Secondmind

WHITE PAPER

Driving efficiency in ICE calibration

Transforming model-based calibration with Secondmind Active Learning

Executive summary

Despite the ongoing shift toward electrification, internal combustion engines (ICE) will remain a vital part of the global transportation energy mix for the foreseeable future—particularly in hybrid powertrains and regions where infrastructure or cost constraints limit electrification. Continued ICE development is therefore essential. However, meeting increasingly stringent emissions regulations makes engine calibration more complex, time-consuming, and resource-intensive. There is a growing need for smarter, faster calibration solutions that help engineers deliver compliant and competitive products more efficiently.

Working with Secondmind, Mazda Motor Corporation was able to achieve a 59.7% reduction in engineering hours for model-based calibration.

Secondmind Active Learning was proven to significantly speed up model-based calibration processes by intelligently automating Design of Experiments (DoE), reducing the dependency on physical testing and cutting data requirements.

By enhancing model-based calibration with Active Learning, OEMs and Tier 1 suppliers can improve precision, accelerate development cycles and substantially reduce costs.

Why engine calibration matters

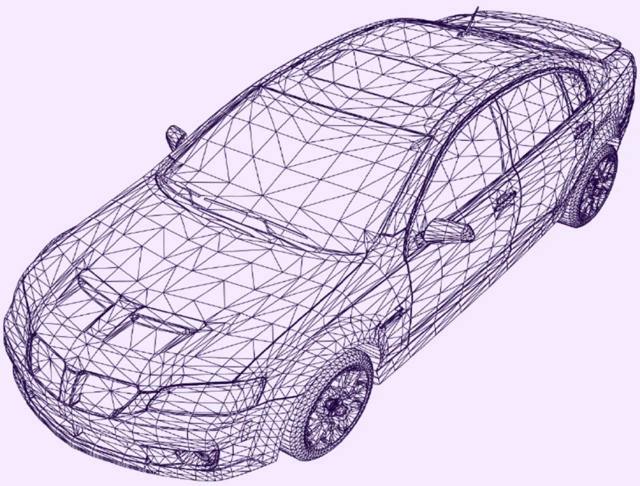
While the shift to electrification faces ongoing hurdles including infrastructure development, cost parity, and range anxiety, internal combustion engines (ICEs) continue to play an integral role in the automotive industry's sustainability strategies.

Today, engine performance is no longer simply a measure of peak power. Engines must now meet stringent environmental regulations, such as Euro 6 and 7, which mandate significant reductions in emissions. Failure to comply results in substantial financial penalties, making engine efficiency and emissions compliance paramount. At the same time, engineers must balance the need to design products that are optimized for performance, driveability and fuel economy, in order to deliver attractive, high-performing vehicles that captivate customers and sustain market demand.

Calibration is crucial for meeting these competing objectives, and requires the control of numerous combustion parameters. With so many parameters to consider, engineers face a high-dimensional optimization challenge that traditional calibration processes struggle to effectively address.

As competitive pressures from new entrants increase and time to market pressures intensify, established automotive manufacturers are increasingly exploring advanced machine learning techniques to optimize calibration processes, enabling faster delivery of high-performing, fuel-efficient engines.

This white paper will discuss the key challenges facing modern internal combustion engine calibration today and demonstrate, through a case study with Mazda Motor Corporation, how Secondmind 's advanced machine learning system, Secondmind Active Learning, can enhance model-based calibration (MBC) efforts to reduce engineering effort, minimize test cell utilization and accelerate development timelines.



Model-based calibration today

Engine calibration involves both physical and virtual testing of the engine to adjust parameters and measure engine behaviour under controlled conditions. This iterative process continues until the desired performance is achieved and optimum control parameters are identified across the operating range of an engine.

Many automotive engineers have adopted model-based calibration to reduce the reliance on physical prototypes and expedite calibration.

The methodology involves four main stages:

1. The Design of Experiments (DoE) identifies points for optimal performance
2. Collecting data based on the DoE
3. Modeling to understand engine characteristics
4. Optimizing to determine the best control parameters

The process starts with a DoE where engineers outline a more refined range of test points based on previous successes instead of testing every eventuality of each control parameter. This significantly reduces the number of physical tests but still allows enough exploration to discover the optimal calibration.

