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FINAL PROJECT REPORT

A Multi-cylinder Transient Plasma Ignition System for Increased Efficiency and Reduced Emissions in Gas Engines

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PREFACE

The California Energy Commission's (CEC) Energy Research and Development Division manages the Gas Research and Development Program, which supports energy-related research, development, and demonstration not adequately provided by competitive and regulated markets. These research investments spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution and transportation.

The Energy Research and Development Division conducts this public interest natural gas-related energy research by partnering with research, development, and demonstration entities, including individuals, businesses, utilities and public and private research institutions. This program promotes greater reliability, lower costs and increases safety for Californians and is focused in these areas:

- Buildings End-Use Energy Efficiency.
- Industrial, Agriculture and Water Efficiency.
- Renewable Energy and Advanced Generation.
- Gas Infrastructure Safety and Integrity.
- Energy-Related Environmental Research.
- Transportation.

A Multi-cylinder Transient Plasma Ignition System for Increased Efficiency and Reduced Emissions in Gas Engines is a final report for the Developing Innovative Low Emission Gas Engine and Vehicle Technology for Medium- and Heavy-Duty Vehicles project (Contract Number 500-18-003) conducted by the National Renewable Energy Laboratory. The information from this project contributes to the Energy Research and Development Division's Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the CEC's research website (www.energy.ca.gov/research/) or contact the CEC at ERDD@energy.ca.gov.

ABSTRACT

California’s transportation sector accounted for 41 percent of the state’s greenhouse gas emissions at 418.2 million metric tons of carbon dioxide equivalent in 2019. Many vehicles — particularly those used in commerce, industry, and public transportation — are diesel fueled and cannot easily be modified to take advantage of the electrification option that avoids carbon dioxide emissions. Reducing greenhouse gas emissions from these vehicles is critical to achieving California’s climate change goals.

Gas engines, largely fueled by methane, emit significantly less carbon dioxide and almost no particulate matter for the same amount of energy output as diesel engines. Although some companies have developed ultra-low oxides of nitrogen emission gas engines for heavy-duty trucks, widespread adoption has not occurred.

Advanced ignition is a key enabler for the improved efficiency, maintenance, operational costs and reduced emissions necessary to compete with diesel alternatives and gain market acceptance. Transient Plasma Systems, Inc. (TPS) made significant progress in advanced ignition technology for heavy-duty gas engines. Combustion results from previous work have shown that this technology can improve brake thermal efficiency and reduce emissions by enabling stable operation at higher dilution levels. This project built on previous development work by focusing on electronics packaging, system integration with the main electronic control unit of the engine, operability improvements, and advancing the system toward commercialization. Specifically, custom device bonding, interconnect methods, and hermetic encapsulation were developed to increase performance, miniaturize size, and achieve a commercially viable form factor; closed-loop sense and control was developed to optimize energy draw and delivery to maximize plug durability; and improvements at the plug and cabling level were implemented to improve overall system performance. This project resulted in a compact multi-cylinder ignition system design based on receptively pulsed nanosecond discharges that is ready for commercial development with an engine technology supplier.

Keywords: Heavy-Duty Gas Vehicles, Energy Efficient, Environmentally Friendly, Ignition, Non-thermal Plasma, Nanosecond Pulsed Power, Dilute Combustion, Transient Plasma, Plasma Assisted Combustion

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EXECUTIVE SUMMARY

Introduction

California’s transportation sector accounted for 41 percent of the state’s greenhouse gas (GHG) emissions at 418.2 million metric tons of carbon dioxide equivalent in 2019. Many vehicles cannot be easily electrified today, including heavy-duty trucks, delivery vehicles, buses, trains, ships, boats and barges, farm and construction equipment, and heavy-duty military vehicles and equipment. Reducing GHG emissions from these vehicles is critical to achieving California’s climate change goals and improving air quality in communities impacted by emissions from these vehicle types.

Gas engines, largely fueled by methane, emit significantly less carbon dioxide and almost no particulate matter for the same amount of energy output as diesel engines, which are predominantly used in nearly all the vehicle types previously mentioned. Gas engines need to compete favorably with their diesel alternatives in terms of efficiency, maintenance, and overall operational costs, and whereas drivers and owners may not emphasize improved efficiency as a desired goal, it is through efficiency improvements that one can deliver the desired characteristics of a long driving range between fill-ups, the torque to pull a heavy load uphill, and the emissions performance necessary to meet increasingly strict regulations.

Advanced ignition is a key enabler to unlock efficiency improvements and reduced emissions; however, no advanced ignition system has ever been adopted on a large scale. This is because no technology has demonstrated it can meet all of the requirements of an advanced ignition system simultaneously. These requirements include extension of current dilution limits, a compact size with a cost that matches benefits, good transient performance, a nominal load on battery power, a seamless fit with current engine architectures, and durability. All of these requirements are related, and this project focuses on a developing a package that meets those requirements.

Project Purpose

The goal of this project was to advance previously demonstrated transient plasma low-energy ignition technology toward a production system. Short, high-voltage electrical pulses produce transient plasma, which consists of low-temperature gas and high-energy electrons. The high-energy electrons enhance ignition and assist with the combustion process. Transient plasma ignition can achieve stable combustion with much lower energy than conventional spark ignition, extending spark plug durability and reducing maintenance costs and associated down time. Previous work successfully demonstrated transient plasma ignition in a multi-cylinder engine test, proving that the technology has matured beyond the component level and can operate in a relevant environment as a unified system.

This project focused on moving the unified system design toward commercialization, including tasks centered around electronics packaging, system-integration with the main electronic control unit of the engine, and associated operability improvements.

Transient plasma ignition systems will benefit California’s gas ratepayers by improving the efficiency, performance, and competitiveness of low emission gas vehicles. Transient plasma ignition systems can provide these benefits by enabling stable and efficient combustion of dilute gas mixtures using low-energy pulses. High dilution levels reduce knock tendencies — premature combustion — by lowering combustion chamber temperatures, but higher ignition energy is required to maintain stable combustion. Mitigating knock enables engine design decisions that can increase fuel efficiency, such as increasing the compression ratio of the pistons. Additionally, due to the low energy of each individual transient plasma pulse relative to traditional spark ignition, spark plugs are expected to have a much longer useable lifetime, resulting in reduced maintenance and the associated down time.

The potential benefits of converting large numbers of California's medium and heavy-duty truck fleet from diesel to gas using transient plasma ignition include:

- A greater than 20 percent reduction in greenhouse gas emissions.
- Reductions in petroleum consumption — saving 140 million gallons of diesel fuel per year in California at a 10 percent adoption rate.
- Significant reduction (90 percent) in particulate matter in the exhaust, as well as reductions in the emission of sulfur dioxide by 99 percent, nitrogen oxides by 75–95 percent, volatile organic compounds by 89 percent, and carbon monoxide by 70–90 percent.
- Higher engine efficiency – higher boost pressures and compression ratios can be used compared to conventional ignition systems.

Project Approach

The team consisted of Transient Plasma Systems, Inc. (TPS), responsible for technology development, and Argonne National Laboratory, responsible for laboratory testing on a production engine. Additionally, Cummins Westport Inc. provided the engine and engineering support for setting up and running the demonstration.

This project built on a previous effort that scaled transient plasma ignition to enable a demonstration on a six-cylinder heavy-duty gas engine. As initial prototype hardware, this exploratory system was designed to accommodate design changes as necessary and was far from optimized. In the current project, TPS refined the design to reduce size and improve operability, thereby maturing the system from a technology readiness level of 6 to a target of 7 — a system capable of being validated in an operational environment beyond an instrumented laboratory setting.

The approach began with refining pulse parameters (including peak pulse voltage, reduced electric field, pulse repetition frequency, and number of pulses per ignition event) based on data from the previous multi-cylinder engine test conducted in 2019. TPS also collected data in static cells and engine tests funded internally and by other grants and potential customers to provide guidance when selecting the most important parameters.

TPS then developed a real-time pulse train feedback control system to improve energy efficiency per ignition event and extend spark plug lifetime. Leveraging the efficiency improvements achieved with the real-time pulse train feedback control system, the existing multi-cylinder prototype was miniaturized by optimizing system layout and employing revised cylinder gating circuitry that made use of more power dense devices. Thermal management of the system was also redesigned to enable a hermetically sealed enclosure. These efforts reduced the overall size of the system by a factor of 50 compared to the initial prototype built at the beginning of this effort. This significant reduction was a result of minimizing the voltage requirement by means of plug and pulse train optimization, new charging circuitry that reduced footprint requirements by a factor equal to the number of cylinders, and design modifications to increase instantaneous power density to eliminate device count.

TPS then worked with a supplier to develop a DC-to-DC converter to convert the vehicle power source into useable power for the TPS ignition system.

Finally, TPS validated that the changes in pulse strategy of the new design would still provide the performance benefits in a commercially available 12-liter gas engine provided by Cummins Westport Inc.

Project Results

The outcome of this project was the design of a transient plasma ignition system that has the potential to meet size, cost, and performance targets required of a gas engine manufacturer looking for an advanced ignition solution. Multi-cylinder engine data was once again collected to test the desired pulse delivery strategies. TPS, as a technology development firm, took the technology to the point where it could work with an engine technology manufacturer with deep experience and the resources and infrastructure available to advance the technology through design validation and product testing. The outcome of this development was intended to attract the interest of existing heavy-duty engine manufacturers to help drive a more rapid transition to commercially viable gas replacements for diesel.

Standard spark ignition was compared to transient plasma ignition under standard engine conditions. The new design of transient plasma system performed reliably resulting in similar performance to standard spark ignition in overall efficiency, stability, and emissions. The benefits of transient plasma ignition were observed when the team pushed the performance of the engine beyond the limits of the standard spark ignition system. Today's engines are limited in the amount of dilution they can tolerate in the air-fuel mixture. While the potential efficiency gains from increasing dilution are significant, exceeding the manufacturer's dilution limit leads to unstable operation when using traditional spark ignition. Performance testing demonstrated that transient plasma ignition can increase dilution rates without losing engine stability. As part of operating at the increased dilution enabled by transient plasma ignition, the team observed a reduction in nitrogen oxide emissions from greater than 4 grams per kilowatt-hour to less than 1 gram per kilowatt-hour. The results are significant because the fuel map for this production engine was not changed — to optimize the efficiency gains for an advanced ignition system, one normally must update the applicable fuel map and ignition timing. Based on prior single cylinder engine tests with transient plasma ignition technology, enabling additional dilution tolerance and updating the fuel map can result in fuel economy gains of more than 20 percent.[1]

The development of this technology combined with combustion testing resulted in pulsed strategy that significantly reduced the amount of energy required to achieve desired engine

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[1] Sjöberg, Magnus, et al., 2014, "Combined effects of multi-pulse transient plasma ignition and intake heating on lean limits of well-mixed E85 DISI engine operation," *SAE International Journal of Engines* 7(4): 1781-1801.

performance. At the same level of dilution, the energy required for ignition was reduced by a factor of 3 when using the pulse train feedback control system. This is also a practical benefit because it reduces the power requirements of the ignition system and therefore the cost and complexity at the circuit level.

This research sets the stage for follow-on projects. Developing a new ignition system for production engines must be done in well-established, manufacturer-defined stages, and with the resources and infrastructure available at such manufacturers. The design of a transient plasma ignition system that has the potential to meet size, cost, and performance metrics of gas engine manufacturers is a key milestone along the roadmap of developing a production ignition system. The next step is for TPS to collaborate with a commercial ignition system or engine manufacturer to get the current design commercially ready, by advancing it through their design validation and production process.

Technology and Knowledge Transfer

TPS communicated the outcomes of this project to industry stakeholders through direct meetings and presentations with known entities such as engine manufacturers. By partnering on the project with key industry players such as Cummins Westport Inc., TPS ensured the potential for continued progress toward commercialization after project completion. TPS shared project updates to industry stakeholders at the Natural Gas Vehicle Technology Forum in May of 2021

The technology has applications in both the gas and the gasoline engine markets. TPS also used a press release through Cision PR News Wire for description of results from gasoline engine testing in June of 2022. TPS plans to target the medium- and heavy-duty engine applications in transportation and power generation sectors in addition to the passenger car market. The publication of this report should inform regulatory agencies, engine original equipment manufacturers, fuel suppliers, and end users about the potential of transient plasma ignition technology to reduce fuel consumption and greenhouse gas emissions from gas engines.

Benefits to California

Transient plasma ignition systems will benefit California’s ratepayers by accelerating a transition to lower emission gas engines from diesel for use in heavy-duty vehicles. Combusting gas in engines produces 23 percent fewer carbon dioxide emissions than the combustion of diesel fuel; however, gas engines are less efficient than diesel engines, offsetting some of the carbon dioxide emission reductions. If future gas engines are made more efficient, gas will be even more favorable from a carbon dioxide standpoint compared to diesel. Turbocharging and increasing compression ratio are two strategies to improve the efficiency of gas engines; however, both necessitate improved ignition systems such as the one developed through this project.

If gas engines can be improved to within 10 percent of the efficiency of diesels for Class 8 heavy-duty vehicles, fuel savings will translate to about $6,500 saved and 7,660 pounds of carbon dioxide emission reductions per year per vehicle. If just 10 percent of the 1,720,000 registered Class 8 vehicles nationwide transitioned to gas engines, the annual savings would be $1.1 billion per year and carbon dioxide emissions would be reduced by 1.3 billion pounds per year. California would see annual fuel cost savings of $82 million and 97 million pounds of carbon dioxide.

Key barriers to adoption of transient plasma ignition technology for transportation applications include system cost, durability, and size. Through system improvements such as real-time pulse train feedback control and redesigned thermal management, the project reduced energy consumption by a factor of 3 and size by a factor of 50 compared to previous prototypes. Reducing energy consumption contributes to cost reduction, improved durability, and size reduction. This makes the system ready for a Tier 1 partner to begin the process of preparing the system for commercialization.

CHAPTER 1: Introduction

California’s transportation sector accounts for 41 percent of the state’s greenhouse gas (GHG) emissions. Reducing GHG emissions from vehicles is critical to achieving California’s climate change goals and clean air standards. Gas engines, largely fueled by methane, releases significantly less carbon dioxide (CO_2) and almost no particulate matter (PM) for the same amount of energy as diesel fuel, the fuel used in nearly all heavy duty-trucks, delivery vehicles, buses, trains, ships, boats and barges, farm and construction equipment, and heavy duty military vehicles and equipment. Companies such as Cummins Westport (CWI) have developed ultra-low oxides of nitrogen (NOx) emission gas engines for heavy-duty trucks, certified to a NOx emission level that is 90 percent below the existing federal standard. These engines need to compete favorably with their diesel alternatives in terms of efficiency, maintenance, and overall operational costs. This project developed a solution to help meet those targets for use in existing or future heavy-duty gas vehicles, thereby improving the competitiveness of gas vehicles by enabling performance similar to diesel engines.

