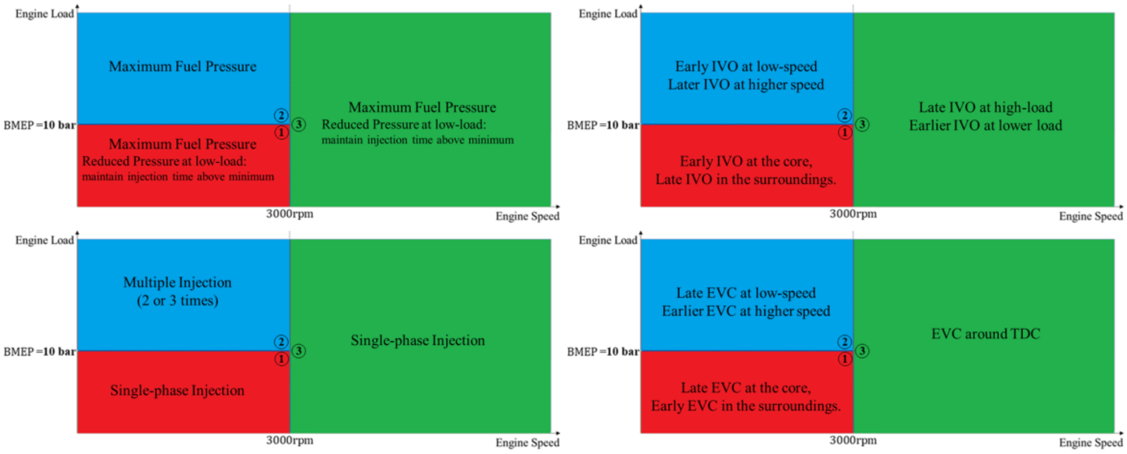

Figure 1 Zoning of the engine map to reduce the states required for sweeping independent variables

4- Results and Discussion

In GDI engines, gasoline is typically delivered to the injectors at rail pressures of up to 200 bar; in some applications, such as Engine 4, this pressure is increased to as high as 350 bar. The general control strategy is to employ the highest feasible rail pressure in order to improve mixture preparation and combustion, while particularly reducing particulate matter (PM) emissions. However, at certain operating points—most notably under low-speed and low-load conditions—the rail pressure must be reduced sufficiently to avoid constraints associated with the minimum injector pulse width.

Because the injection duration is subject to a lower physical limit, the injection strategy and fuel rail pressure are inherently coupled. For instance, under mid-load and low-speed operating conditions, multi-injection strategies used to mitigate knock tendency may shorten the duration of each individual injection event. Depending on the injector flow characteristics, this can necessitate the use of a lower rail pressure to maintain controllable injection timing and fuel delivery. Figure 2 illustrates the operating range of the high-pressure fuel system across the investigated engines.