Once these DoE tests are conducted on a test bench, the measurements are used to build a mathematical model which visualizes the relationship between the control parameters and objective functions. 2D/3D plots can then be extracted from this mathematical model and analyzed to identify the optimum value for each condition.

Model-based calibration is a time-consuming process due to the manual effort involved in the development of the DoE and reliance on many physical tests on the test bench. For example, calibrating just three control parameters for a modern petrol engine would typically require more than 1,000 sets of physical tests, with each test taking up to 10 minutes. As a result, engineers have to wait a long time for data to be collected before they can start building the mathematical models.

This necessity for brute-force DoE testing not only incurs significant costs, but also consumes the valuable time of engineers, preventing them from completing more challenging tasks. The result is that calibration of a modern engine utilizing model-based calibration techniques can take many months.

AI-enhanced model-based calibration

Secondmind has pioneered a new approach to model-based calibration which harnesses Artificial Intelligence (AI) to accelerate traditional processes, while achieving the same levels of accuracy.

Secondmind for Calibration is cloud-native software powered by Secondmind Active Learning, an advanced machine learning system which intelligently automates Design of Experiments, intuitively selecting only the most important data needed to meet the optimization objective of the engineer.

This data-efficient approach has helped automotive OEMs cut time spent on test benches by 50% and data requirements by 80%.

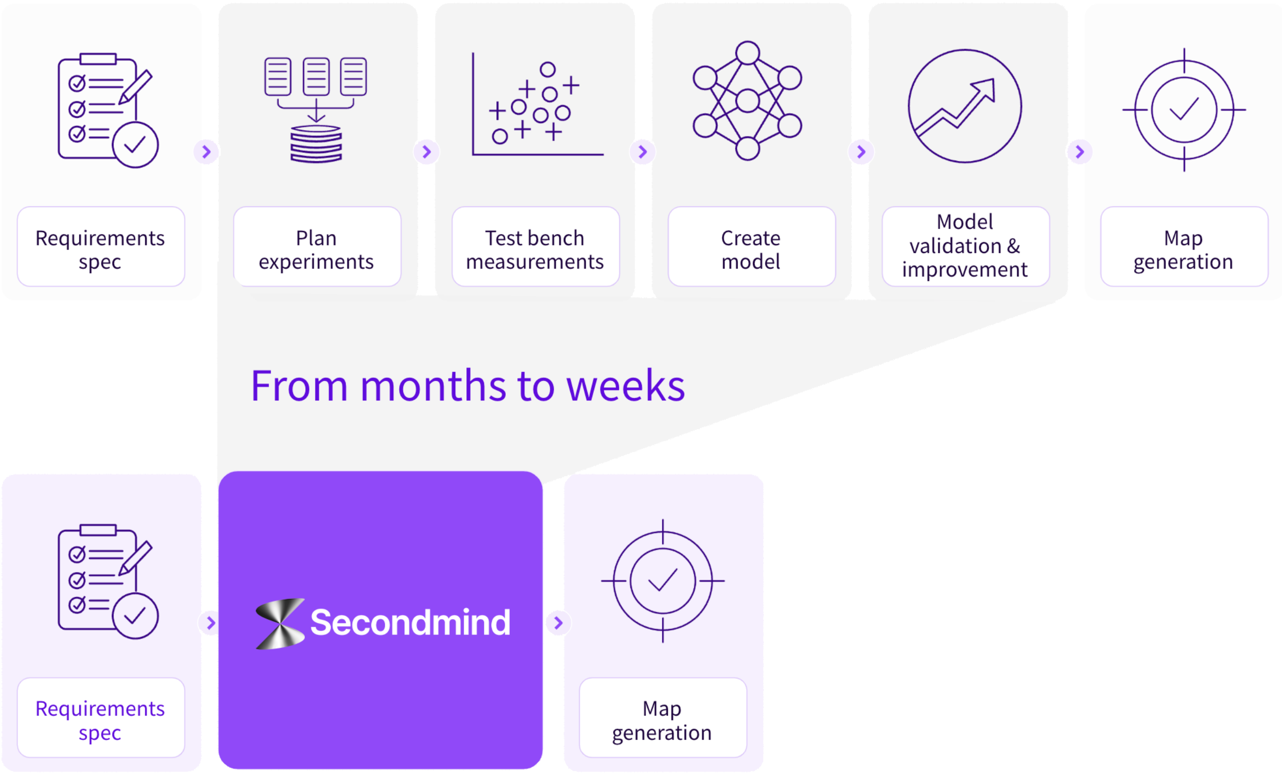


Figure 1: Secondmind for Calibration software intelligently automates Design of Experiments to streamline the overall engine calibration process