Although gas engines emit fewer GHG, PM, and NOx emissions than diesel engines, there is a need to increase gas engine efficiency with minimal additional capital or operational costs to improve competitiveness with diesel. The ignition characteristics of gas fuel present challenges for meeting these requirements: today, high energy sparks are often used to ignite the high-pressure fuel-air mixture that can lead to premature erosion of the spark plugs. At a fundamental level, combustion engines burn an air-fuel mixture. The higher the amount of air in that mixture, the more fuel-efficient the engine can be. Most ignition systems (e.g., traditional spark, dual coil, plasma jet, etc.) struggle to ignite air-fuel mixtures with higher amounts of air and less fuel. Higher energy sparks might help ignite such lean mixtures, but that approach leads to premature erosion of the spark plugs. In transient plasma ignition, though, radicals are produced directly, which is much more efficient and, therefore, less energy is needed to achieve ignition even under increasingly dilute conditions. Transient plasmas can be produced with other methodologies such as radiofrequency advanced corona ignition systems, rather than nanosecond pulses, but the fast-rising voltage in Transient Plasma Systems’ (TPS) approach creates more radicals by more efficiently transferring energy into the fuel-air mixture.

The goal of this project was to advance previously demonstrated transient plasma low-energy ignition technology toward a production system. Previous work successfully demonstrated transient plasma ignition in a multi-cylinder engine test, proving that the technology has matured beyond the component level and can operate in a relevant environment as a unified system. This project focused on moving the unified system design toward commercialization, including tasks centered around electronics packaging, system-integration with main electronic control unit of the engine, and associated operability improvements.

This transient plasma ignition (TPI) system will benefit California’s gas ratepayers by improving the efficiency, performance, and competitiveness of low emission gas vehicles. TPI can provide these benefits by enabling stable, efficient, dilute-burn combustion of gas using low-energy pulses.

The potential benefits of changing large portions of California's medium and heavy-duty truck fleet from diesel to gas using transient plasma ignition include:

- A greater than 20 percent reduction in greenhouse gas emissions.
- Reductions in petroleum consumption — saving 140 million gallons of diesel fuel per year in California at a 10 percent adoption rate.
- Significant reduction (90 percent) in PM in the exhaust, as well as reductions in the emission of sulfur dioxide by 99 percent, NOx by 75–95 percent, volatile organic compounds by 89 percent, and carbon monoxide by 70–90 percent.
- Higher engine efficiency — higher boost pressures and compression ratios can be used compared to conventional ignition systems.

This project focused on moving the system design toward commercialization, including tasks centered around electronics packaging, system-integration with the main electronic control unit of the engine, and associated operability improvements. This project intended to design a compact multi-cylinder ignition system based on repetitively pulsed nanosecond discharges that is ready for commercial development with an engine technology supplier. Multi-cylinder engine data was once again collected to test the desired pulse delivery strategies. The outcome of this development is intended to attract the interest of heavy-duty engine manufacturers to help drive a more rapid transition to commercially viable gas replacements for diesel.

CHAPTER 2:
Project Approach

Multi-cylinder Transient Plasma Ignition System Development

The goal of this project was to build on the previously described efforts funded by the U.S. Department of Energy and the California Energy Commission (CEC) that demonstrated the capability of TPS's TPI technology to significantly extend dilution tolerance with enhanced stability as a means of achieving higher break thermal efficiency (BTE). Chapter 2 describes the development approach taken by TPS to design a new multi-cylinder ignition system, as well as the work conducted by the team at Argonne National Laboratory to implement the engine test setup.

Refine Pulse Parameters

Based on both TPS's previous experience conducting single cylinder engine tests and peer-reviewed academic papers,[2] nanosecond pulsed power parameters, including rise time, pulse repetition rate/burst rate, pulse duration, and voltage amplitude all impact the combustion process by contributing to the enhancement of reactive species production. The initial pilot studies were discussed in greater detail in the PIR-16-024 final report.[3]

TPS selected the specifications outlined in Table 1 for the six-cylinder system, which is referred to as the transient ignition module. Based on the results that showed the positive effect of the pulse repetition rate, TPS decided to engineer a system capable of achieving a rate of 100 kilohertz (kHz), an order of magnitude higher than the 10 kHz TPS had previously used for most engine experiments.

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[2] Cathey, Charles D., et al., 2007, "Nanosecond plasma ignition for improved performance of an internal combustion engine." *IEEE Transactions on Plasma Science* 35.6: 1664-1668; Gundersen, Martin, et al., 20014, "*Combined Effects of Multi-Pulse Transient Plasma Ignition and Intake Heating on Lean Limits of Well-mixed E85 SI Engine Operation*," No. SAND2014-1536C. Sandia National Lab (SNL-CA), Livermore, CA (United States); Sevik, James, et al., 2016, "Extending lean and exhaust gas recirculation-dilute operating limits of a modern gasoline direct-injection engine using a low-energy transient plasma ignition system," *Journal of Engineering for Gas Turbines and Power* 138.11: 112807; Singleton, Dan, et al., 2010, "The role of non-thermal transient plasma for enhanced flame ignition in C2H4–air," *Journal of Physics D: Applied Physics* 44.2: 022001; Singleton, Daniel, et al., 2017, "Demonstration of improved dilution tolerance using a production-intent compact nanosecond pulse ignition system," *International Conference on Ignition Systems for Gasoline Engines (CISGE 2016)*. Springer, Cham; Sjöberg, Magnus, et al., 2014, "Combined effects of multi-pulse transient plasma ignition and intake heating on lean limits of well-mixed E85 DISI engine operation," *SAE International Journal of Engines* 7(4): 1781-1801.

[3] Sanders, Jason, Dan Singleton, and Thomas Wallner. 2020. Development and Demonstration of a Production-Intent Transient Plasma Ignition System for High Efficiency Natural Gas Engines. California Energy Commission. Publication Number: CEC-500-2020-043.

Table 1: Target Specifications for Multi-cylinder Ignition Module

Pulse Parameter	Target Specification
Peak Voltage into 50 Ohm	20 kV
Pulse Duration	10 ns
Pulse Risetime (10-90%)	5-7 ns
Maximum Pulse Energy	75 mJ
Max Pulses per Burst	20
Pulse Repetition Rate	100 kHz

Note: kv=kilovolt; ns=nanosecond; mJ=megaJoule; kHz=kilohertz.

Source: Transient Plasma Systems, Inc.

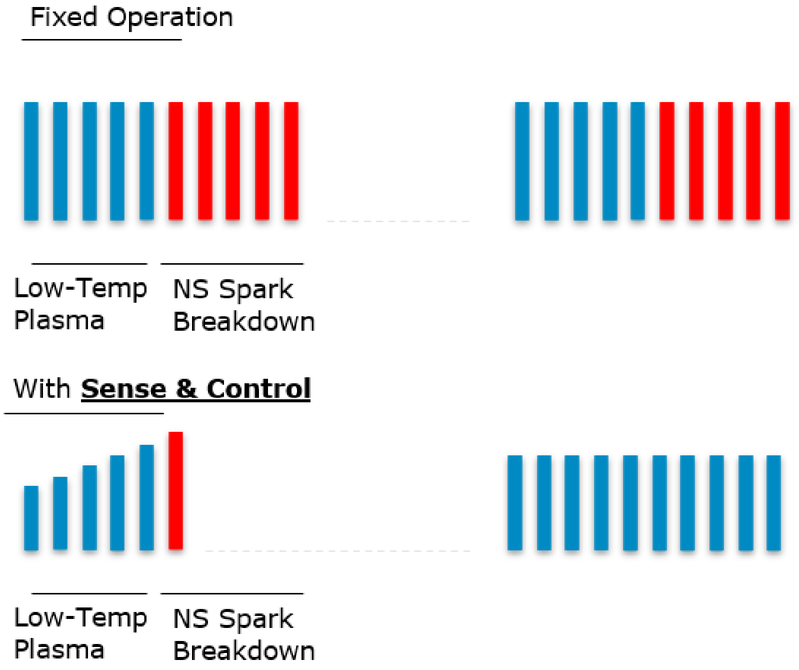
A more thorough investigation of the effect of pulse risetime and repetition rate on plasma chemistry and combustion efficacy remains an important topic in this application space; however, some technical breakthroughs must be made in pulsed power technology and components to realize a practical system with near-term commercial application.

Design and Incorporate a Pulse Tracking Feedback System

As part of this project, TPS developed a real-time pulse train feedback control system as means of further extending spark plug lifetime and reducing current draw from 12 Volt or 24 Volt bus. Existing TPS technology that has been used in previous demonstrations generated multiple nanosecond duration pulses per ignition event. The number of pulses could be adjusted, but not in real time. By employing real-time signal processing to analyzing voltage and current waveforms, it was possible to detect the beginning of ignition and cease the delivery of additional pulses. A feedback loop of this type can optimize energy delivery to the plug, increasing lifetime, and also improving overall efficiency.

TPS developed two new assets critical to enable higher system efficiency (Figure 1), potentially improving spark plug lifetime and reducing cost and size: (1) pulse sense, which enables fast current measurement to detect spark and low temperature plasma discharges; and (2) pulse-by-pulse power control, which enables pulse modulation without additional components.

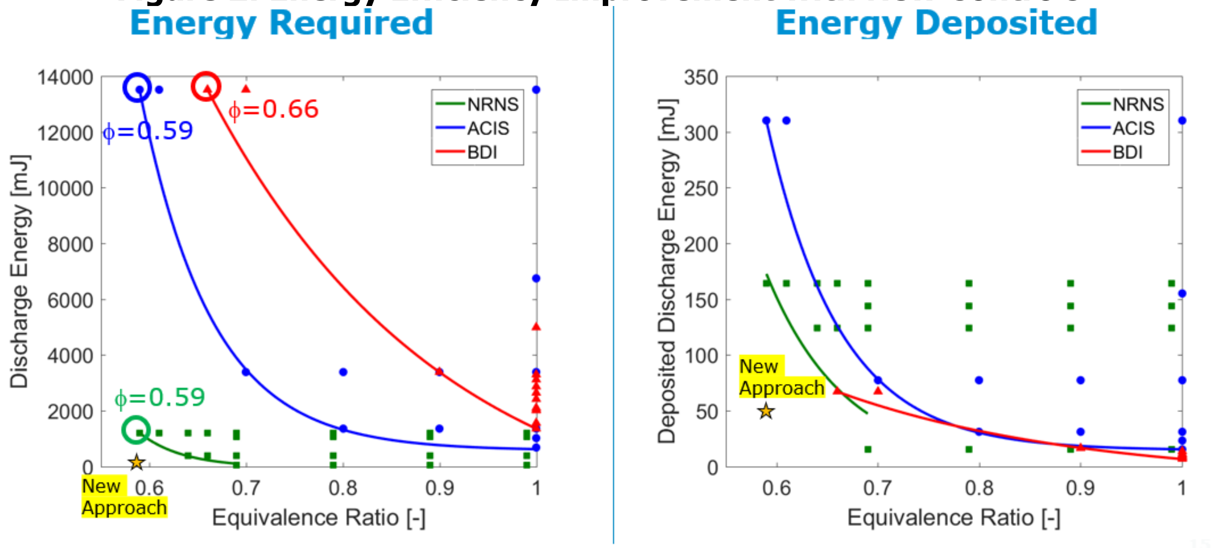
Figure 1: Pulse Sense and Control Technology



Source: Transient Plasma Systems, Inc.

Using these assets plus a new spark plug tip design, TPS demonstrated that it was possible to operate an open electrode gap style plug using a specific series of fast-rising nanosecond-scale high voltage pulses, with significantly higher energy efficiency. Figure 2 shows that the total energy required was reduced by more than a factor of 3 at the leanest point. This approach took advantage of plasma-assisted spark to achieve more volumetric ignition and a faster initial flame front while using less energy. The spark plug and pulse train worked together to deliver the right amount of energy at the right time to ensure successful ignition kernel development.

Figure 2: Energy Efficiency Improvement with New Controls



Source: Transient Plasma Systems, Inc.

Miniaturize Existing Multi-Cylinder Prototype

Before this effort began, TPS had developed a prototype six-cylinder transient plasma ignition system as part of a program with the CEC to demonstrate the feasibility of extending dilute burn limits in a practical, real-world engine (CWI ISX12N). To enable multi-cylinder operation, custom high voltage, high current transmission gates were developed that consisted of a 3.4 kilovolt rated four quadrant switch which could block voltage in both directions and conduct current in both directions. These transmission gates were switched between blocking and conducting states by the engine controller to steer pulse energy toward the correct cylinder based on the firing sequence of the engine. The purpose of this prototype system was to validate a new hardware architecture and to demonstrate that it could meet or exceed the performance gains that TPS plasma ignition technology had shown in previous single cylinder tests (described in preceding sections). Since this initial prototype was new hardware, TPS used a fairly flexible design so that modifications could be added as necessary. As a result, the system was not optimized for size, resulting in a footprint that was approximately 24” x 24”. The purpose of this task was to reduce the overall size of the system by at least 50 percent, which was feasible by employing new layout techniques such as chip on board that would shrink printed circuit board (PCB) footprints, and also by increasing the density of the system layout. To achieve the target 50 percent size reduction, TPS refined the previously developed transmission gate architecture using the following approaches:

1. Miniaturized the existing multi-cylinder prototype by designing a revised high voltage transmission gate circuit that makes use of more power dense devices.

2. Reduced PCB size by eliminating passive components and employing chip on board assembly techniques to eliminate space taken up by the packaging of semiconductor devices.

3. Increased system layout density by encapsulating high voltage components to reduce creepage/clearance requirements for voltage hold-off.

TPS was able to exceed the target volume reduction of 50 percent by reducing PCB size and increasing system layout density; however, implementation of high voltage transmission gates at the output of the pulse generating circuit was not leveraged. For reasons related to size and gate drive complexity, a revised design was selected that used a pulse generating module per cylinder and gated charging circuit that steered charging current from a direct current (DC) step-up converter to the appropriate pulse generating module according to cylinder timing.

Redesign Thermal Management

The multi-cylinder prototype previously developed during the effort funded by CEC used forced air for temperature control. This was insufficient for a commercial product because forced-air cooling requires ventilation, which is not possible for an under-the-hood ignition module. Two methods were investigated to redesign the thermal management system: 1) the semiconductors were mounted to a ceramic material that provided good electrical isolation from the grounded enclosure and moderate thermal conductivity; 2) the high voltage components were either encapsulated or submerged in a dielectric fluid. Calculations were done for both approaches, and it was decided that the second approach was the best choice for this project because it enabled testing of both thermal and packaging design ideas in a non-destructive way. Thermal testing was conducted using a test-rig that was designed and built to allow TPS engineers to measure the case-to-enclosure thermal conductivity for the power electronics used in the design.

12 Volts of Direct Current Compatibility

Previous TPS systems used for ignition applications were compatible with 24 volts of direct current (VDC) input, which was suitable for some applications, but many others still required 12 VDC. Although 24 VDC batteries are common for heavy duty applications and vehicles, like semi-trucks, TPS identified that 12 VDC compatibility was important for mass-adoption of this technology for mobile and industrial applications. A decision was made to design a 12 VDC compatible system, realizing that a modification to operate with 24 VDC or 48 VDC input voltages would simplify the design.

A custom, efficient 12 VDC compatible converter was developed in collaboration with a consultant with expertise in developing highly efficient custom DC-DC solutions. TPS developed conservative specifications, assuming what was understood to be the high-end of power draw and provided size specifications to the consultant. The consultant then worked with TPS to develop a solution with 95 percent efficiency.

