

Optimization of an Advanced Combustion Strategy Towards 55% BTE for the Volvo SuperTruck Program

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ABSTRACT

This paper describes a novel design and verification process for analytical methods used in the development of advanced combustion strategies in internal combustion engines (ICE). The objective was to improve brake thermal efficiency (BTE) as part of the US Department of Energy SuperTruck program. The tools and methods herein discussed consider spray formation and injection schedule along with piston bowl design to optimize combustion efficiency, air utilization, heat transfer, emission, and BTE. The methodology uses a suite of tools to optimize engine performance, including 1D engine simulation, high-fidelity CFD, and lab-scale fluid mechanic experiments. First, a wide range of engine operating conditions are analyzed using 1-D engine simulations in GT Power to thoroughly define a baseline for the chosen advanced engine concept; secondly, an optimization and down-select step is completed where further improvements in engine geometries and spray configurations are considered. Next, simultaneous high-fidelity simulation using StarCD and OpenFOAM as well as lab-scale unsteady jet mixing experiments are used to understand the interplay between fuel injection and piston bowl designs. A key to the success of this design and analysis process is the accuracy of both the 1-D and high-fidelity simulations; these tools have been significantly improved and benchmarked against a range of engine operating conditions throughout the program. We conclude by outlining future directions for this methodology.

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INTRODUCTION

This paper describes a design and analysis process developed as part of the Department of Energy SuperTruck program [1]. The SuperTruck program outlined a number of goals for improvement of vehicle efficiency, including demonstration of a 50% increase in freight efficiency (ton-miles per gallon) as compared to a 2009 baseline vehicle, achievement of a 50% brake thermal efficiency (BTE) in a new heavy-duty diesel engine, and identification of a pathway that identifies a 55% BTE engine. This work focuses on the development of the "pathway" to 55% BTE, in which the Department of Energy required the use of modeling and analysis to identify "critical components and/or systems needing specific development to achieve this goal."

A thorough review of the limiting factors and potential areas for improving the engine's efficiency using analytical simulations was performed. The preliminary assessment included alternative

thermodynamic cycles and new engine design concepts. The final assessment of the chosen engine concept measured against the 55% efficiency goal included the additional gains expected from the use of a Rankine waste heat recovery system, optimized auxiliaries, and reduced friction losses.

There are a number of significant challenges in achieving 55% BTE in a commercially viable engine. Both mechanical and thermodynamic aspects of an ICE must be optimized to achieve these high values. Designing engines that will achieve ambitious efficiency and emissions goals requires the use of tools capable of simulating new engine operation regimes. Volvo and partners took a holistic approach in improving the tools that guide engine design by employing new methods for analysis and combining them with traditional methods of simulating aspects of engine operation.

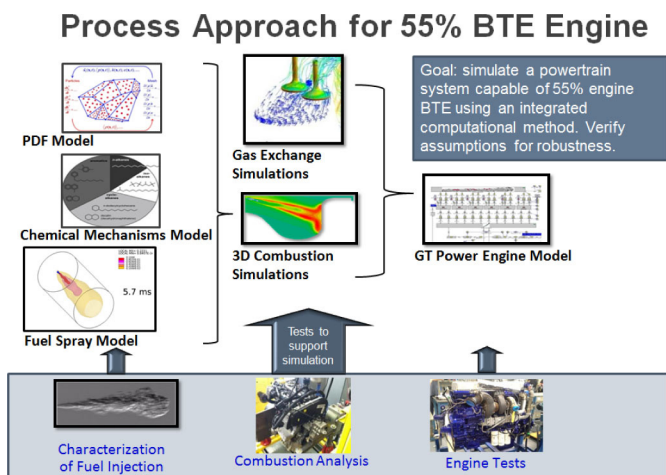


Figure 1. Key steps in the process development towards 55% BTE.

For example, as indicated in Figure 1, a process flow that relies on traditional tools and data has been combined with an analytical approach capable of determining the output of new hardware and combustion phenomena. The complex characterization of fuel injection was achieved via the combination of fuel mechanisms, computational fluid dynamics (CFD) and the continued development of Volvo's in-house fuel spray model which was corroborated by lab-scale fluid mechanics experiments. Secondly, combustion analysis included a separate study of the gas exchange process along with a parametric review of in-cylinder combustion parameters. This combustion analysis also included a robust comparison of standard mRIF (multiple Representative Interactive Flamelet) CFD techniques that were aligned with the transported probability density function (PDF) method discussed later. The final, high fidelity results were then input into a developed GT Power model to gain BTE as an output.