How it works

Secondmind plugs into existing calibration toolchains and runs Secondmind Active Learning in the cloud. The process starts with an engineer defining the constraints and providing some initial test points, or 'seed' data, via the Secondmind user interface.

Secondmind Active Learning then intelligently and automatically builds a model, analyzes it against the optimization objectives, and identifies regions of interest for the next experiment before automatically requesting new data from the test bench.

With each iteration, the model is refined with real data from the test bench until enough is acquired to output an accurate model which is then used to create a base calibration map.

In this way, Secondmind replaces traditional brute-force DoE with a more data-efficient approach that requires far fewer physical tests.

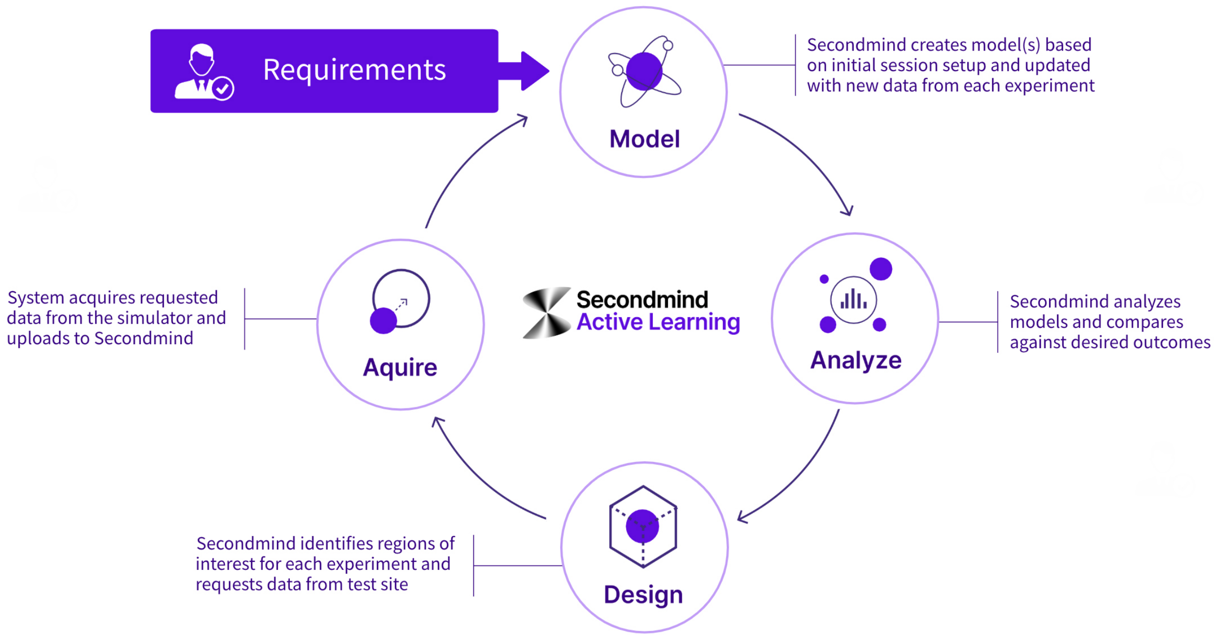


Figure 2: How Secondmind Active Learning works. It can run in collaboration with the engineer or fully automated.

> "The intelligent automation aspect is a potential game-changer. By drastically reducing manual work and idle time, this efficiency boost could significantly enhance calibration.
>
> **Mohammad Behroozi**
> Senior Vehicle Dynamicist, General Motors

How Mazda cut engineering hours by 59.7% with Secondmind

Mazda Motor Corporation launched its 'Sustainable Zoom-Zoom 2030' strategy with a commitment to internal combustion engines powering over 85% of its fleet until 2035. It has since continued to develop new SKYACTIV internal combustion engines, widely recognized as one of the most innovative internal combustion engines in terms of driving pleasure and excellent environmental performance.