Engine Test — Experimental Equipment Description

Engine Description

The ISX12N engine is an 11.9 liter, inline six-cylinder gas engine manufactured by CWI, as shown in Figure 3. The engine is rated at 400 HP (298 kilowatts) with a peak torque of 1,966 Newton meters (Nm), or 1,450 pounds per foot. The engine oil lubrication loop was not modified, and the engine holds approximately 45 liters (approximately 12 gallons) of motor oil. The stock gas fuel system was maintained at a fuel pressure in the range from 60–150 pounds per square inch (4.1–10.3 bar). The engine uses either the stock engine ignition system or the prototype transient plasma ignition system. The engine’s fueling, ignition, and exhaust gas recirculation rate was controlled by the stock engine control unit via an engine control interface. All rotating parts on the engine were covered to avoid accidental contact. The rest of the engine test setup is described in detail in the PIR-16-024 final report.

There was one major change, which was in the flowrate of the gas. Two Hydrovane HV07G compressors for the previous tests were replaced with a G30RS compressor that can flow up to 164 cubic feet per minute. This change ended up requiring a significant amount of the budget and time allotted for testing; however, it was a requirement to be able to run at the high-load operating point.

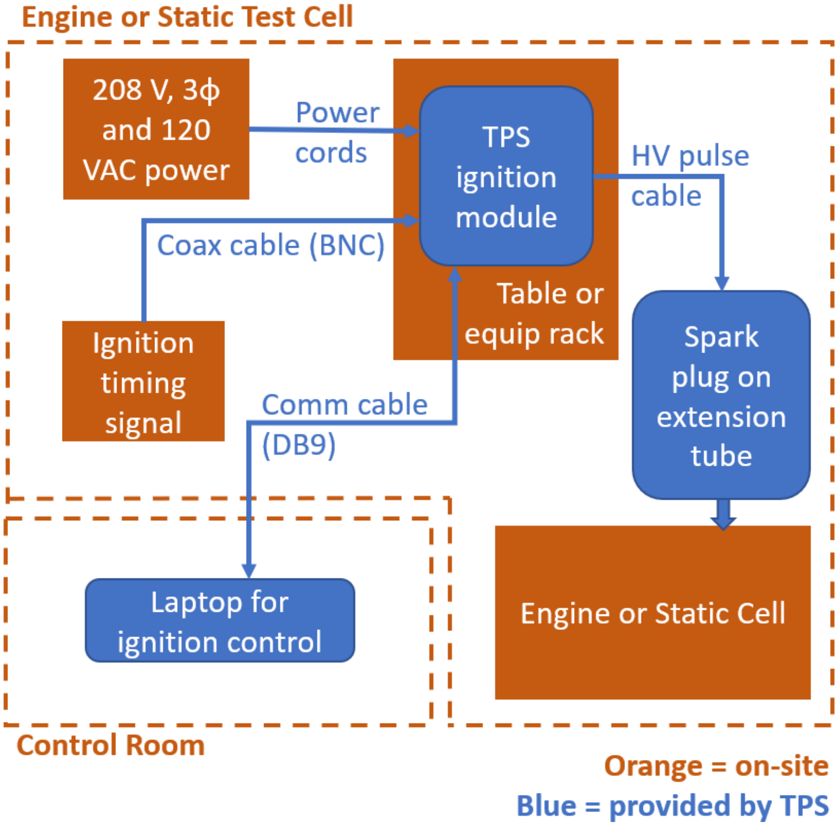
Figure 3: ISX12N Engine Setup

Source: Argonne National Laboratory

Engine Ignition System

The engine was either operated with the stock engine ignition system or the prototype transient plasma ignition system. The stock engine ignition system was powered as part of the engine control unit using an external 12 VDC power supply. Figure 4 shows a block diagram describing how the TPS ignition modules connected to the test cell's prime power supply, as well as how it was controlled using an ignition timing signal and a laptop, which was used to program or change the smart-pulse sense and control parameters as needed. The TPS module's high voltage output was connected with a cable to the TPS designed extension-to-plug interconnect, which was threaded into the engine.

Figure 4: TPS Ignition Test Block Diagram



Source: Transient Plasma Systems, Inc.

CHAPTER 3:
Project Results

Transient Plasma Ignition System Design

Refine Pulse Parameters

Two different architectures were developed around the pulse parameter specifications described in Chapter 2, one with the intention of demonstrating thermal performance required for ignition technology, and the other with the intention of providing a development platform to demonstrate sense and control feedback. A third architecture was designed that incorporates lessons learned during this effort to incorporate sense/control technology, thermal design requirements, and pulse parameter requirements.

Follow-on testing focused on electrode design that occurred in parallel with this effort showed that electrode geometry had significant impact on the peak voltage required and the pulse train. Further research and development into the impact of electrode geometry and pulse parameters on ignition and combustion parameters, such as required applied voltage, pulse energy, and pulse train duration, informed the design of the third architecture to reduce size and cost.

Pulse repetition rate of 100 kHz (and potentially higher) was shown to be an important parameter and remained a requirement across all designs. To address commercialization requirements regarding cost and size, research and development focused on reducing the peak voltage requirement by means of optimizing plug design. This work is ongoing, although, based on recent engine testing, the third design appears to be a feasible approach for achieving sufficient voltage, pulse repetition rate, and burst duration to achieve significant dilute burn extension.

Identifying optimal pulse parameters and realizing them in hardware capable of addressing the requirements of durability, size/cost, and high temperature operation was a non-sequential process that was ongoing through this effort. Accordingly, these efforts are reported in the subsequent sections in an anachronistic timeline.

Design and Incorporate a Pulse Tracking Feedback System

This section describes the design and implementation of a new closed loop control scheme for TPS' repetitively pulsed ignition system. By implementing this sense and control approach to delivering pulses, TPS expected to be able to improve ignition system performance (e.g., extend dilution limits), tailor the energy delivery as needed during each ignition event, and reduce electrode erosion. Pulsed power systems that generate pulses with durations under tens of nanoseconds are typically open loop systems, requiring an operator to set parameters such as output voltage, pulse repetition rate, and number of pulses generated in a burst of pulses. Those settings are then fixed until an operator manually intervenes to adjust one or more of the settings. TPS developed a new sense and control approach to allow for autonomous intervention and modification within a given pulse train as well as automatic adjustments of parameters to tune the subsequent pulse train in preparation for the next ignition event.

TPS developed a system and method for differentiating between different modes of pulsed electrical discharges via the use of an amplitude to time (ATC) conversion circuit. A bipolar ATC circuit added together the positive and negative portions of an attenuated and filtered signal derived either from the voltage or current measurement of a pulse. Alternatively, a unipolar ATC circuit could be employed. The resulting processed signal was compared against a reference voltage to generate an output signal that was active for the amount of time that the processed signal exceeded the reference voltage. The discharge mode was determined based on three factors: (1) whether a pulse occurred; (2) assuming a pulse occurred, when the pulse started relative to the original pulse event; and (3) the duty cycle of the pulse. Subsequent pulses generated could be controlled accordingly.

In the process of conducting experiments to demonstrate the efficacy of nanosecond duration pulses to improve engine efficiency, it became clear that if a practical closed loop sense and control approach could be developed that operated under the timing constraints imposed by such short duration pulses. Closed loop sense and control approach could be employed to optimize energy delivery and Coulomb transfer through an igniter or spark-plug, potentially extending electrode lifetime. Closed loop sense and control could also, for example, be used to modify the pulse train during a burst to further improve combustion performance.

A method and circuitry were developed to detect and/or determine the nature of a discharge event. Types of possible discharge events include (a) no discharge (high impedance), (b) transient plasma glow or corona discharge (moderate impedance), and (c) nanosecond spark (low impedance). Once the type of discharge mode was detected, subsequent pulses in the pulse train could be adjusted based on logic or an algorithm (*e.g.*, a pre-programmed or defined algorithm) executed by circuitry (*e.g.*, microcontroller). The circuitry received as input an indication of the type of discharge and an indication of the amplitude of the most recent discharge, and in response produced outputs that modified the pulse parameters of a subsequent pulse. For this project, the approach for determining the type of discharge that resulted from each individual nanosecond pulse applied to the igniter was developed based on an ATC circuit that produced an output that was pulse width modulated in a way that indicated the type of discharge (*e.g.*, no discharge, transient plasma discharge, or nanosecond spark) that occurred. The ATC circuit produced a control signal that could be used to drive algorithmic decision making by a processor (*e.g.*, microcontroller) to enable dynamic pulse train control.

TPS's approach for differentiating the type of discharge or discharge mode took advantage of the fact that the waveform of the voltage and/or current reflected from a load had certain characteristics particular to each type of discharge or discharge mode. An attenuated signal derived from a voltage and/or current measurement of a high-power pulse contained sufficient information to determine what type of discharge occurred. The voltage/current measurements could be made at one or more of: an output of a pulse generator, at a cable/igniter interface or cable/sparkplug interface, or anywhere along a cable that connected the pulse generator to an igniter or sparkplug.

Extracting the information from the attenuated voltage and/or current signal for use in differentiating between loads was challenging using conventional techniques (such as analog sampling and subsequent digital signal processing) because of the short duration of the waveforms used in nanosecond pulse applications. Analog sampling at these speeds was expensive and sensitive to electromagnetic interference, and thus was ruled out. After evaluating several different approaches, an ATC circuit developed by TPS was selected as the sense circuit because the ATC circuit can be made with inexpensive, rugged components suitable for automotive applications, and it is significantly more immune to electromagnetic interference than conventional analog sampling circuits. Additionally, data processing using the described approach was not computationally intensive and could be done with microcontrollers that are typically used in automotive modules.

TPS developed a closed loop pulsed power system that used the ATC circuit to close the feedback loop by providing a pulse width modulated signal to a microcontroller that determined the discharge mode by measuring the duration of the ATC signal. A pulse width modulated charging circuit was also designed for the pulsed power system, enabling the pulsed power system to run off a fixed DC input supply and to achieve output pulse amplitudes that varied as a function of the pulse width of a charging control signal. This system thus enabled a designer to employ different algorithms that, within a given pulse train, enabled pulse-to-pulse voltage amplitude adjustment based on the discharge mode and amplitude of a previous pulse. The number of pulses and pulse repetition rate could also be adjusted on a pulse-by-pulse basis based on the previously detected or determined discharge mode.

The approach required very little computational power and used time space, which could be measured with conventional timer and timer/capture modules commonly found in microcontrollers. Although variations were possible, a representative algorithm is as follows:

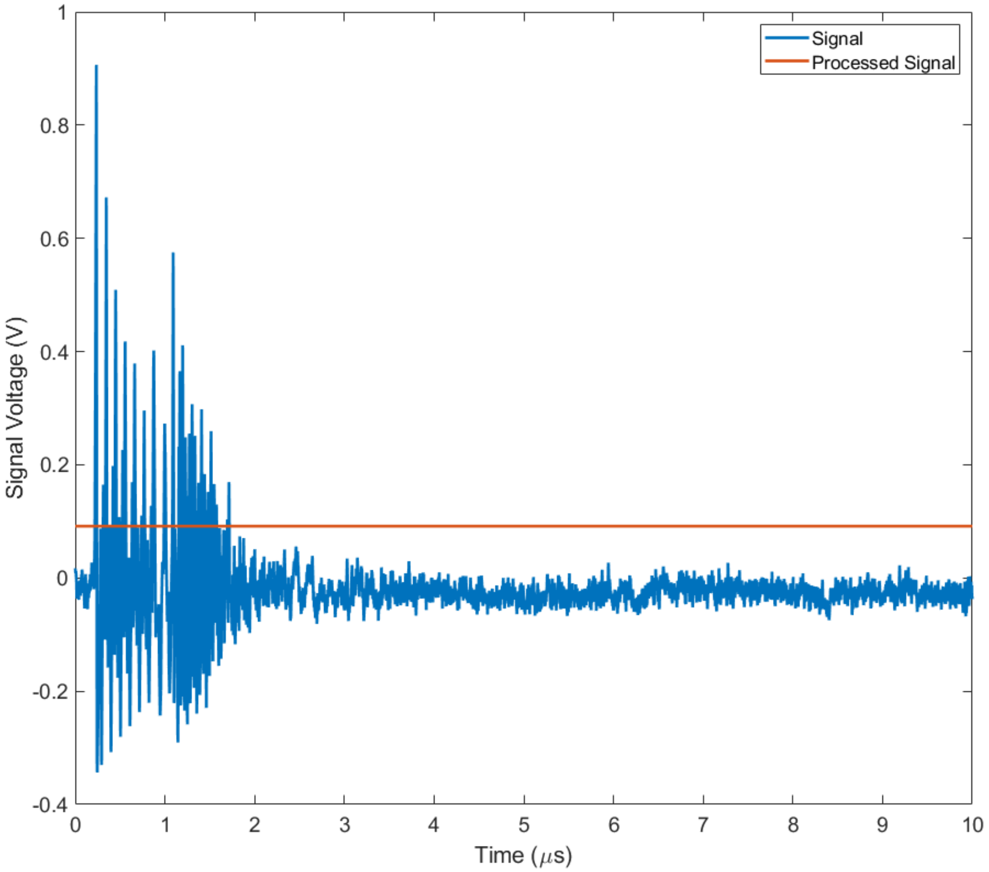
1. Start of pulse sequence
    a. End energy dump phase (energy dump was initiated at the end of the sequence to reset the system)
    b. Reset timers for pulse generation and pulse measurement
2. Start the timer(s) used for pulse generation and the timer(s) used for pulse measurement concurrently
3. Wait until the pulse repetition rate period has nearly expired
4. Check the following measurements
    a. Did a measurement pulse occur?
    b. When did the pulse occur relative to the start of timers?
    c. What was the pulse width?
5. Apply dump feature
6. Based on the measurements, determine discharge type or discharge mode
7. Make adjustments (e.g., make algorithmic adjustments, for instance adjusting power, terminating pulse train, etc.)
8. Wait for next event

If the algorithm determined to end the pulse train, the microcontroller ceased to output trigger signals to the charging circuit. If the algorithm determined that the pulse amplitude should be adjusted based on the previous discharge mode, the microcontroller changed the duration of the pulse width modulated signal.

Determining discharge mode enabled a new approach to control of the TPS ignition system. For example, the determined discharge mode could be employed in controlling the generation and/or characteristics of subsequent pulses. To do so, in addition to the previously described determinations (i.e., did a discharge occur, delay, duration), the system could further determine when a particular discharge mode occurred relative to an overall pulse train. This permitted the system to not just target a particular discharge mode, but to use logic (e.g., preprogrammed algorithms) to optimize performance. For example, the system could apply a specific number of non-ignition pre-pulses to achieve improved combustion chemistry. Similarly, the system could be used to apply a specific number of post-spark pulses that were added to improve kernel growth for a particular air-fuel mixture.