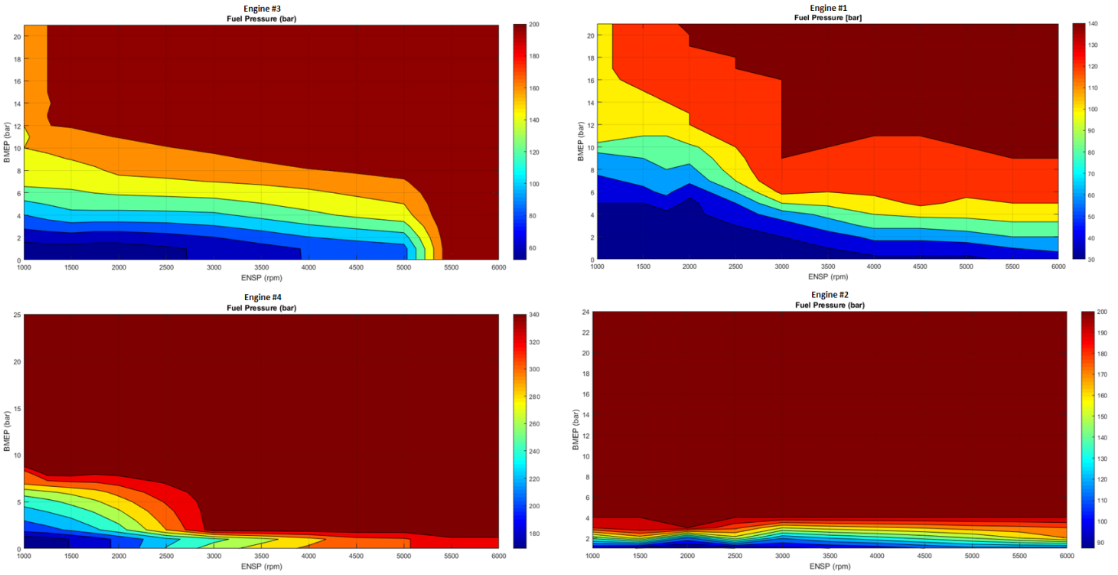

Figure 2 Fuel rail pressure range in the investigated engines

Numerous studies have demonstrated that split-injection strategies not only enhance combustion efficiency and torque output but also significantly mitigate knock propensity. Consequently, multi-event injection is predominantly utilized within the low-to-medium speed and high-load regions of the engine operating map, where two- or three-stage injection strategies are typically deployed. Figures 3, 4, and 5 illustrate the mass fractions of the first, second, and third injection events, respectively, relative to the total injected fuel mass. Notably, in contrast to the other investigated GDI engines, Engines 2 and 3 do not utilize a third injection event under any operating conditions.

Correlating these findings with the calibration zones defined in Figure 1, split injection was entirely inactive in Zones 1 and 3 across all four benchmarked engines. In contrast, within Zone 2, approximately 50% of the total fuel mass is delivered during the primary (first) injection event. The remaining fuel mass is distributed among the subsequent events, depending on whether a double- or triple-injection strategy is activated.