These advancements have led to even higher levels of complexity in engine calibration. In the face of tight deadlines and resource allocation challenges, Mazda sought to accelerate processes, partnering with Secondmind to address these significant challenges.

Conventional model-based calibration

Prior to the partnership with Secondmind, Mazda had utilized model-based calibration, relying on brute force DoE testing, modeling and then optimization to determine the control parameters. Although this methodology had significantly cut the amount of physical testing, the complexity of Mazda's latest engines meant that achieving effective calibration required hundreds of physical tests and consumed significant resources. Furthermore, as model-based calibration is a sequential process, engineers had to wait for measurement data before progressing to the next stage. This resulted in a lengthy and laborious calibration process that could take many months for a single brand-new engine.

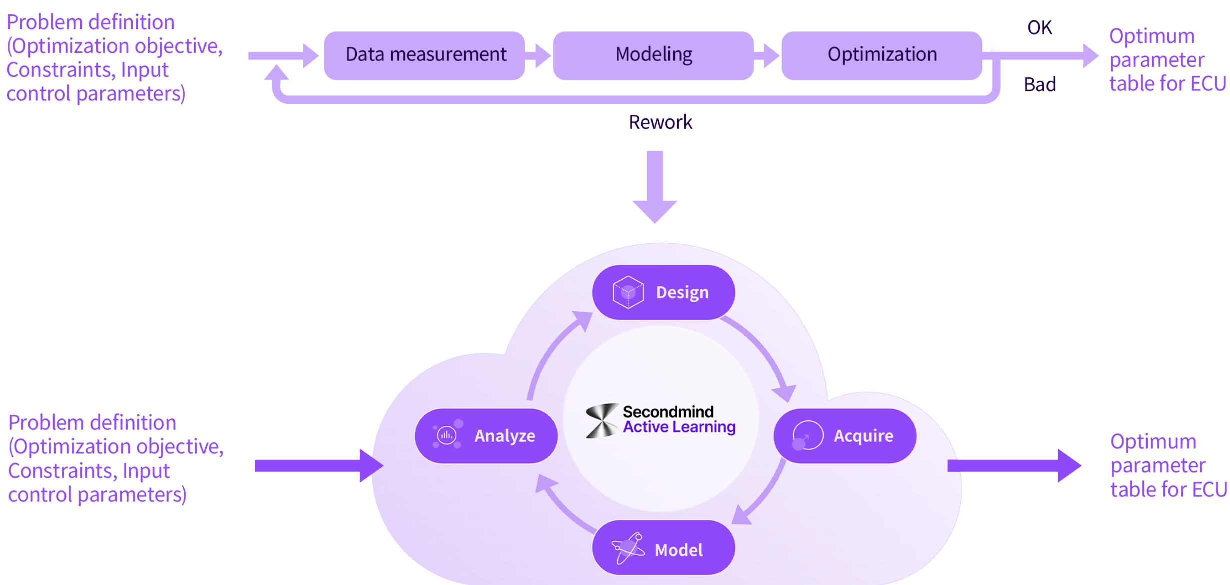
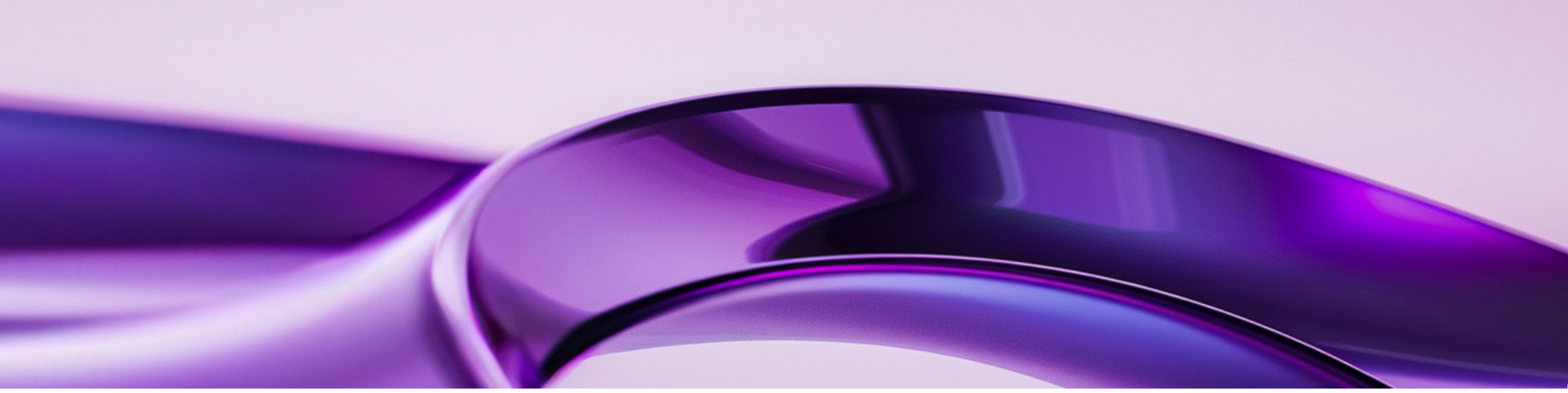