This paper describes the pathway by which the Volvo SuperTruck team, including partners from Volvo, the Pennsylvania State University, and the University of Michigan, achieved a 55% BTE concept through the development of high-fidelity tools that supported the design of an advanced combustion strategy. In particular, the result of the effort is a set of tools that were verified using a unique combination of low- and high-fidelity simulation, scaled laboratory experiments, and prior baseline engine test results. The pathway to 55% BTE outlined by the Volvo SuperTruck team provided modeling, analysis, and experimental verification of the models, to support the proposed pathway. While these tools were developed in support of the SuperTruck program, we will show that they can be used to understand a range of advanced combustion strategies.

The remainder of this paper describes the design process and provides details about the tools and their verification. The result of this effort is a methodology that can be used to design combustion strategies outside the bounds of normally-validated models. First, we provide an overview of the design and analysis process developed to show the connectivity between simulation, analysis, and experiment. Next, we detail each step of the process, using example results from analyses of different components to highlight the importance of these

steps towards achieving the Department of Energy goals. Finally, we discuss the implications of this process for the design of next generation engines.

OVERVIEW OF THE DESIGN PROCESS

The design process and tool verification effort consisted of a feedback loop between various simulations and experiments. Figure 2 provides an overview of this process.

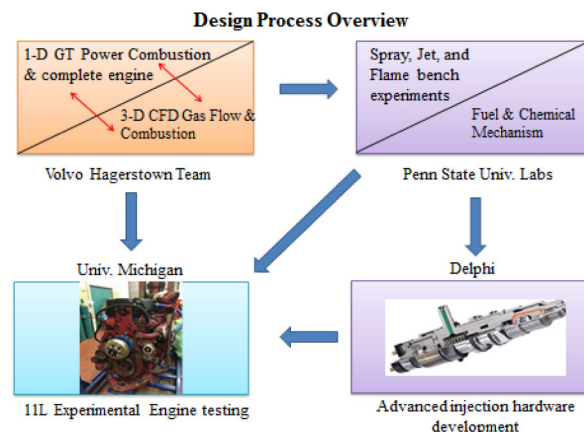


Figure 2. Feedback loop depiction of the design process through experimental and simulation collaboration between partners.

In a step-wise procedure, the Volvo team utilized both, 1-D complete engine and 3-D combustion/gas flow simulations to work in parallel to develop a series of broad spectrum design of experiments (DOE) that were used to validate and facilitate downstream lab and bench level tests. These DOEs are filtered for key engine operation parameters that can be verified using conventional engine test cell data, backed with previously calibrated simulations. As these DOEs were post processed, they were evaluated for consistent and agreeable trends towards the 55% BTE goal, where a selected group of parameter values were used to further develop tools, experiments, and hardware downstream. The results of the detailed 3-D parameter analysis aided in the selection of engine hardware to be used in future experiments.

These selected key parameter values were then passed to the team at the Pennsylvania State University where further testing was done to validate the 1-D/3-D simulations loop in a scaled gas jet experiment. Parallel high fidelity simulation was also carried out in order to provide continued agreement with both the 1-D and 3-D engine and combustion simulations. While many of the key engine parameters for fuel injection, combustion, and heat transfer need continued investigation, other parameters (engine speed, torque, start of injection, etc.) were correlated and analyzed with respect to baseline engine data.

After validation and selection of the remaining parameter values from the tests and simulation were concluded, the final fuel injection strategy and hardware development process began with the partners at Delphi. Advanced fuel injector, rail, pump, nozzle tip, and software were developed based on the results of the previous design process loop steps. With the collected combination of developed hardware

bench experiments, and simulation parameter validation, future testing at the University of Michigan will include a series of fired single cylinder engine cell tests, dedicated to validating the design process described here.

DETAILS OF THE DESIGN PROCESS

The goal of the design process was to simultaneously optimize piston bowl shape, fuel injection, and operating gas exchange conditions, in order to maximize efficiency within reasonable emissions limits. Traditional limits of compression ignition combustion were stretched, resulting in a larger design space. In particular, we considered a large number of intake conditions, high peak cylinder pressures, and nontraditional injection timings to maximize both power and efficiency.

To accomplish this, 1-D GT-Power simulations were carried out to parametrically evaluate the 55% BTE engine performance, with a Volvo internal predictive combustion model implemented in GT-Power. The 1-D GT-Power simulations predicted the engine performance and provided the boundary conditions for the 3-D CFD simulations. Generally, the design of experiment function in GT-Power was used to run detailed engine evaluations at a variety of different operating conditions, in order to define the relationships between controlling quantities and input variables. The best engine performance points were then selected from the DOE results at a variety of different engine speeds and loads. The DOE results can provide the steady conditions such as mass of trapped charge, and pressure/temperature boundaries to the 3-D CFD simulations, which significantly simplifies the analysis for the initial simulations. The 3-D simulations in return provided the heat release, heat transfer, and emission calculations to correct the 1-D simulation assumptions as depicted in Figure 3.