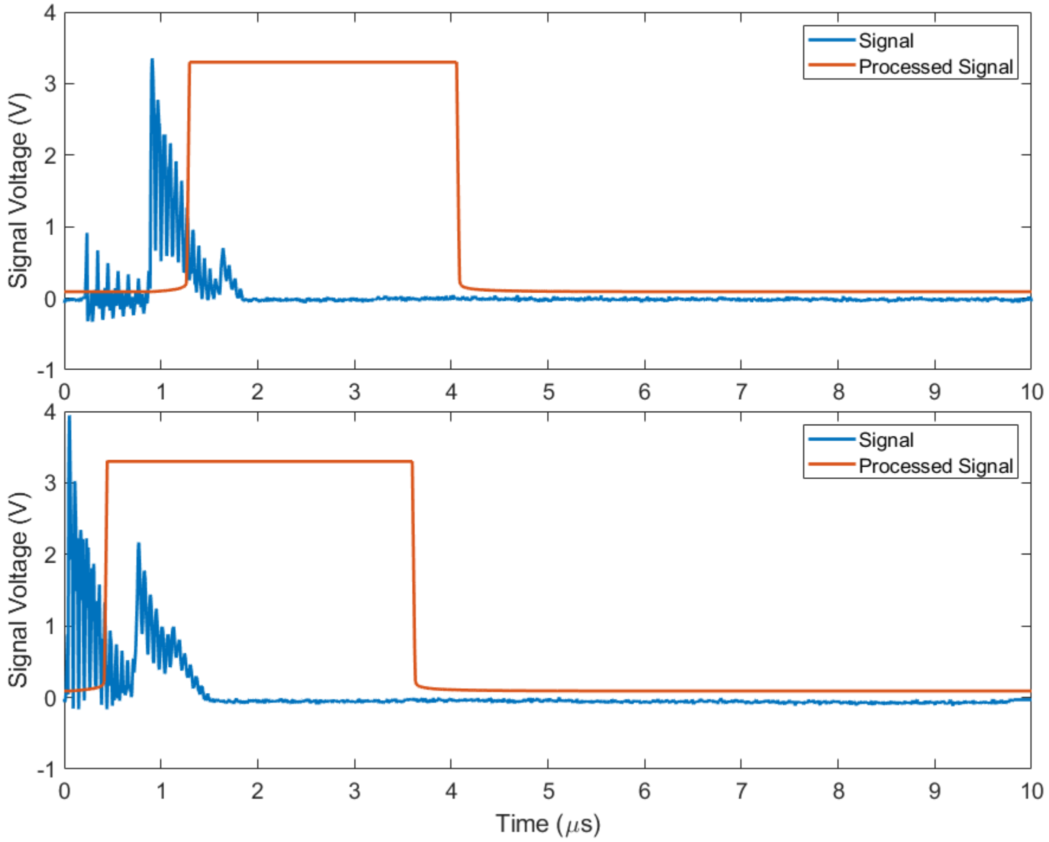
Example data is shown in the following two figures to help describe how the system operated in practice. Figure 5 shows an example plot of an output pulse that, when fed into the ATC circuit, did not produce an output signal. This corresponds to an occurrence of a “no discharge” mode. Figure 6 shows an example plot of an output pulse that, when fed into the ATC circuit, did produce an output signal.

Figure 5: Waveforms Corresponding to the Absence of a Discharge



Source: Transient Plasma Systems, Inc.

Figure 6: Waveforms Corresponding to the Detection of a Discharge



Source: Transient Plasma Systems, Inc.

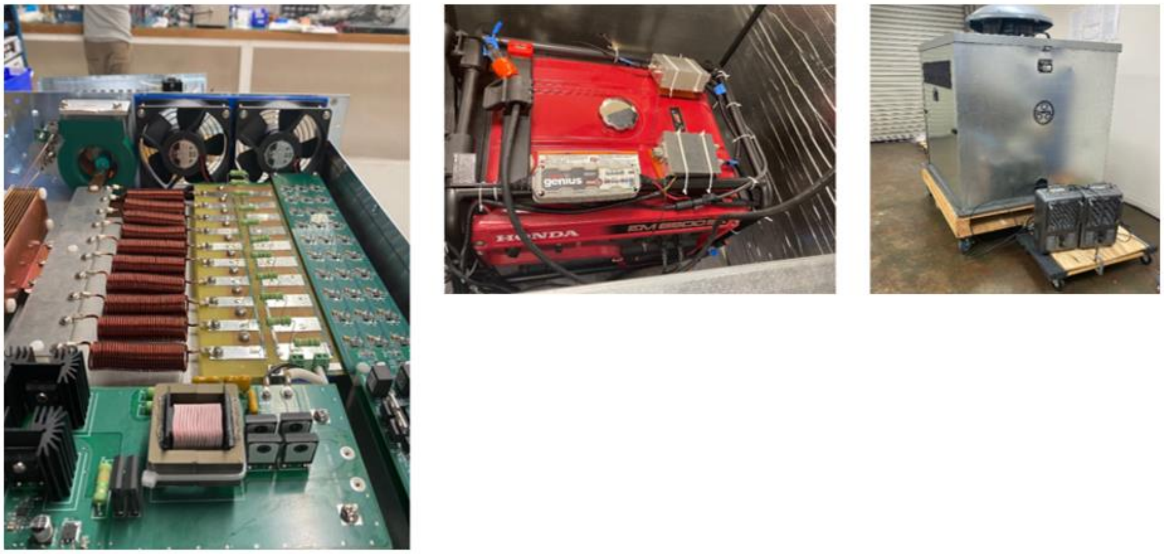
Initial work to develop analog sense circuits to determine discharge mode was done using existing hardware. As data was accumulated, a custom system was developed to refine sense and control technology.

Figure 7 illustrates a rack-mount pulse generator capable of producing 100 kHz bursts of pulses up to 40 kilovolts at the electrode, and the in-house generator that was used to benchmark sensing discharge mode at TPS. The photograph on the left shows the full-scale pulse generator that was designed and built and implemented in a large rack mount enclosure for ease of experimentation (lots of space, easy to test new sense techniques). The photographs on the right show a Honda EM 6500 generator that was used for testing.

Figure shows a basic system diagram (left) and test setup (right) to record and validate sense and control operation.

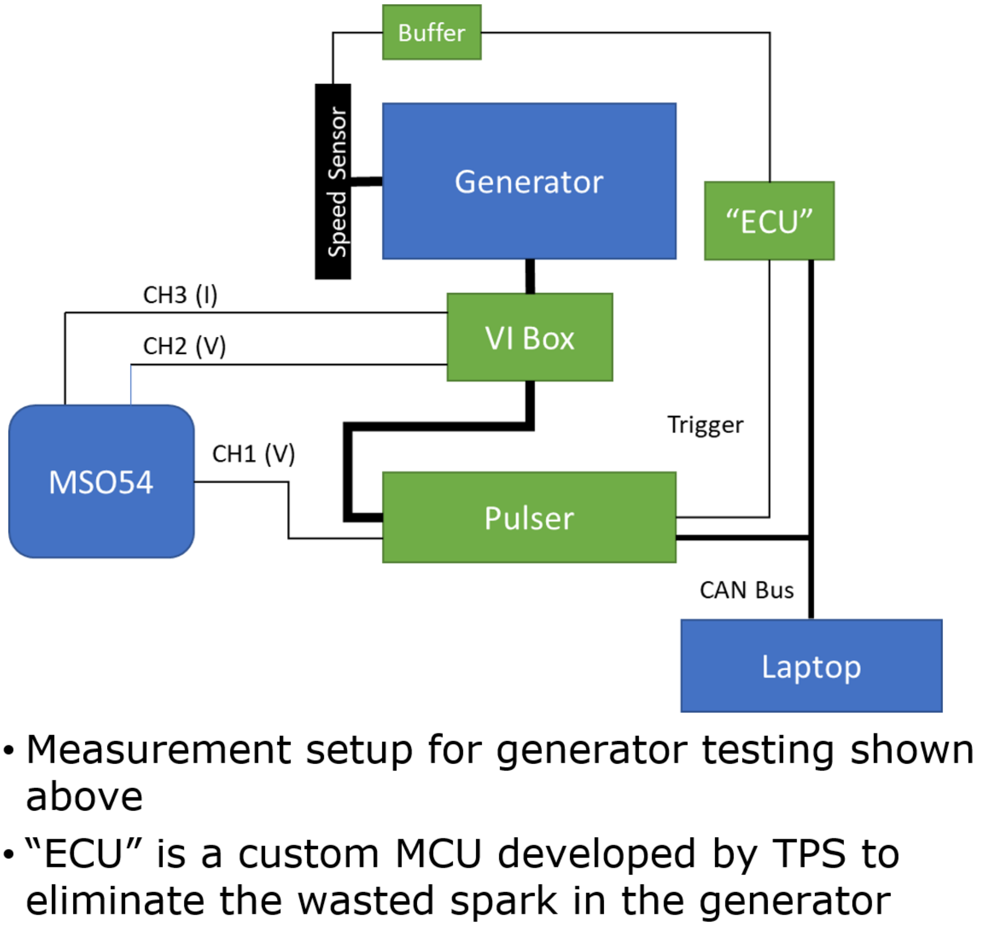
The development of this technology combined with combustion testing resulted in pulsed strategy that significantly reduced the amount of energy required to achieve desired engine performance. At the same level of dilution, the energy required for ignition was reduced by a factor of 3 when using the pulse train feedback control system. This was also a practical benefit because it reduced the power requirements of the ignition system and, therefore, the cost and complexity at the circuit level.

Figure 7: Pulse Generators used for Sense and Control Research and Development



Source: Transient Plasma Systems, Inc.

Figure 8: System Diagram for Recording Discharge Mode Data and Data Recording Setup in Operation at TPS



- Measurement setup for generator testing shown above
- "ECU" is a custom MCU developed by TPS to eliminate the wasted spark in the generator

Note: ECU = engine control unit; MCU = microcontroller.

Source: Transient Plasma Systems, Inc.

Redesign Thermal Management

Analysis was conducted to understand heatsinking requirements for removing heat for semiconductor junctions at high temperature. Work began with first-order models for estimating temperature differentials between semiconductor junctions and ambient temperature, as well as calculations for thermal expansion consideration and coefficient of thermal expansion mismatch. TPS anticipated the need to maintain an internal operating temperature at or below approximately 176° F (80° C), so two approaches were considered that could meet that target.

The first relied on bulk heat transfer flowing from semiconductors to circulating oil and then to heatsinked surfaces. The second was the direct transfer of heat from semiconductors through a ceramic material to the enclosure wall/heat sinking surface.

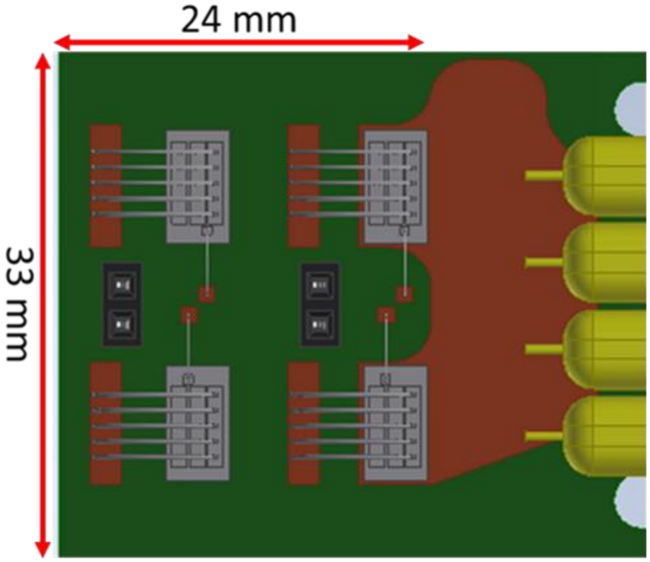
It was decided to pursue the device-oil-heatsink approach initially because it enabled testing of direct chip-on-board wire bonding technology while avoiding the cost of application specific packaging. This was a hybrid approach in which the high voltage components were mounted to a ceramic substrate that made direct contact to heatsinked metal enclosure of the pulse modules. The parts were directly wire-bonded to the ceramic substrate and encapsulated. Heat was conducted from the junction through the part-ceramic-metal enclosure interface and then released through convection.

For both approaches, it was determined that custom die attach, and component layout were required. The following subsections summarize initial work on this front.

Custom Die Packaging

A conventional package for a high speed, high current, switching device commonly used in modern solid-state pulsed power systems is the TO-247 package, a 3-pin device, for which the die occupies less than 10 percent of the total package area when considered across the largest two-dimensional face. TPS worked with a wirebond and die mounting company to develop a custom solution where the chip was placed directly on the board and wirebonding was used to make the appropriate connections. A 3-D model of this board can be seen in Figure 9 and represents a dramatic size reduction relative to using TO-247 packages. This type of chip attach allowed for superior electrical and thermal performance.

Figure 9: Bare Die and Wirebond Packaging

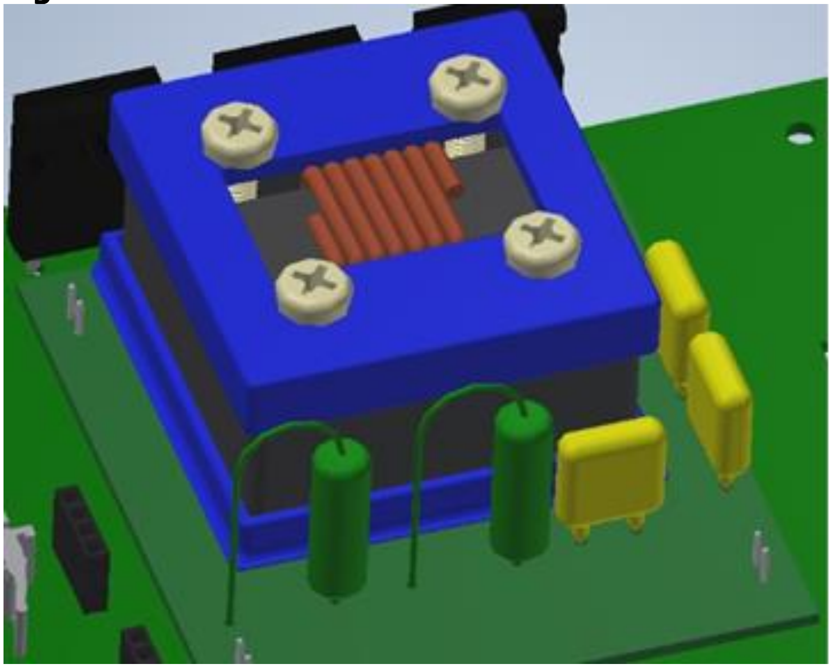


Source: Transient Plasma Systems, Inc.

Direct-to-Board Inductor Cores

A novel technique for eliminating the bobbins of power devices was employed where appropriate. The technique involved mechanically mounting the magnetic core of the power inductor directly to the PCB (Figure 10), which reduced the space required by a conventional bobbin. A winding technique was developed to place windings directly across the center terminal of the magnetic e-core circuit to eliminate the space typically occupied by a bobbin. The two e-cores and winding were then held in place and secured to the PCB using a custom 3-D printed part This technique reduced the total volumetric space required by the coil by a significant factor.