Figure 4: Unlike conventional model-based calibration (top), Secondmind for Calibration builds a model using Secondmind Active Learning (bottom), intelligently automating the model-based calibration process, ensuring the optimum control parameters are identified quickly and efficiently



Mazda easily integrated Secondmind for Calibration into its existing calibration toolchain and test bench hardware using a simple API. Calibration engineers then accessed the cloud-native software through a web-based user interface, where they could set-up sessions and monitor the calibration progress.

Figure 5 illustrates the overall process, with the optimization objectives (green), operating constraints (red) and control parameters (blue) all defined by the calibration engineer. In this case study, the optimization goal was to maximize fuel efficiency (represented by torque) on a map of engine speed and air charge efficiency.

This required seven input variables, such as engine speed and air charge efficiency, as well as 11 constraints including engine knocking and combustion stability.

Once these variables were defined, Secondmind software explored the potential performance of the engine and built a mathematical model to optimize control parameters.

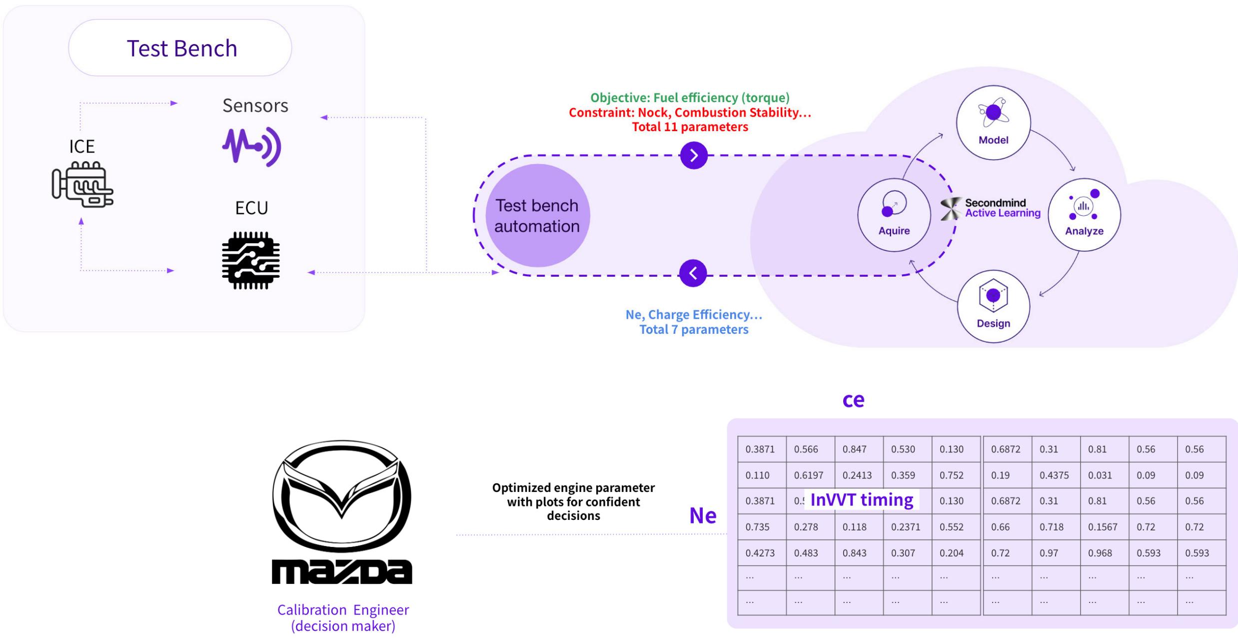


Figure 5: Mazda integrated Secondmind for Calibration into its existing ICE calibration toolchain

Results

The results of this study are displayed in Figure 6 and, as you can see, the optimum value of torque fluctuates across the iterations. This is expected and a result of the model updating and refining each time new data is acquired.