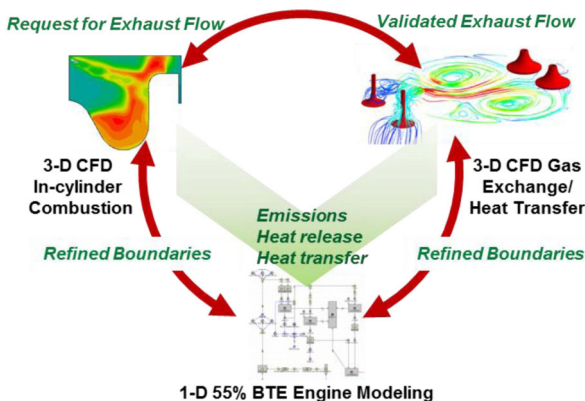


Figure 3. Methodology of Volvo 55% BTE engine concept evaluation and optimization.

Preliminary Engine Performance Screening

Comprehensive 1-D engine performance screening was carried out in order to investigate the brake thermal efficiency potential of the chosen Volvo 55% BTE engine concept. A number of engine speed key points varying from 900 rpm to 1800 rpm were simulated by sweeping the air-fuel equivalence ratio, EGR rate, rail pressure, and injection timing, respectively, as shown in Figure 4.

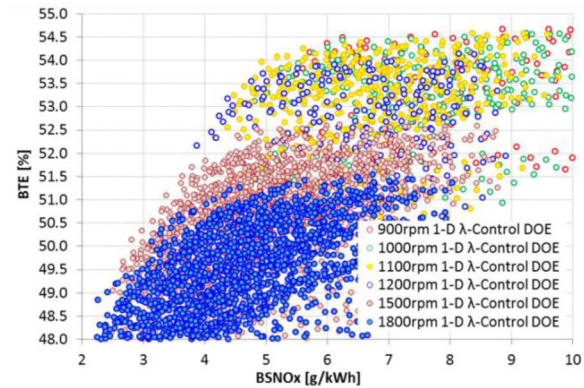


Figure 4. Trade-offs of BTE vs. BSNOx from 55% BTE engine performance screening based on air-fuel equivalence ratio sweep.

The trade-off of BTE and BSNOx from the lambda controlled design of experiments studies in Figure 4 indicates the best potential performance with the maximum brake torque occurs at a lower range of the engine speed, 900 rpm – 1200rpm. Thus additional 1-D engine performance screening was carried out at a selected engine speed of 1200 rpm and air-fuel equivalence ratio 1.3, varying from brake torque of 740 Nm up to 1550 Nm, by sweeping EGR rate, fuel rail pressure and injection timing, respectively, as shown in Figure 5.

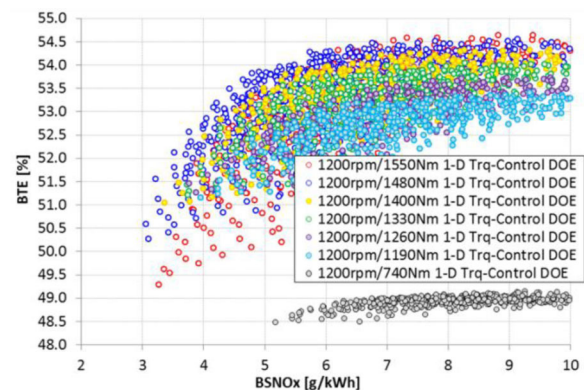


Figure 5. Trade-offs of BTE vs. BSNOx from 55% BTE engine performance screening based on brake torque control sweep.

The brake torque controlled DOE studies in Figure 5 indicate the optimum potential performance of the BTE-BSNOx trade-offs up to 54.0% with the peak cylinder pressure constraint of 300 bar at BSNOx of 8 g/kWh.

Parameter Space Down-Select

With the results of parameter space exploration completed, a further parameter space down-select was done to further reduce the number of cases to explore using higher fidelity tools. This simulation process was done using Volvo in-house multidimensional CFD modeling, including spray modeling and combustion modeling. The Lagrangian VSB2 spray model [2] is based on the idea of constructing a model that treats the spray and its breakup as one process, instead of summing individual, fragmenting droplets to a spray. The VSB2

model, with its proven stability and practically no tuning parameters, is well-suited for engine simulations covering large variations in engine operating conditions. The model used for thermodynamics and combustion is the mRIF combustion model. Initially developed at RWTH Aachen [3], the model assumes that a typical diffusion flame consists of a large number of very small laminar flames stretched by turbulence through the scalar dissipation rate. The scalar dissipation rate varies by orders of magnitude in the cylinder, particularly along the spray. One way to overcome this problem is to solve for more than one flamelet and couple each with its own fuel tracer, then average the scalar dissipation rate only in the zones that the tracer currently occupies. Thus, the mRIF model uses different flamelets in different parts of the spray. In the case where flamelets overlap in space, the feedback to the CFD solver, e.g. local mean of temperature, is tracer weighted from different flamelet solutions. The ideal gas law is the equation of state and the Sutherland viscosity law is employed. The turbulence model is the standard $k-\epsilon$ model, and the Star-CD solver from CD-Adapco is used for the simulations.