Figure 10: Direct Attach Method of Core to PCB Sin

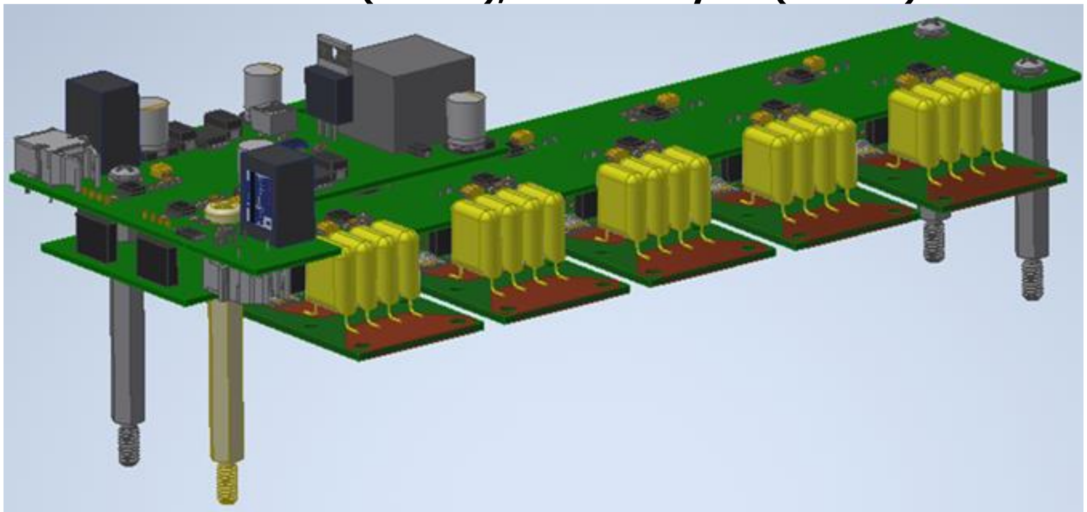


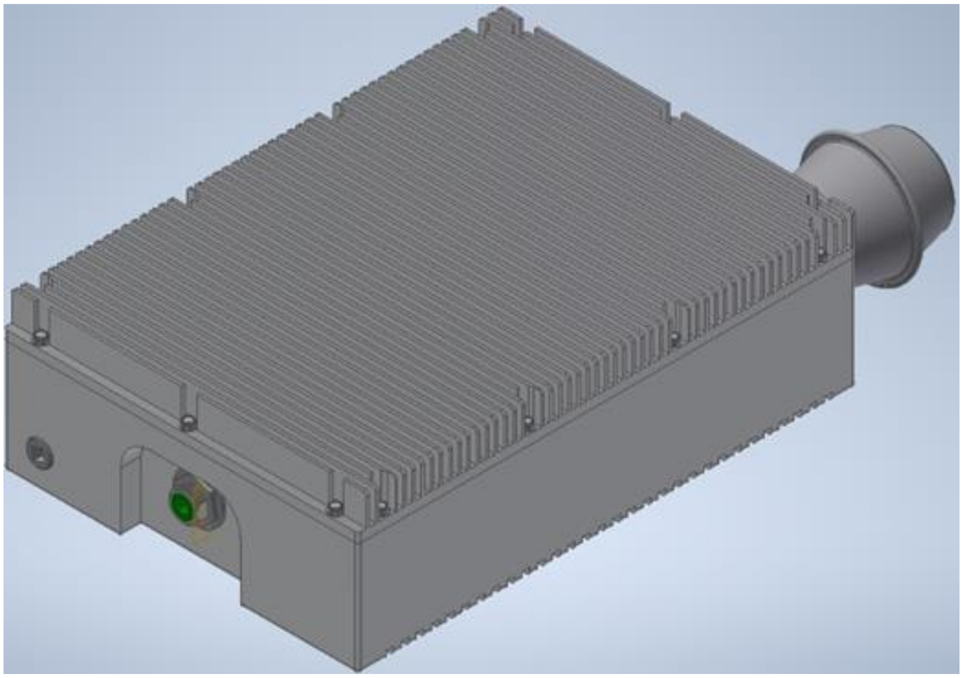
Source: Transient Plasma Systems, Inc.

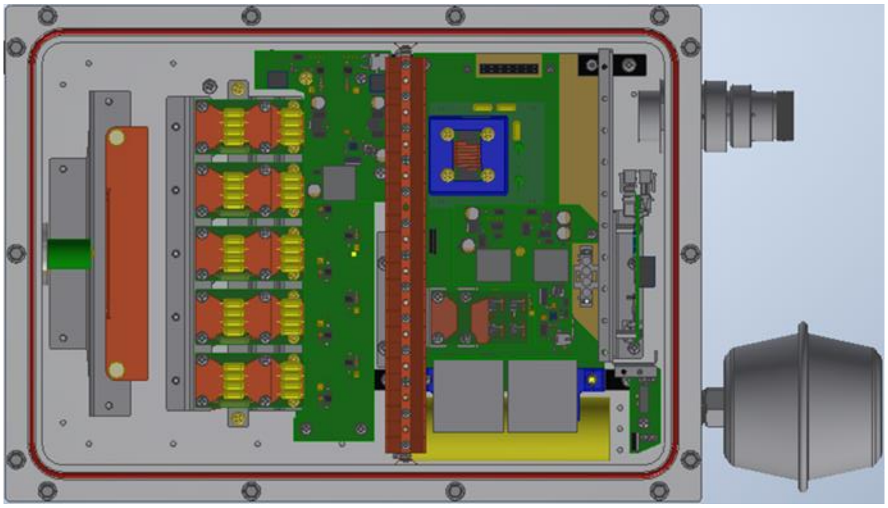
Board-to-Board Connection Methods

By using single in-line package and other standard connector parts, TPS minimized cable harnessing through direct board-to-board connection, allowing for increased power density and assembly simplicity. An example of this approach can be seen in Figure 11.

Figure 11: Single In-line Packaging to Eliminate Cable Harnessing (top); Heatsinked enclosure (middle); Interior Layout (bottom)







Sources: Transient Plasma Systems, Inc.

A prototype system was built to test these layout designs. For reasons related to research and development and cost, it was decided to build this prototype system in an oil-immersed enclosure, according to the first design procedure previously outlined. This approach allowed TPS to conduct research and development on the approaches previously outlined without the costly loss of components that would have occurred if each part were insulated using glob-top or other conventional insulating technology. This system also provided a test platform to evaluate component heating relative to ambient temperature without risking the loss of fully assembled PCBs.

Thermal performance was evaluated using a test setup as shown in Figure 12. An enclosure was filled with oil, a resistive load for heating, and a circulation pump. A 40W heat load was applied to the system with oil circulating and allowed to reach equilibrium. At thermal equilibrium, temperatures were measured in the oil and at the external surface of the heatsink. The heatsink-to-air thermal resistance was lower than expected, likely due to the unaccounted-for surface area in the original calculation. The original thermal analysis only considered the heatsinking lid and did not consider the surface area of the entire body of the enclosure. This led to slightly better thermal performance than expected.

This test setup was used to ensure that this prototype could be used at high ambient temperatures and that application-specific bonding processes previously described were feasible for this nanosecond high voltage pulsed application. Testing was conducted to confirm design assumptions made for thermal conductivity of materials that connected semiconductor junctions to the heatsinked surface of the hermetically sealed enclosure. Corrections were made to the model as necessary based on measurements. Thermal performance achieved all targets for engine testing, and TPS is working with partners to establish max temperature ratings for different configurations under the hood.

Figure 12: Test Setup to Determine Thermal Conductivity from Heatsink to Ambient

Source: Transient Plasma Systems, Inc.

12 VDC Compatibility

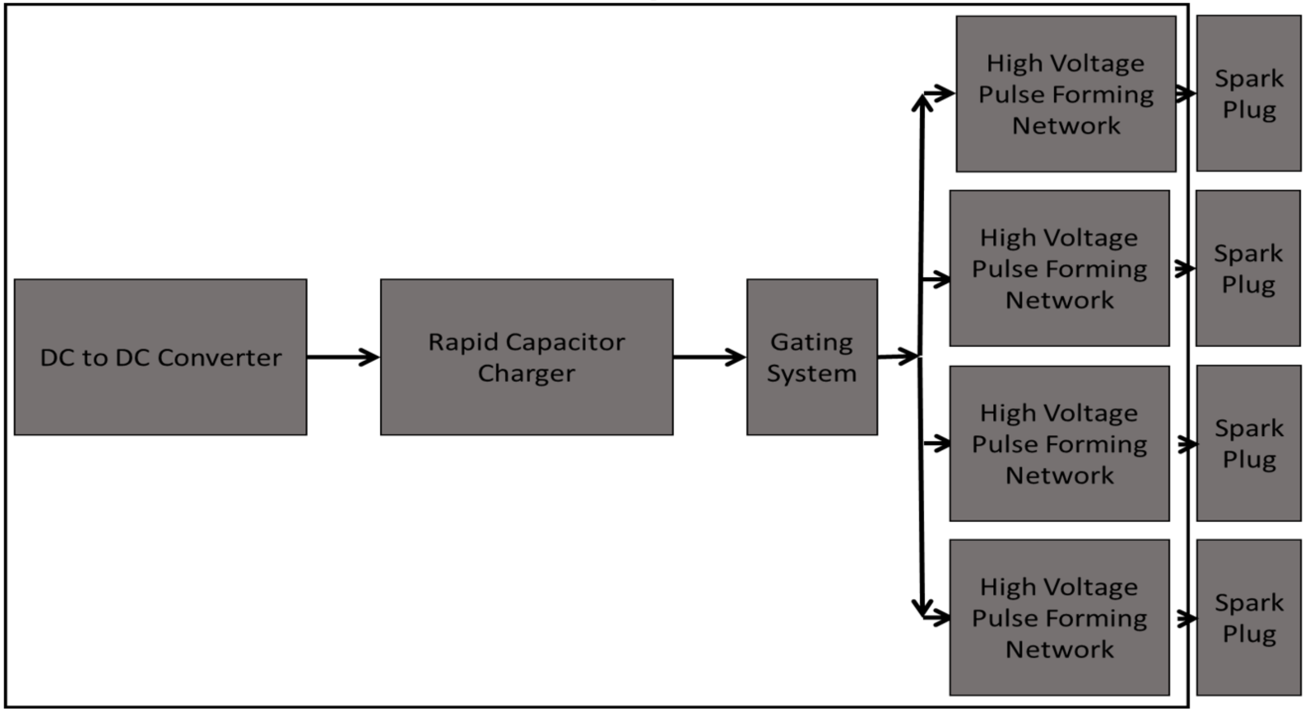
Recognizing the lack of commercially available charging supplies that are compatible with 12 VDC/24 VDC buses, TPS initially investigated unconventional approaches, initially studying the feasibility of using existing low-cost technologies, like existing ignition coils, to achieve the required step-up from the vehicle's 12 VDC bus voltage.

The result of this effort determined that an application specific DC-DC converter was the most feasible solution, specifically, a cost efficient, high efficiency resonant step-up converter.

Miniaturize Existing Multi-Cylinder Prototype

A significant design modification identified early during this effort toward miniaturization was to move the gating circuit back from the output switch-to-plug interface to the charger-to-high voltage pulse forming circuit, as shown in Figure 13. This relaxed switching requirements and isolated gate drive requirements for isolation between channels and resulted in a smaller total footprint.

Figure 13: Block Diagram of Revised Architecture



Source: Transient Plasma Systems, Inc.

Subsequent static cell and engine testing using optimized igniters with sense and control feedback showed that a miniaturized system using specifically developed device packaging was feasible for extending dilute burn operation.

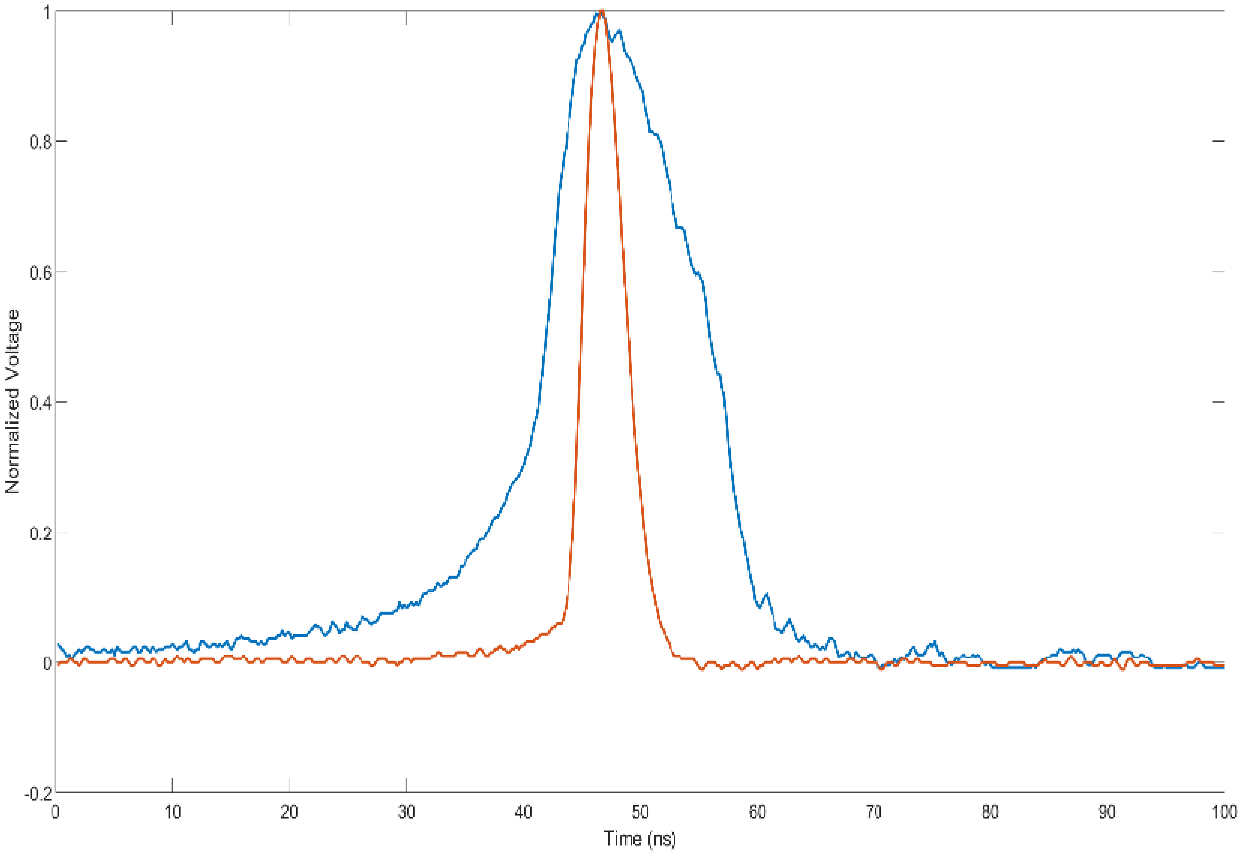
In addition to work focused on component layout, plug optimization, and DC power compatibility, TPS developed a semiconductor component and cabling solution to miniaturize a commercial ignition system. This new component, which was developed with TPS funding and some supplementary funding from the Office of Naval Research, was implemented in a circuit that benefitted from improved instantaneous power density and thermal design to realize a significantly smaller footprint. This new smaller footprint owed not only to these circuit design and packaging improvements, but also to lessons learned regarding the peak voltage and average power required when driving optimized electrodes that were ignited using smart pulse trains enabled by the sense and control circuitry previously described.

Figure details one of the major ways that size reduction was realized. The improved switching efficiency of new semiconductor developed at TPS enabled significant gains in pulse compression, which reduced size and energy requirements to achieve a target peak voltage for required reduced electric field at a given pressure and temperature.