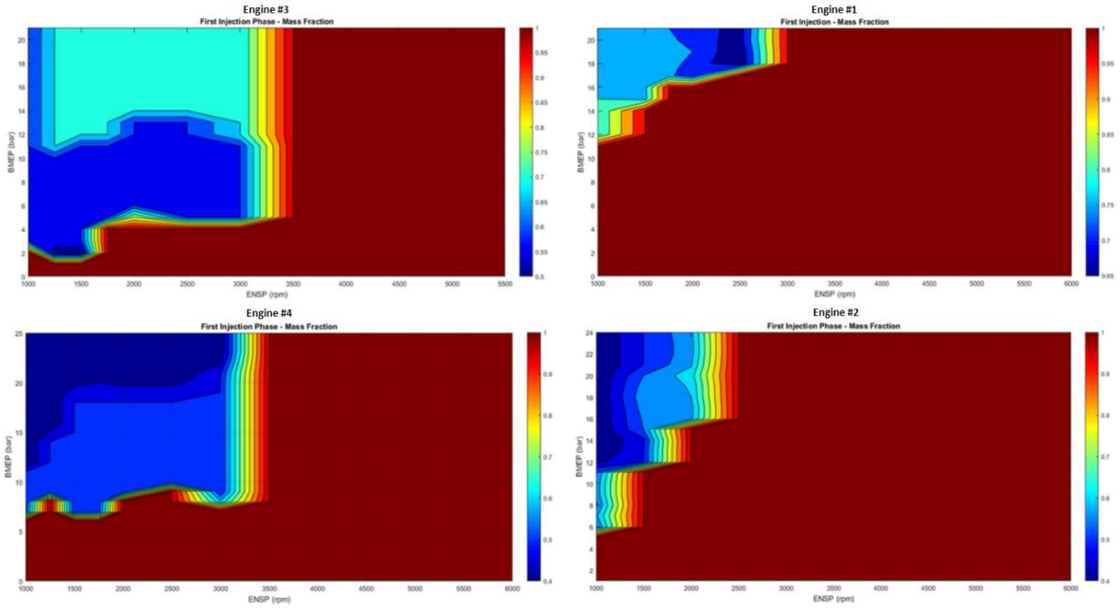

Figure 3 Mass fraction of first injection phase relative to total injected fuel

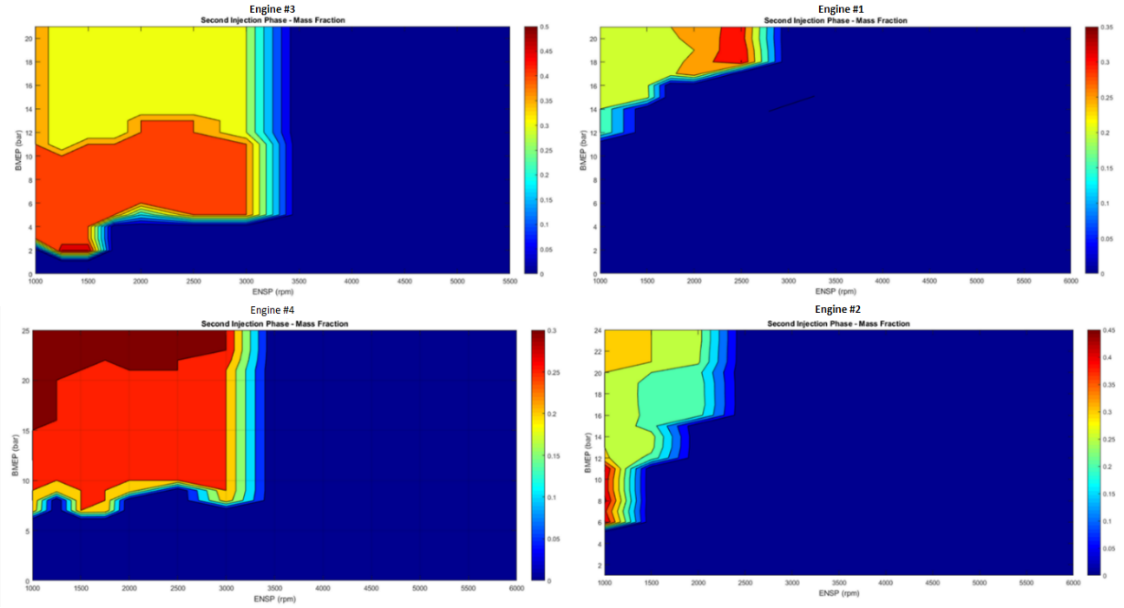

Figure 4 Mass fraction of second injection phase relative to total injected fuel

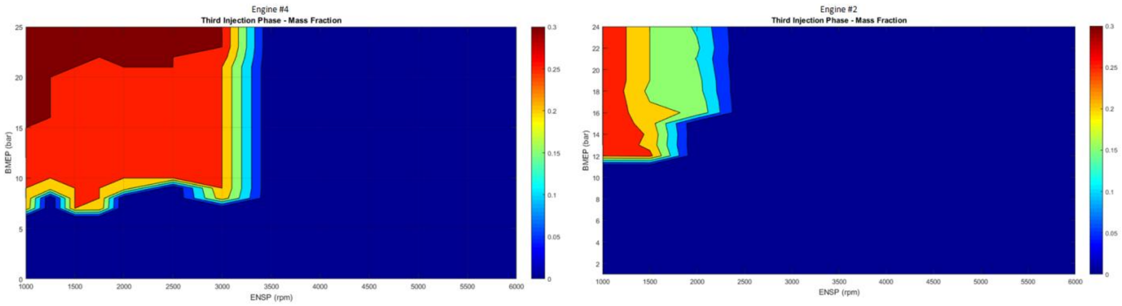

Figure 5 Mass fraction of third injection phase relative to total injected fuel

Regarding injection timing, the primary injection event is typically scheduled entirely within the intake stroke. The secondary injection event is initiated near bottom dead center (BDC). Under a triple-injection strategy, the start of the secondary injection is advanced slightly, initiating in the late intake stroke; conversely, under a dual-injection strategy, the secondary event may be retarded into the early compression stroke. The tertiary injection, when utilized, is typically shifted but generally takes place during the second half of the compression stroke, with its timing constrained by the spark timing. The calibrated injection timings of the investigated engines are illustrated in Figures 6, 7, and 8 for the first, second, and third events, respectively. Throughout this study, injection timing is defined in crank angle degrees before top dead center of the combustion stroke (CAD bTDC$_{\text{comb}}$).

A key observation is the monotonic trend in injection timing as a function of engine speed and load. The experimental data indicate that an increase in engine speed advances the injection timing (expressed in CAD bTDC$_{\text{comb}}$) to accommodate the reduced physical time available for fuel-air mixture preparation. Conversely, increasing the engine load retards the injection timing to optimize charge cooling and mitigate knock propensity under high-load conditions.