Piston Bowl Optimization

The combustion chamber design is critical to the overall performance of the heavy duty diesel engine. Changes to this portion of the system can dramatically affect the efficiency and emissions of the engine. One way to change the combustion process in the chamber is to modify the injection spray/piston bowl interaction. This change can be accomplished through modification of the design of both the injector nozzle and piston bowl. The process of changing and optimizing the design of these components and their interaction can be analytically streamlined by using modeling and engine testing in concert. The present work proposes to improve engine efficiency and validate the combustion chamber design through this approach. A number of piston bowl shapes for 55% BTE engine concepts were proposed, designed to enhance the flame recirculation and mixing paired with high swirl ratio conditions. 3-D CFD combustion simulations were carried out in order to investigate the influence on heat release and emissions from the bowl shapes and selected injection configurations.

Figure 6 demonstrates the combustion analysis based on the 3-D CFD simulation results of in-cylinder combustion with baseline piston bowl and proposed piston bowl option 2, respectively. The calculated rate of apparent heat release against crank angle during injection and combustion processes are compared to indicate improved heat release in the early combustion stage, caused by enhanced fuel-air mixing by fluid motions to dominate the combustion process in the chamber. The re-entrant shape forms stronger flame recirculation to improve the mixing process to speed up the combustion, and the bowl diameter is tuned for optimum spray-wall impingement timing. The apparent heat release rate predicted by the combustion CFD was then fed back to 1-D engine modeling. The coupled 1-D/3-D simulation results indicate the proposed piston bowl option 2 improved BTE by about 0.3% at the selected operating condition (900rpm /1550Nm).

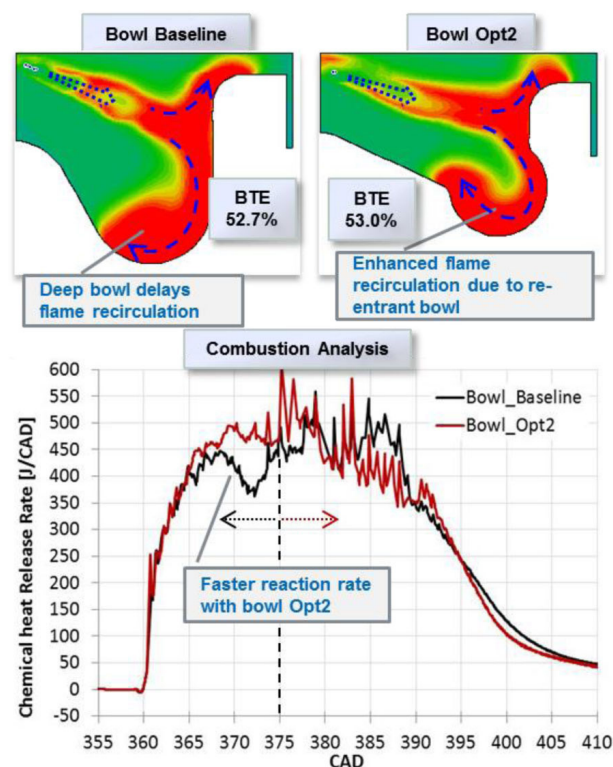


Figure 6. Combustion analysis of piston bowl via 3-D CFD simulations (900rpm /1550Nm).

Gas-Exchange Optimization

The Volvo 55% BTE engine has gained thermal efficiency through improvement of the gas exchange process between cylinders. Preliminary 1-D engine modeling indicated challenges remain in selecting detailed design elements for unconventional engine concepts. When unexpected heat or flow loss were identified by the modeling, new valve and port layouts were created to reduce these losses and achieve optimum volumetric efficiency from gas exchange. Detailed numerical analyses in 3-D Converge CFD were carried out to investigate gas exchange, as demonstrated in Figure 7. The simulated engine conditions were selected from the 1-D simulation results to provide the boundary conditions such as mass of trapped charge, and pressure and temperature boundaries to the 3-D CFD for gas exchange and heat transfer simulations.

The performance optimization of the gas exchange process includes the engine re-compression and the engine performance screening. The engine re-compression tuned the valve timing to gain the optimum pressure phasing during gas exchange. The engine performance screening was also carried out by varying the injection rail pressure, the injection timing, and the EGR rate. The evaluation results in Figure 8 indicate a significant BTE improvement up to 0.6% from gas exchange optimization based on the re-designed exhaust valve/port.