The improvements afforded by this component and other circuit improvements, informed also by data from engine experiments with a more optimized electrode driven by smart pulse train control, resulted in the most recent design illustrated in Figure 15. This design of a transient plasma ignition system has the potential to meet size, cost, and performance metrics of gas engine OEMs, which is a key milestone along the roadmap of developing a production ignition system. The next step is for TPS to collaborate with a commercial ignition systems (or engine) manufacturer to get the current design commercially ready by advancing it through their design and production process validations.

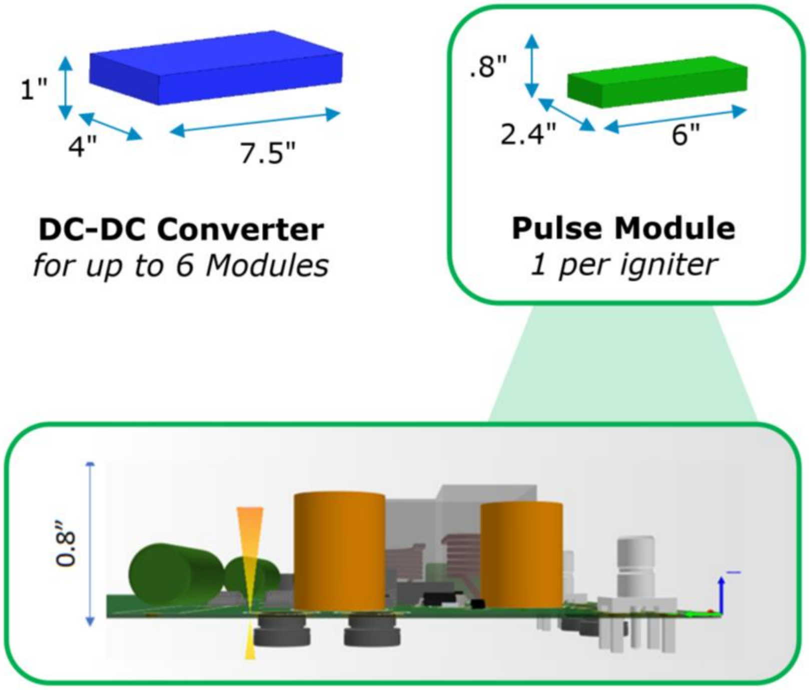
Existing scientific literature has demonstrated that faster pulse rise times create more streamers and higher electron densities within those streamers. Denser streamers can also improve the coupling of energy from the incoming electrical pulse to the transient plasma. Preliminary ignition performance tests in a static cell showed improved pressure performance when sharpening the pulse from a 10 ns rise time to a 5 ns rise time. The project team investigated the potential of implementing faster rising, shorter duration pulses for the transient plasma ignition system. The latest approach increases pulse compression without the previously experienced reductions in overall efficiency – aiming at rise times < 5 ns with pulse durations < 10 ns.

Figure 14: Faster Rising, Shorter Duration Pulses for Ignition System



Source: Transient Plasma Systems, Inc.

Figure 15: DC-DC Converter That Drives Pulse Modules (top); 3D Model of Circuit Layout for a Pulse Module (bottom)



Note: There is one DC-DC converter per engine and one pulse module per cylinder.

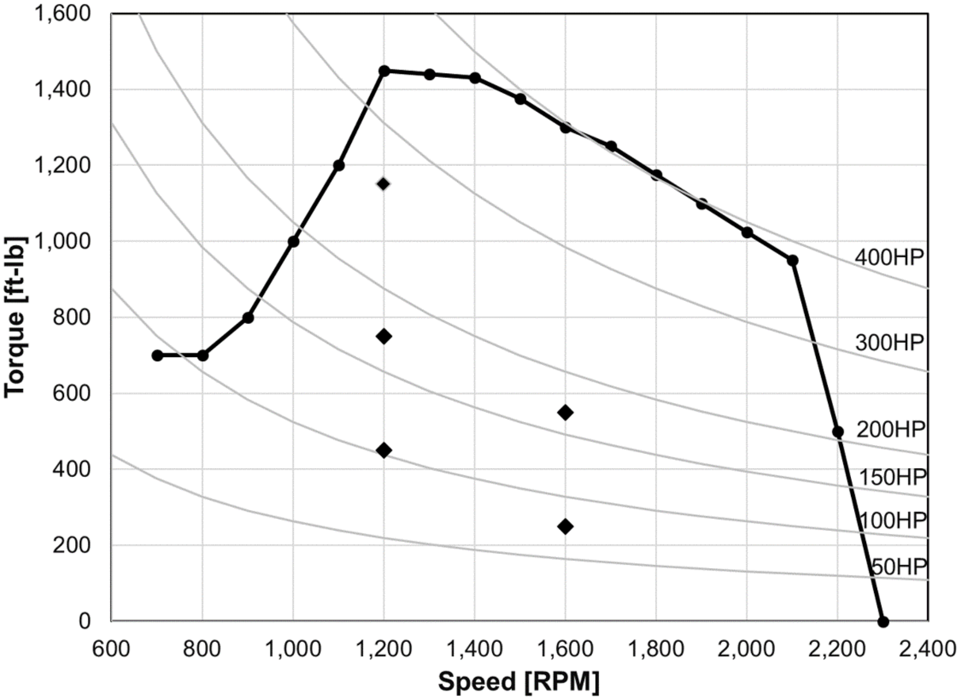
Source: Transient Plasma Systems, Inc.

Engine Test Results

Operating Point Selection

The objective of the baseline tests was to establish a data set against which to compare the performance of the TPS system and to ensure that the data generated with this particular engine setup was consistent with in-house data provided by CWI. A set of five representative operating conditions was selected for the baseline tests. The operating points were chosen at 1200 and 1600 RPM covering a range of mid-load conditions from 250 to 1,150-pound feet (ft-lb) of torque (339 to 1,558 Nm) (Figure 16). The five data points shown as solid black diamonds in the figure were successfully tested. All operating points selected had a nominal rate of exhaust gas recirculation above 10 percent, which was desirable since advanced ignition systems are expected to show performance benefits under dilute operating conditions. Low speed data (pressure, temperatures, flows, etc.) for each operating point were averaged over 60 seconds; high-speed crank angle resolved data was collected for 75 consecutive cycles within the 60-second interval.

Figure 16: Selected Operating Points in the Engine Torque Map

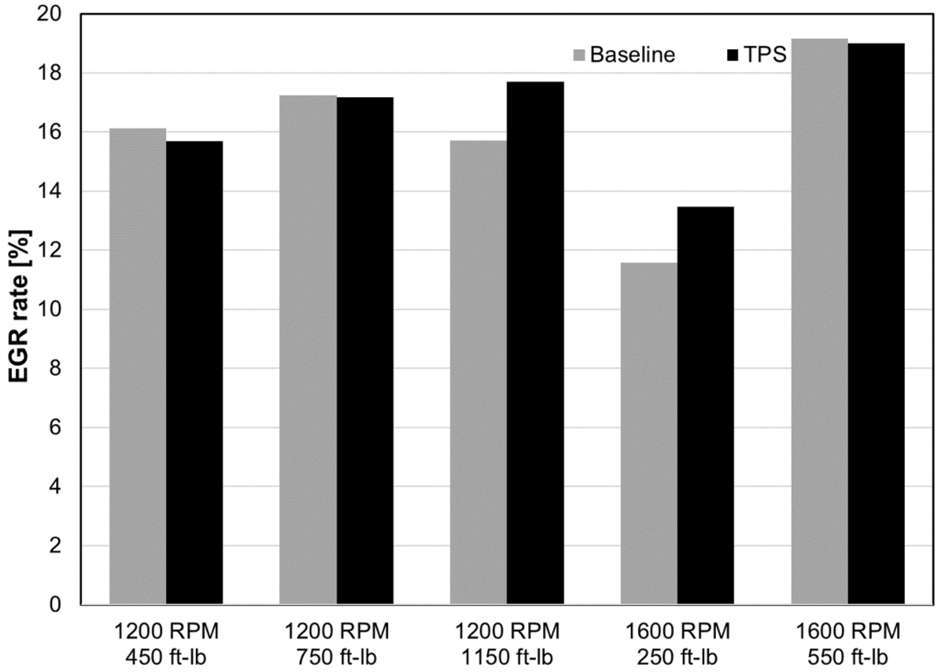


Source: Argonne National Laboratory

Comparison of Baseline Stock Ignition and Transient Plasma Ignition Results

Engine performance and emissions results for an engine operating stoichiometric with exhaust gas recirculation (EGR) depend on the resulting EGR rates at specific operating conditions. For the initial comparison between the baseline stock ignition system and the transient plasma ignition (TPI) system provided by TPS, stock calibration values were used. The system tested was not the miniaturized version of the system being designed as part of this effort. It instead was a more flexible platform used to confirm the specifications required for the new design. Figure 17 compares the resulting EGR rates derived from CO_2 measurements in the engine intake and exhaust showing that the in-cylinder conditions in terms of EGR dilution between the baseline and TPI system were very similar across the range of operating conditions.

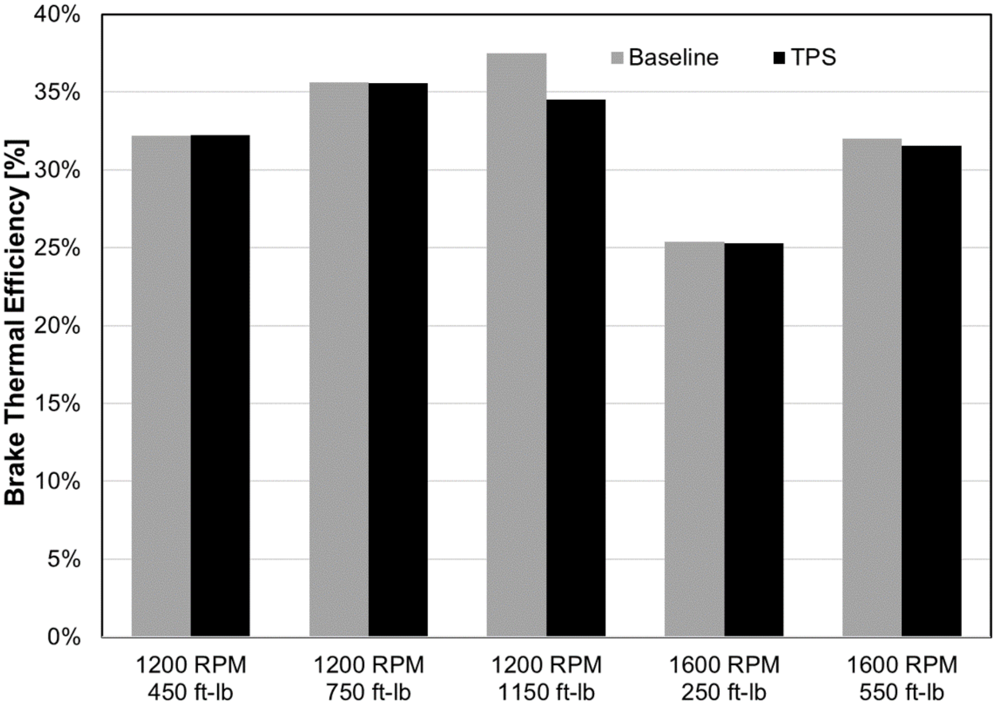
Figure 17: Comparison of EGR Rates across Operating Conditions



Source: Argonne National Laboratory

Figure 18 compares the resulting brake thermal efficiencies for the baseline ignition system and the one provided by TPS across the range of operating conditions. The expectation for this portion of the test was that they should be the same, as all engine parameters were matched. Later, the EGR rate was increased to show that the TPS system could enable improvements efficiency by increasing stability at higher EGR rates. Brake thermal efficiencies were calculated based on measured brake torque as well as gas fuel flow and gas composition. As seen in the figure, the resulting engine efficiencies at base calibration were almost identical between the two ignition systems with marginal benefits for the TPS-provided system, except at 1200 RPM, 1150 ft-lb. The cause of the drop in efficiency at this point was unclear. Due to limited time and budget for testing, this point was not repeated.

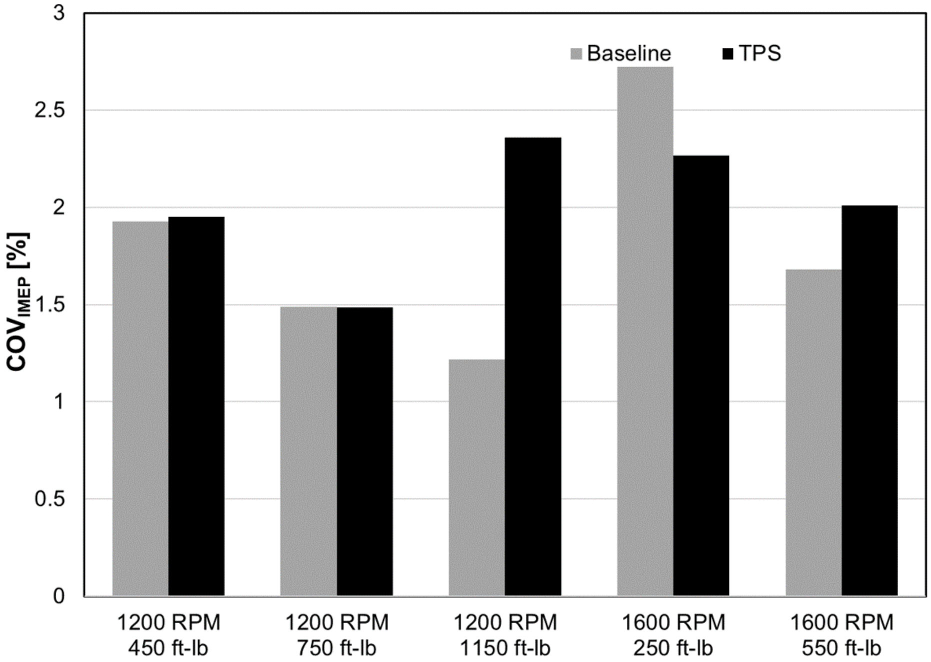
Figure 18: Comparison of Brake Thermal Efficiency across Operating Conditions



Source: Argonne National Laboratory

As a measure of combustion stability, Figure 19 compares the coefficient of variation of the indicated mean effective pressure of the baseline ignition system relative to the TPI provided by TPS. In general, COV_{IMEP} values below 5 percent are considered stable in terms of combustion stability for research engines. Production engines tune the engine even further to typically achieve COV_{IMEP} values at or below 3 percent. The combustion stability values were quite similar between the two systems and well below the stability limit, as would be expected for the base calibration. Again, the cause of the difference at 1200 RPM 1150 ft-lb was unclear. Due to limited time and budget for testing, this point was not repeated.