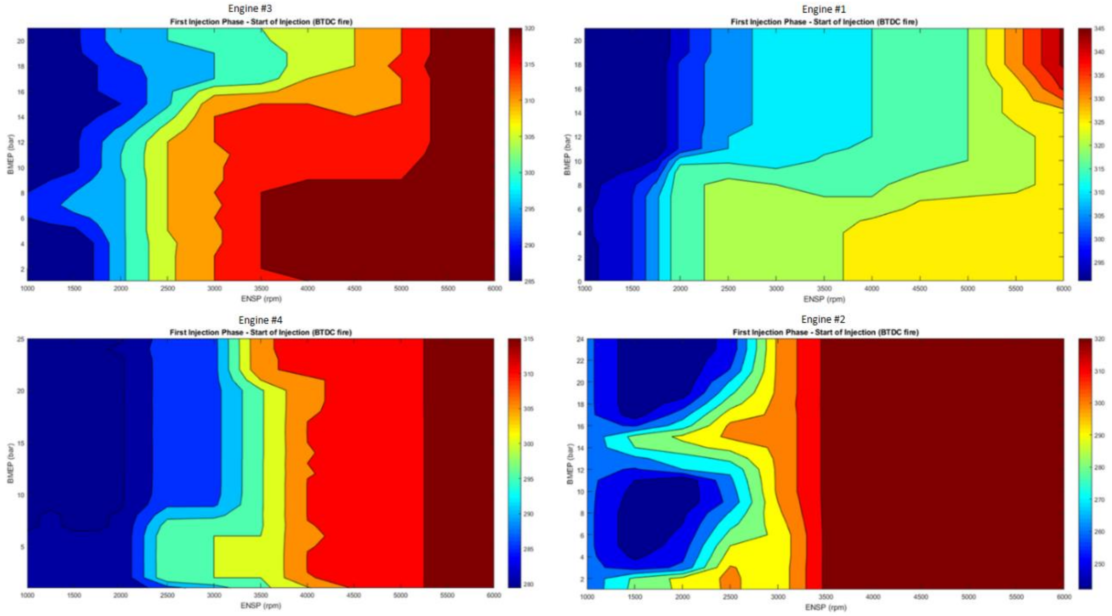

Figure 6 First injection angle before top dead center (BTDC)

To characterize the valve event timings, the database was expanded to include three additional IPCO-calibrated engines alongside the previously introduced commercial units. Figure 9 illustrates the intake valve opening (IVO) timing, exhaust valve closing (EVC) timing, and the resulting valve overlap across the operating map. A distinct region of maximum valve overlap is observed under medium-speed and medium-load conditions. At very low engine loads, there is a pronounced tendency to retard the intake valve closing (LIVC). This strategy shifts the engine operation toward a late-intake-closing Atkinson cycle, thereby reducing throttling losses and minimizing pumping work.

Conversely, in the low-speed, high-load regime, valve overlap is deliberately maximized to exploit scavenging. This dynamic utilizes the positive pressure gradient across the cylinder to purge residual gases and draw a fresh charge into the combustion chamber, which also accelerates turbocharger spool-up. At elevated engine speeds, where the primary objective is to maximize power output, the CVVT calibration points do not exhibit a single monotonic trend. Instead, they reflect a complex multi-variable trade-off between maximizing volumetric efficiency, managing exhaust gas temperatures, and respecting the knock borderline.