However, after 330 iterations, these results stabilize, indicating that Secondmind Active Learning has thoroughly explored the control space to identify the torque settings that maximize engine power output while minimizing fuel consumption, thus improving overall fuel-efficiency.

This is also illustrated in the graph plotting the uncertainty of the model in Figure 6. At 330 iterations, the results have clearly converged, giving engineers the confidence that the model has now achieved acceptable levels of accuracy.

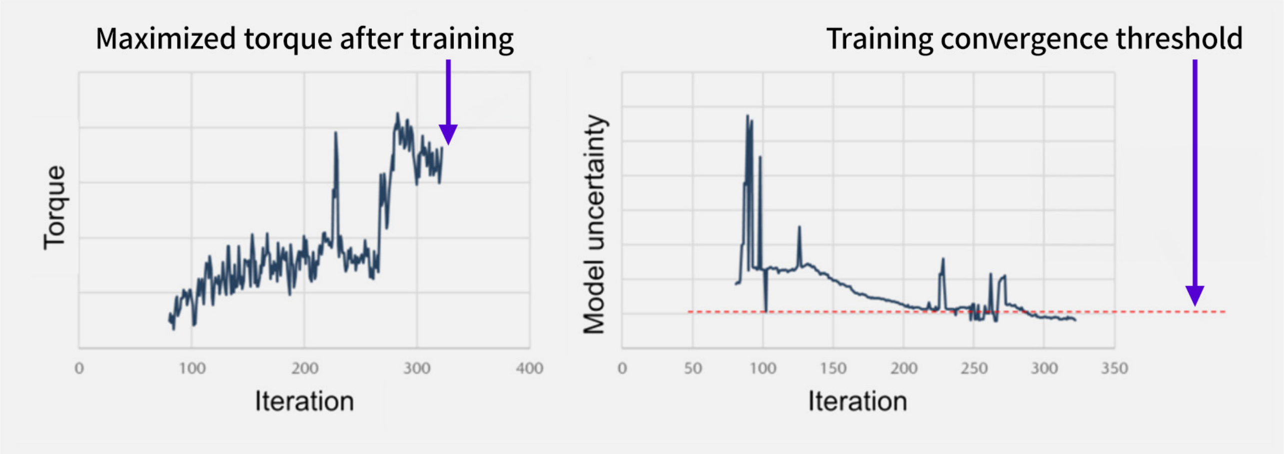


Figure 6: Graph showing the transition of the optimum torque value (left) and the uncertainty of the model (right)

To visualize the optimum control parameter identified by Secondmind for Calibration, Figure 7 shows a slice of the calibration map between exhaust valve timing and injection timing. The shaded region represents areas of constraint, and the non-shaded region is the feasible control area. The optimum value discovered by Secondmind's software not only lies within this feasible area but also close to the boundary - typically where the best performance is found. This demonstrates the effectiveness of Secondmind Active Learning technology in safely determining the true optimum.

The results proved to Mazda that Secondmind for Calibration could generate calibration maps with the same fidelity as an experienced calibration engineer, but far more efficiently. By implementing this software, Mazda achieved a 59.7% reduction in engineering hours when compared to its conventional calibration process, meaning that engineering experts could be re-deployed to other, higher-value tasks.