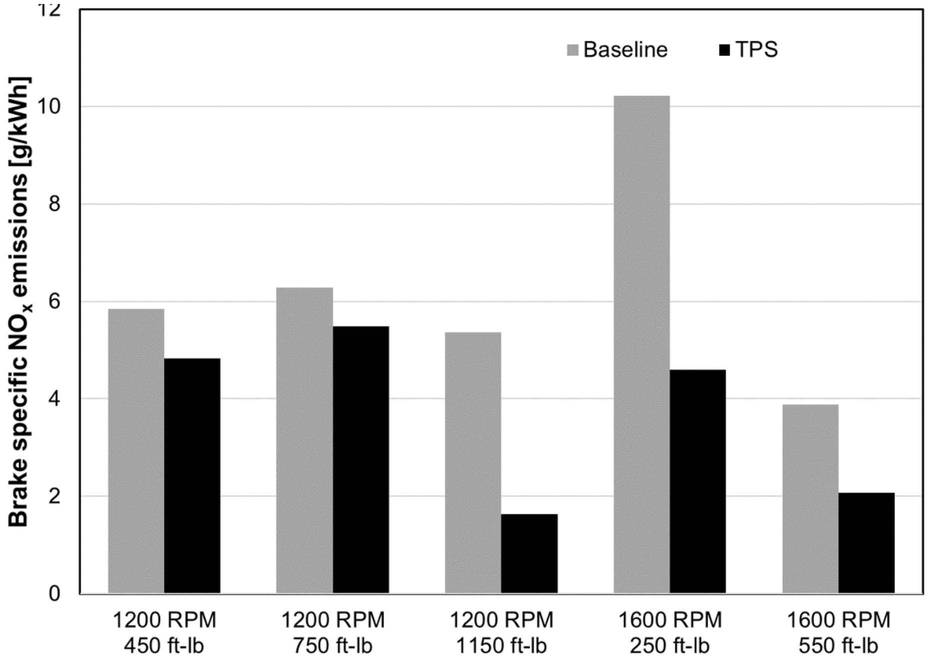
Figure 19: Comparison of Combustion Stability across Operating Conditions



Source: Argonne National Laboratory

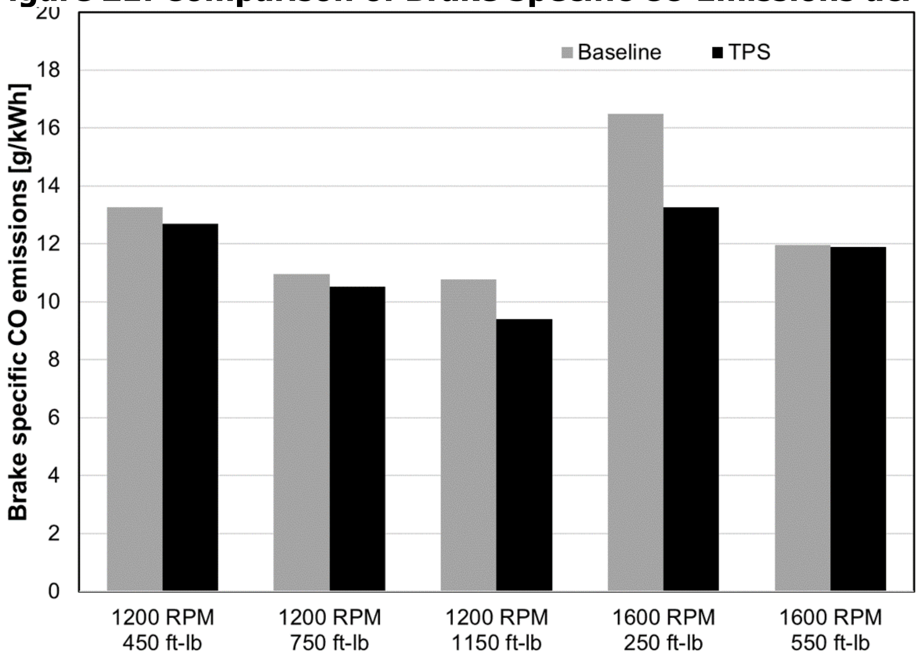
Figure 20 through Figure 23 compare brake specific engine-out emissions including NOx, CO, hydrocarbons, and methane emissions. As can be seen from the figures, NOx emissions and carbon monoxide (CO) emissions from the TPS system were lower across every point. However, changes in emissions levels were largely dependent on operating-point specific calibrations rather than differences caused by the ignition systems.

Figure 20: Comparison of Brake Specific NOx Emissions across Operating Conditions



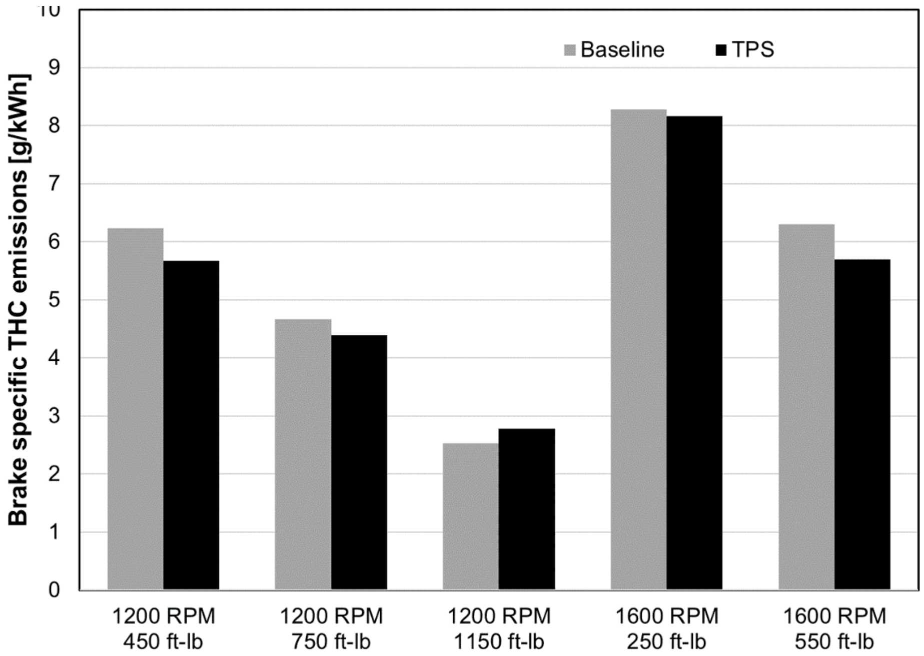
Source: Argonne National Laboratory

Figure 21: Comparison of Brake Specific CO Emissions across Operating Conditions



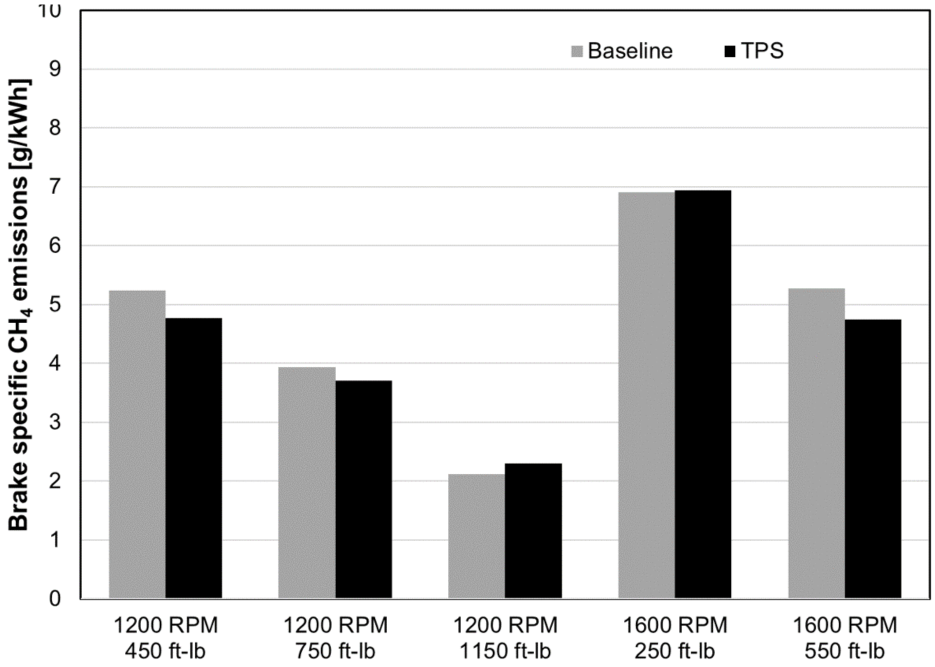
Source: Argonne National Laboratory

Figure 22: Comparison of Brake Specific Hydrocarbon Emissions across Operating Conditions



Source: Argonne National Laboratory

Figure 23: Comparison of Brake Specific Methane Emissions across Operating Conditions



Source: Argonne National Laboratory

Transient Plasma Ignition System Performance Opportunity Testing

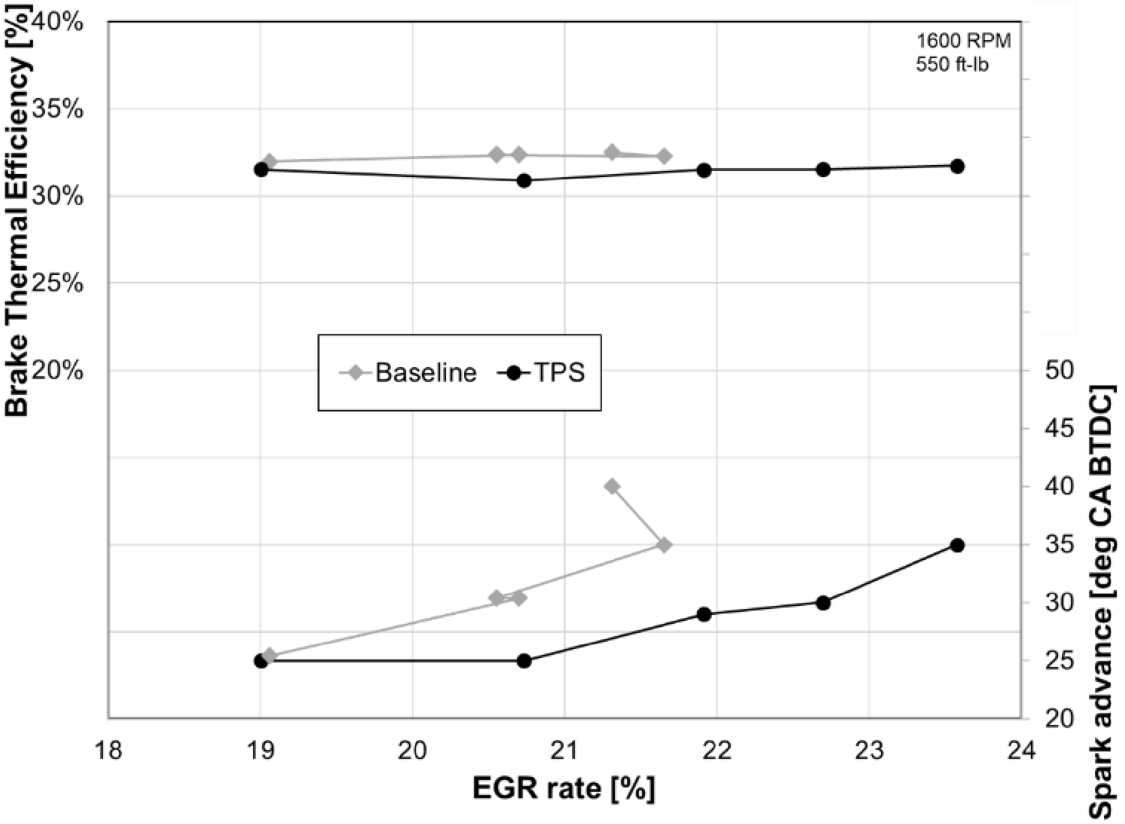
Objective

The objective of the performance opportunity testing was to determine if the TPI system was able to provide combustion benefits compared to the stock ignition system under challenging operating conditions. These challenging operating conditions were achieved by deviating from the stock engine calibration and increasing EGR ratios significantly beyond stock levels. As a result of the increased EGR levels, combustion duration increases, and combustion was expected to become unstable. If the TPI system could maintain combustion stability at increased EGR levels compared to the stock ignition system, then the engine could achieve efficiency benefits as well as emissions improvements — increasing EGR not only lowers the peak in-cylinder temperature resulting in less NOx production, but also opens the throttle thereby reducing associated pumping losses and improving overall engine efficiency.

Results

Figure 24 shows the influence of increasing EGR rates on attainable brake thermal efficiencies with spark timing reported for references at an engine speed of 1600 RPM and a load of 250 ft-lb. With increasing EGR levels, combustion duration increased requiring more spark advance to maintain consistent combustion phasing. As seen in the figure, consistent spark timing advance for both the baseline and TPI system provided by TPS was required to offset the slower combustion duration with increasing EGR levels. Increasing EGR levels initially resulted in similar brake thermal efficiencies for both ignition systems. However, the brake thermal efficiency for the stock ignition system dropped off sharply beyond 22 percent EGR, while the ignition system from TPS maintained brake thermal efficiency beyond 22 percent EGR levels. Assuming that the same safety margin to unstable combustion was to be maintained, the TPS system could be run at or above 22 percent EGR resulting in an absolute efficiency improvement compared to the stock ignition system.

Figure 24: Comparison of Brake Thermal Efficiency and Spark Advance as a Function of EGR Rate

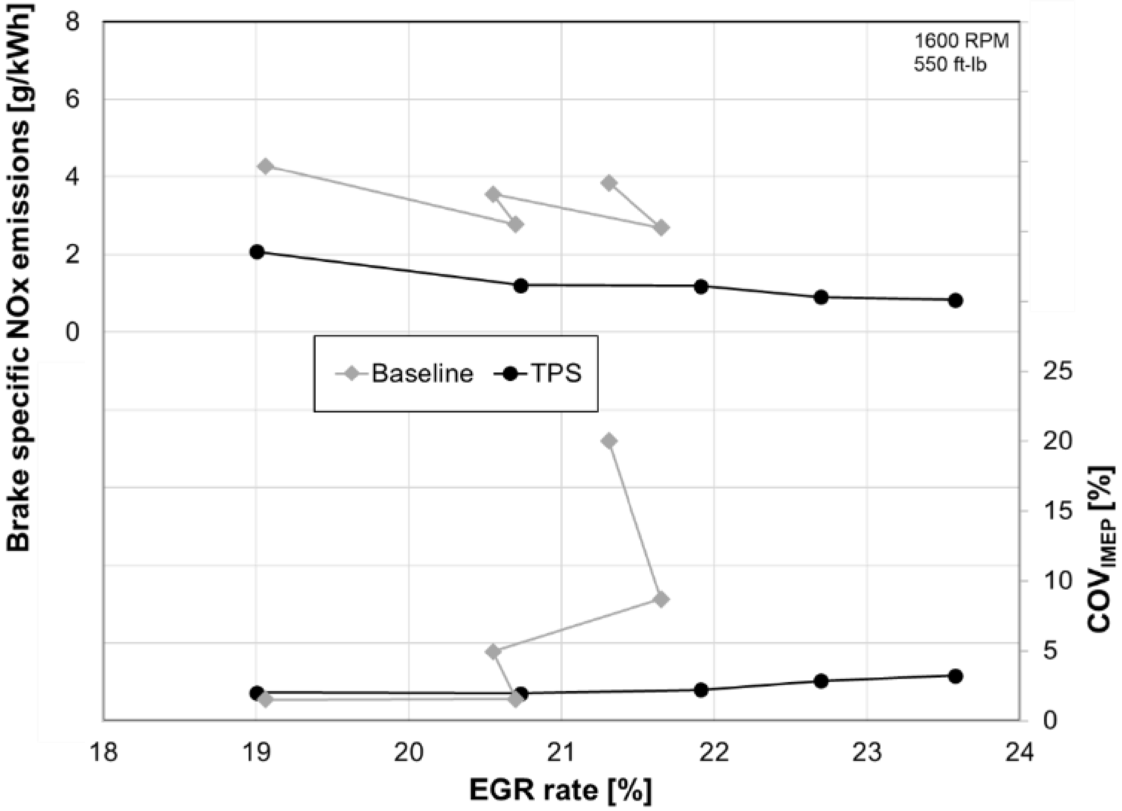


Source: Argonne National Laboratory

In the results from PIR-16-024, a meaningful increase of about 1 percent in BTE was observed. The reason that was not seen here had to do with the adjustment of other parameters such as ignition timing. While it was sufficient to show the potential for improvement in BTE by showing increased stability at higher dilution levels, it would be desirable to make adjustments in timing to capture the improvement in BTE. Due to limited testing time, that was not done this time.