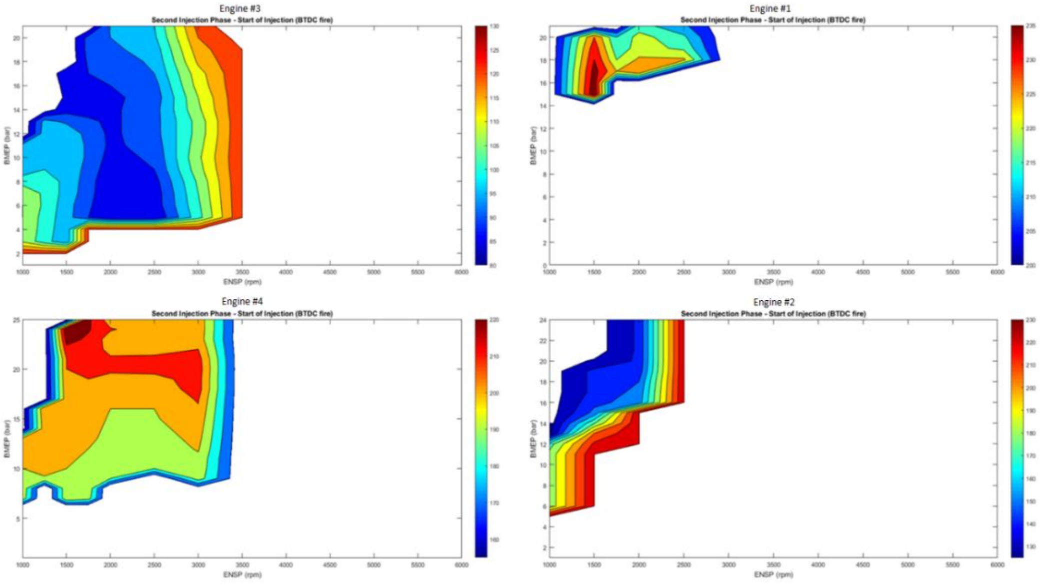

Figure 7 Second injection angle before top dead center (BTDC)

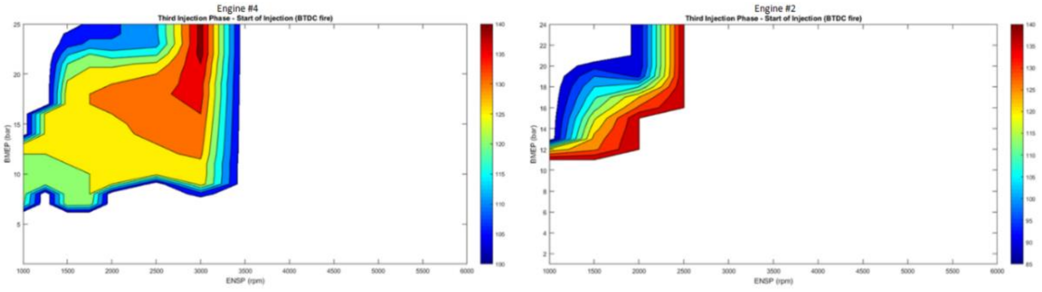

Figure 8 Third injection angle before top dead center (BTDC)

Benchmarking the investigated engines and performing a comparative analysis of the experimental dataset reveal a significant overlap in actuator trajectories. This convergence is fundamentally governed by the underlying thermodynamic and fluid dynamic similarities shared among modern turbocharged GDI systems. By exploiting these physical commonalities, the operating envelopes of the key calibration variables can be systematically constrained within the predefined zoning boundaries. This pre-calibration boundary reduction effectively eliminates non-feasible design spaces, thereby streamlining the selection of optimal test points for subsequent Design of Experiments (DoE) formulations. The bounded operating ranges established for the independent actuators are summarized in Tables 2, 3, and 4 for Zones 1, 2, and 3, respectively.