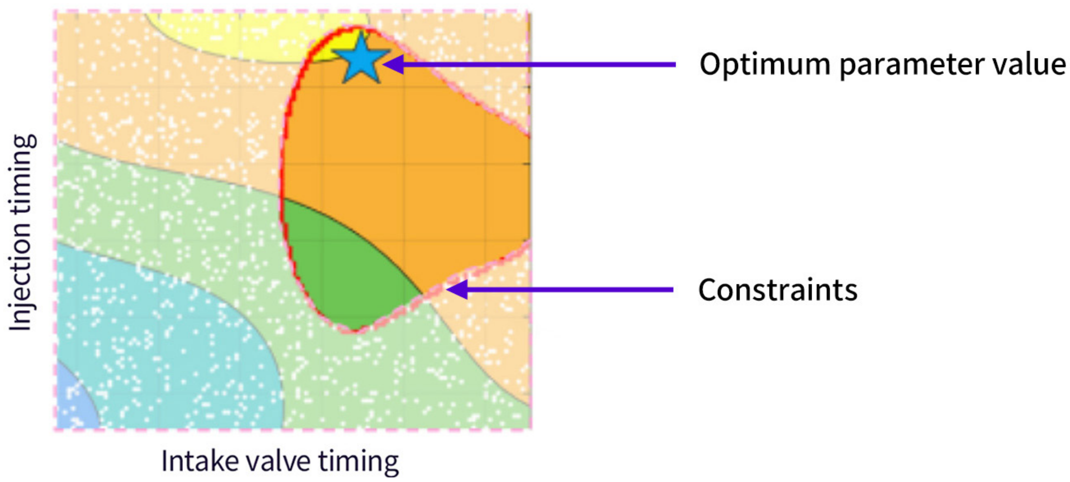


Figure 7: The optimum parameter value determined by Secondmind for Calibration lies in the feasible control area (non-shaded region) and on the boundary where the highest performance is typically obtained

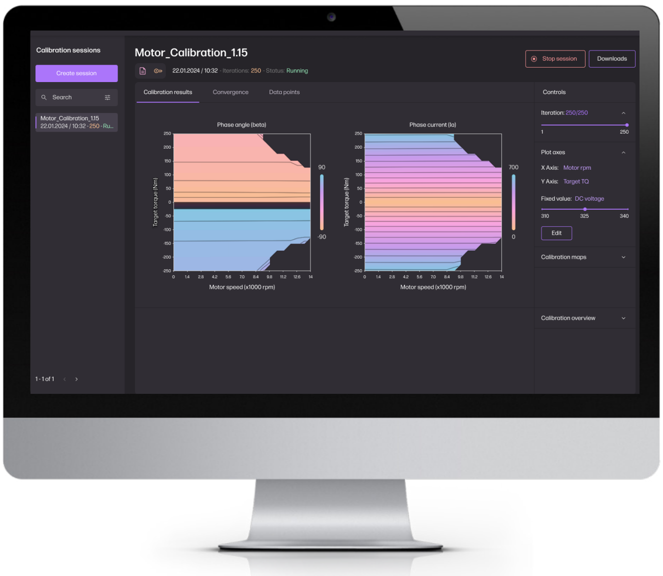
> "By integrating Secondmind's AI-driven calibration software, Mazda achieved a significant reduction in engineering hours, dramatically improving our calibration efficiency.
>
> This allows us to allocate resources more strategically and meet regulatory demands more effectively.

Tomohiko Adachi
Supreme Principal Engineer at Mazda Motor Corporation

Conclusion

As we have seen in this white paper, Secondmind for Calibration has delivered proven value during the calibration process with intelligent, automated DoE that enhances traditional model-based calibration processes. Unlike conventional AI solutions that are data-hungry and lack transparency, Secondmind for Calibration applies data-efficient Active Learning to deliver precise calibration maps in faster timescales and with minimal computational resources.

Secondmind is helping automotive OEMs and Tier 1 suppliers transform their calibration processes, reducing engineering hours and cutting physical test bench testing. This is accelerating engine development, enabling automotive companies to deliver high-performance, fuel-efficient engines to market, faster, and accelerate the transition to more sustainable mobility.



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