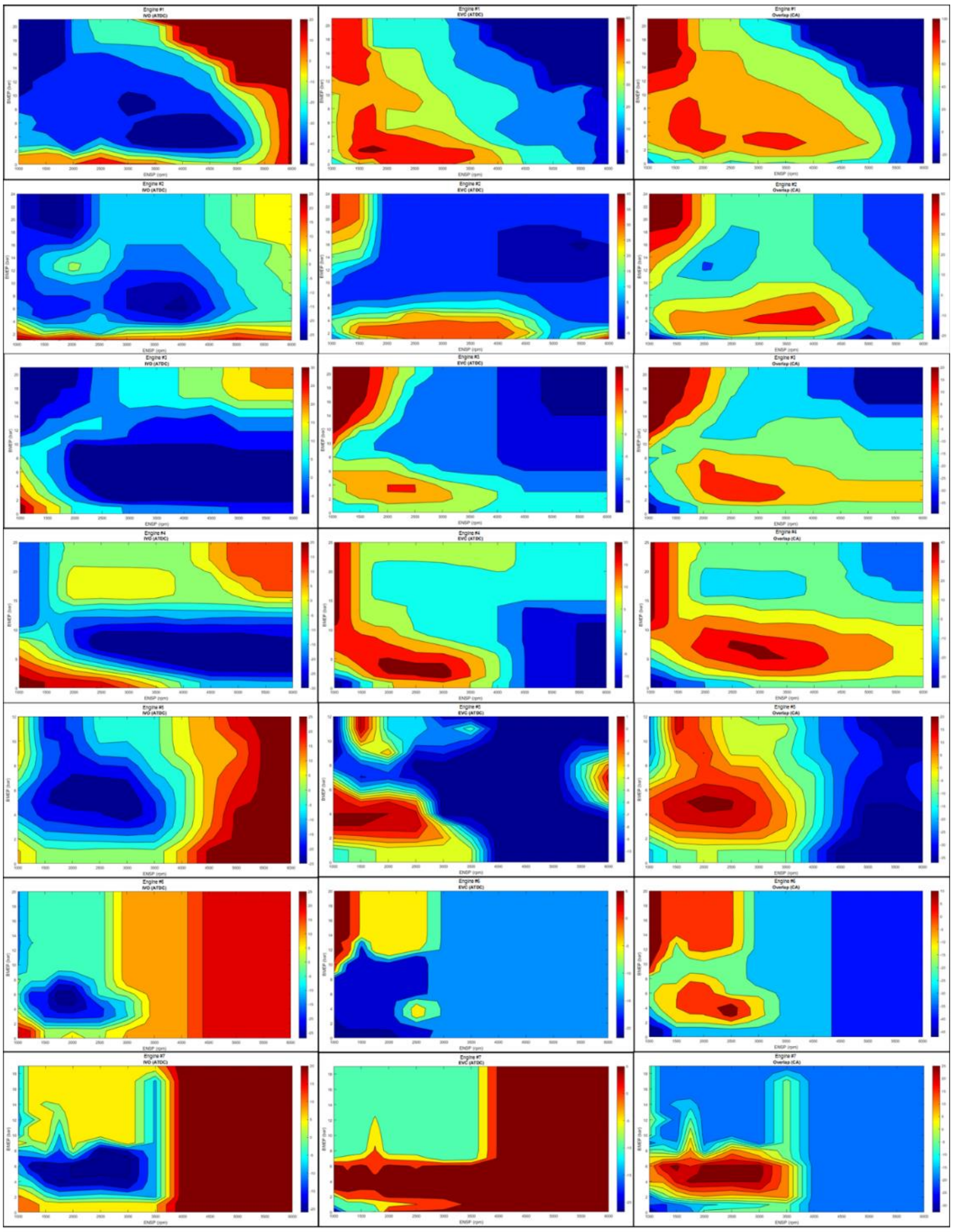

Figure 9 Intake valve opening timing, exhaust valve closing timing, and valve overlap

Table 2 Extracted actuator operating range for Zone 1

Variable	Range	Unit	Description
Fuel pressure	60 to 350	bar	Dependent variable
Injection mass split	Phase 1: 1 Phase 2: 0 Phase 3: 0	–	No need to sweep
Injection timing	Phase 1: 230–330 Phase 2: – Phase 3: –	deg BTDC	One independent variable
Valve timing	IVO: -30 to 25 EVC: -20 to 25	deg ATDC	Two independent variables

Table 3 Extracted actuator operating range for Zone 2

Variable	Range	Unit	Description
Fuel pressure	350	bar	Maximum pressure
Injection mass split	Phase 1: 0.4–1 Phase 2: 0–0.4 Phase 3: 0–0.3	–	Two independent variables
Injection timing	Phase 1: 240–310 Phase 2: 80–240 Phase 3: 80–140	deg BTDC	Three independent variables
Valve timing	IVO: -25 to 10 EVC: -15 to 30	deg ATDC	Two independent variables

Table 4 Extracted actuator operating range for Zone 3

Variable	Range	Unit	Description
Fuel pressure	60 to 350	bar	Dependent variable
Injection mass split	Phase 1: 1 Phase 2: 0 Phase 3: 0	–	No need to sweep
Injection timing	Phase 1: 290–340 Phase 2: – Phase 3: –	deg BTDC	One independent variable
Valve timing	IVO: -30 to 25 EVC: -15 to 15	deg ATDC	Two independent variables

5- Conclusions

Integrating the empirical benchmarking results with the zone-based partitioning of the engine operating map yields physically consistent and optimized operating envelopes for each actuator. Establishing these boundaries priori dramatically streamlines ECU calibration efforts and minimizes the experimental overhead required to identify global optimal operating points. Consequently, the sweep range of each independent control parameter is significantly narrowed, and in specific operating zones, certain degrees of freedom are entirely decoupled.

For instance, the fuel rail pressure is effectively converted from an active independent calibration variable into a boundary-constrained parameter; it is consistently commanded to its maximum physical limit at each operating point, unless restricted by the minimum injector pulse-width limit (below which stable fuel metering is compromised).

Given the high degrees of freedom inherent in a modern turbocharged GDI engine equipped with dual VVT, utilizing traditional full-factorial sweep methodologies for ECU mapping is practically infeasible due to the curse of dimensionality and the resulting combinatorial explosion of test states. By establishing these constrained actuator boundaries, the potential design space is reduced by up to 99% compared to an unconstrained full-factorial grid.

Yet, even with this substantial domain reduction, adjusting the actuators using conventional grid-sweeping remains impractical, as even moderately coarse sweep intervals within the restricted zones would still demand tens of millions of experimental test points across the full operating map. Consequently, the systematic determination of constrained actuator operating ranges presented herein serves as an indispensable precursor, enabling the viable application of advanced mapping techniques such as Design of Experiments (DoE) and Model-Based Calibration (MBC).

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مقاله پژوهشی

استخراج محدوده کاری مناسب عملگرها در موتور توربو GDI مجهز به VVT جهت شروع فرایند طراحی آزمون

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چکیده

ضرورت کاهش مصرف سوخت و آلایندگی در کنار روند کوچک‌سازی موتورهای احتراق داخلی، به پیچیدگی روزافزون این سامانه‌ها منجر شده است. بر این اساس، روش‌های نگاشت نیز باید همگام با فناوری‌های جدید موتور توسعه یابند. از سوی دیگر، افزایش تعداد عملگرها در رایانه موتور، موجب طولانی شدن شدید زمان و هزینه نگاشت می‌شود. یکی از راهکارهای بنیادین و حائز اهمیت برای کاهش هزینه‌های نگاشت، تعیین بازه عملکردی مناسب عملگرها است. این امر امکان تعریف مرزهای کاربردی را برای متغیرهای نگاشت مانند زوایای باز و بسته شدن دریچه‌ها، زاویه مراحل پاشش و نسبت تقسیم پاشش فراهم کرده و در نهایت تعداد آزمون‌های تجربی در سطح موتور را به‌طور چشمگیری کاهش می‌دهد. پژوهش حاضر با تمرکز بر توسعه موتورهای بنزینی پرخوران با پاشش مستقیم مجهز به سامانه زمان‌بندی متغیر دریچه‌ها در شرکت تحقیق، طراحی و تولید موتور ایران‌خودرو (ایپکو) انجام شده است. در این موتورها، تعیین بازه کاری بهینه عملگرها پیش‌نیاز شروع نگاشت و عامل اصلی افزایش سرعت و کیفیت فرآیند نگاشت است. بدون اعمال این محدودیت‌ها، فرآیند نگاشت بسیار پیچیده، زمان‌بر و در برخی موارد غیرممکن خواهد بود. در این مطالعه، متغیرهای پایه نگاشت شامل نسبت هوا به سوخت، زاویه جرقه، زمان‌بندی دریچه‌ها، زاویه پاشش سوخت، کسر جرمی مراحل پاشش و فشار سوخت در چند موتور مشابه بررسی شده و بازه عملکردی مناسب عملگرها از طریق الگوبرداری تعیین گردیده است. بدین منظور، نقشه عملکردی موتور به سه ناحیه تقسیم شد تا دامنه آزمون مقید و تعداد حالت‌های آزمون نگاشت محدود شود؛ به‌طوری‌که نیاز به روبش نقطه‌به‌نقطه برای یافتن نقاط کاری بهینه مرتفع گردد. اعمال این روش، فضای جست‌وجوی عملگرها را در آزمون‌های نگاشت تا ۹۹ درصد کاهش داد.

اطلاعات مقاله

کلیدواژه‌ها:
بازه کاری
موتور پرخوران
تزریق مستقیم
زمان‌بندی متغیر دریچه‌ها
طراحی آزمون

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دریافت ۵ خرداد ۱۴۰۵؛ پذیرش ۱۲ تیر ۱۴۰۵
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