Figure 25 compared the resulting brake specific NOx emissions as well as combustion stability for the same EGR sweep. The sudden drop-off in brake thermal efficiency with the baseline stock ignition system (not shown in Figure 24 because a point could not be captured due to the instability) coincided with a sharp increase in COV_{IMEP} beyond 19 percent EGR, which was the result of engine misfires. The TPS system maintained a COV_{IMEP} below 5 percent beyond 22 percent EGR (although infrequent misfires were observed at that condition). As expected, NOx emissions dropped with increasing EGR rates with absolute levels consistent between the two ignition systems. A significant reduction in NOx emissions (30 percent) could be achieved with the TPS system by increasing the EGR levels due to the improved combustion stability and EGR dilution tolerance (Figure 25).

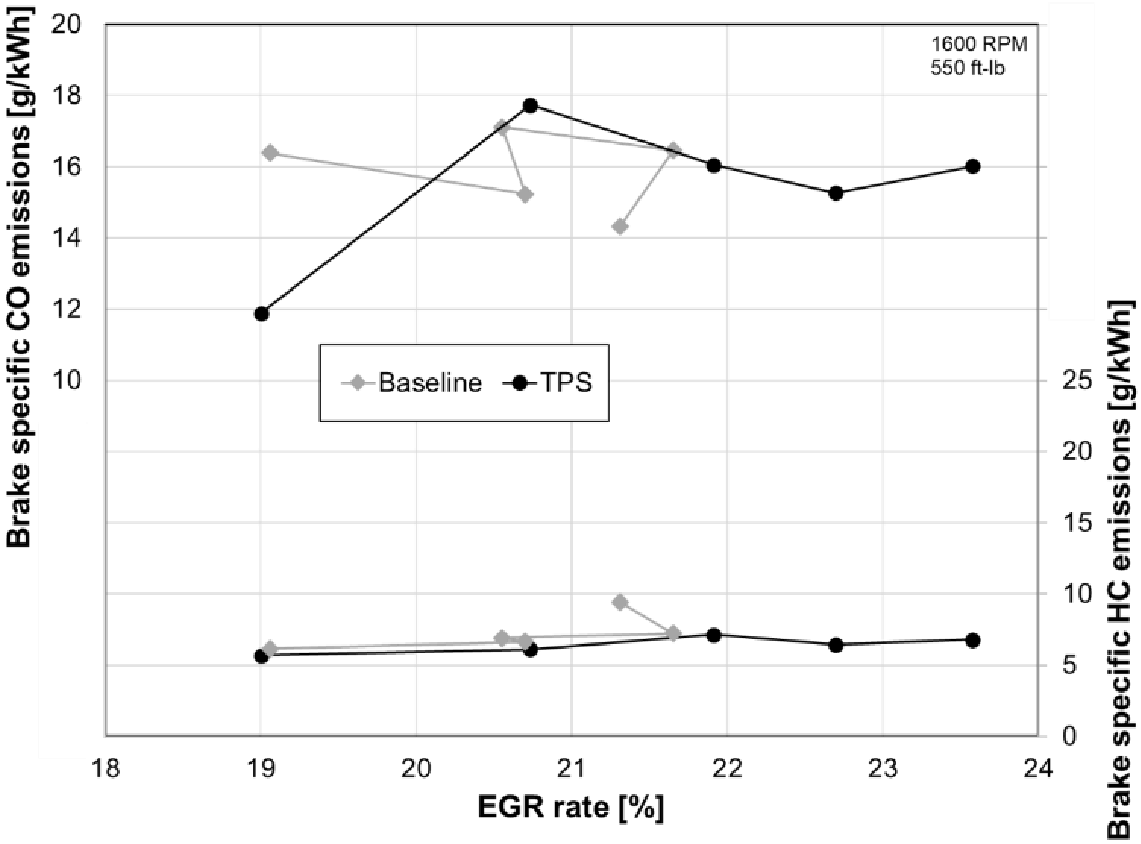
Figure 25: Comparison of Brake Specific NOx Emissions and Combustion Stability as a Function of EGR Rate



Source: Argonne National Laboratory

Figure 26 shows the brake specific CO and hydrocarbon emissions for the EGR sweep. Results were consistent between the two ignition systems except that spark ignition could not go beyond EGR of 19 percent. Applying the same logic as before, CO emissions could be reduced by more than 10 percent with the TPS system by increasing the EGR levels due to the improved combustion stability and EGR dilution tolerance.

Figure 26: Comparison of Brake Specific CO and Hydrocarbon Emissions as a Function of EGR Rate



Source: Argonne National Laboratory

CHAPTER 4:
Technology and Knowledge Transfer

Stakeholder Engagement and Information Sharing

TPS's market transfer plans for achieving industry adoption of this technology involve gaining interest and engagement of stakeholders in the heavy-duty engine market. A key aspect of the plan was to ensure awareness of the goals and intent of this project among the stakeholders in the market, in particular, the engine manufacturers. TPS shared project updates to industry stakeholders at the Natural Gas Vehicle Technology Forum in May of 2021 (https://www.nrel.gov/extranet/ngvtf/past-meetings.html). Additionally, TPS engaged with engine manufacturers at the forum about the project and discussed the potential of the technology in helping mitigate greenhouse gas emissions.

Engagement with stakeholders was underlined by the support of Cummins Westport Inc. (CWI), a leading OEM for heavy-duty on-road gas engines, which provided a current in-production on-road engine for the testing of the TPI system. Additionally, by engaging Argonne National Laboratory, TPS now has a partner that could support the project with combustion expertise and provide exposure to other industry stakeholders given the laboratory's global reputation in combustion research.

Through Technical Advisory Committee meetings, TPS shared the encouraging results with all the organizations involved in the project including the U.S. Department of Energy, CWI, CEC, and Argonne National Laboratory. The results will also be made public via this report which can enable independent review by industry stakeholders building awareness of the capabilities of the TPI technology.

The next step to developing a production ignition system is for TPS to collaborate with a commercial ignition systems (or engine) manufacturer to get its current design commercially ready, by advancing it through the manufacturer's design and production process validations. Sharing these results via this report and direct conversations will encourage fleet providers, transportation services and heavy-duty engine manufacturers to test the technology and explore avenues to accelerate adoption. Additionally, regulatory agencies can investigate inclusion of transient plasma ignition as a solution to drive cleaner emissions standards.

In 2021 and 2022, TPS received press coverage from the following publications that resulted in 27 million unique views:

- Autonews
- Newsweek
- Electronics Design
- Engine Technology International
- Interesting Engineering
- Green Car Congress

The articles covered TPS ignition technology, in general documenting its benefits and applications.

In addition, TPS recently completed a self-funded comprehensive test on a 2021 Toyota Camry LE, 4-cylinder engine. This test was done at FEV, an independent testing and engineering consulting firm. The test results documented impressive gains in fuel efficiency (up to 6 percent) and reductions in emissions in an engine widely considered as one of the most efficient in the passenger car market. TPS issued a press release in June 2022 that received wide press coverage. [4]

The publicity provided exposure to TPS technology and may have been the cause of its current engagement with a large United States-based supplier of gas combustion equipment (supplier name is confidential as part of the engagement agreement). This supplier has been testing TPS ignition solution for igniting EGR-diluted fuel in conjunction with its proprietary pre-chamber technology. The supplier is interested in improving the life of their spark plugs as well in eliminating misfires.

Strategy for Commercializing Transient Plasma Ignition Technology

The distinguishing feature of transient plasma ignition is its ability to achieve stable combustion under extremely dilute conditions with much lower energy, thereby providing a solution to the plug durability problem. The work during this project showed that the energy could be further reduced by a factor of 3, suggesting that the technology will be of value with regards to improving durability.

However, development of a production prototype ready for the light commercial vehicle market will need more resources and a longer time horizon. TPS would like to first successfully penetrate the medium- to heavy-duty gas engine market (e.g., trucks and stationary power generation equipment) with the protype developed in this project and leverage that success to expand to the light commercial vehicle market that makes up a large portion of the new ignition systems market shown in Figure 27.

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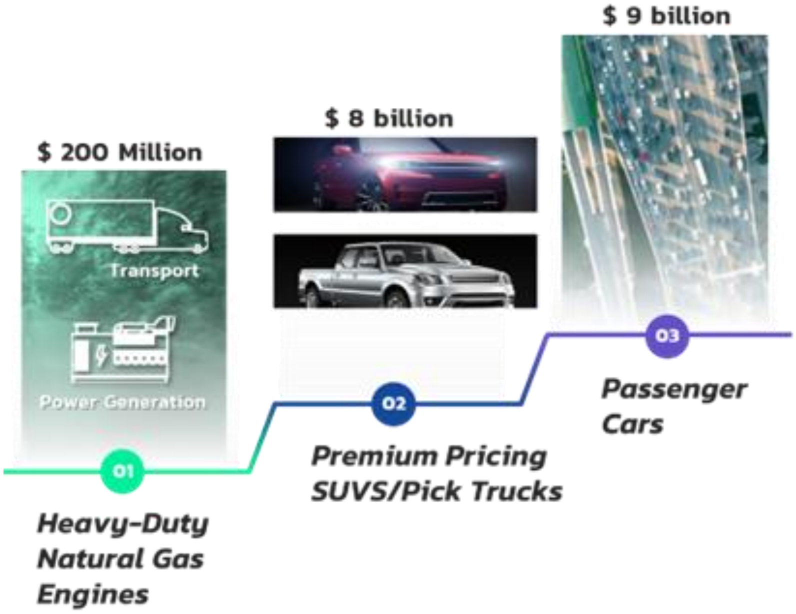
[4] https://www.prnewswire.com/news-releases/ground-breaking-ignition-technology-from-transient-plasma-systems-proven-to-make-gasoline-powered-vehicles-cleaner-and-more-efficient-301563959.html

Figure 27: 2030 Market Sizes for New Ignition



Source: Transient Plasma Systems, Inc.

While there are some overlapping needs of the two segments, the medium to heavy-duty gas engine market is less sensitive to the size and the cost of the product. By addressing the durability problem with the work done in this project, TPS can penetrate the medium- to heavy-duty gas engine market (e.g. trucks and stationary power generation) to bolster its credibility in the automotive market. Additionally, any revenue from such success will add more resources in support of the development efforts in the automotive market.

The key to success in any market is ensuring that the end user needs are met. In the case of the transportation and power generation markets, the consumer using the vehicle or the electric power utility is the end user; however, the OEMs manufacturing the vehicle or the power generation equipment are responsible for the reliability, maintenance and warranty of the car or the equipment. The OEMs also specify the subsystems that they use in the cars or the equipment. The OEMs usually purchase the parts or subsystems such as ignition systems from suppliers labeled Tier 1 suppliers in the automotive industry. Therefore, it is critical for TPS to engage with both the OEMs and the suppliers. Getting the interest and support of the OEMs is often vital to getting attention from the suppliers. It is the "pull" from the OEMs (or the end users) that drives innovation in most industries, including the market segments of interest to TPS.

TPS' aforementioned self-funded test of its ignition system as a drop-in replacement to the stock ignition system on a 4-cylinder Toyota can help strengthen the OEM "pull." The overall approach to the testing was to evaluate the speed and loads where the engine operates frequently in the emission drive cycles (FTP-75). The various tests conducted as a part of this investigation were mapping points per the OEM as-calibrated settings (phaser, EGR, etc.), EGR sweeps, and spark sweeps in the knock limited area of engine operation. The TPS hardware was shown to allow for combustion stability improvements especially at lower load operation, both with and without additional external EGR. The higher EGR tolerance allowed for cooler combustion, as indicated from the lower NOx emissions and lower exhaust gas temperatures. Idle combustion stability was also improved relative to the stock system, meaning the engine would be able to run with equal or more torque reserve without sacrificing noise, vibration, and harshness, resulting in improved driver perception of quality. Due to faster combustion speeds TPI was shown to have the potential to reduce the need for component protection enrichment. All of this was accomplished while using between 4 and 30 Watts average power depending on the operating point, with the key points in the drive cycle using around 10 Watts (1000 – 1500 RPM / 3 bar). All of these benefits can be translated into strategies to improve fuel efficiency and therefore reduce CO_2 emissions. This test further validated that the system is ready for partner to help TPS move the technology to design validation and commercialization.

CHAPTER 5: Conclusions/Recommendations

Conclusions

Transient Plasma Systems, Inc. (TPS) has made significant progress in the development of an advanced ignition technology that enables improved efficiency and competitiveness for heavy-duty gas engines. The result of this project is design of a compact multi-cylinder ignition system based on receptively pulsed nanosecond discharges that is ready for commercial development with an engine technology supplier.

With regard to the engine testing results compared to the results from previous work (PIR-16-024), it should be noted that in prior testing a meaningful increase of about 1 percent in BTE was observed. The reason that was not seen in this project has to do with the adjustment of other parameters such as ignition timing. While it was sufficient for this project to demonstrate the potential for improvement in BTE by showing increased stability at higher dilution levels, it is desirable to make adjustments in timing to capture the improvement in BTE. Due to limited testing time caused by unforeseen challenges related to budget and equipment upgrades, these ignition timing adjustments were not done as part of the engine test.

OEMs requested confirmation of the ability of the system to operate at a high-load point, which was not demonstrated in PIR-16-024. To reach that point, Argonne required an upgrade to the engine test setup to increase the flowrate of gas. That upgrade ended up consuming most of the timeline and budget, leaving only a single day for engine testing.

Given the single day of testing, the team focused on making sure that the testing showed that each operation could be run; however, each operating point was not optimized in terms of timing or pulse parameters. The testing was sufficient to show that given the pulse parameters that the ignition system prototype was able to deliver, the desired objective of increasing dilution tolerance to improve efficiency can be met.

Recommendations

This research sets the stage for follow-on projects. Developing a new ignition system for production engines must be done in well-established, manufacturer-defined stages, and is best done with the deep experienced resources and infrastructure available at such manufacturers. The design of a transient plasma ignition system that has the potential to meet size, cost, and performance metrics of gas engine OEMs was a key milestone along the roadmap of developing a production ignition system. The next step is for TPS to collaborate with a commercial ignition systems (or engine) manufacturer to get its current design commercially ready, by advancing it through the manufacturer’s design and production process validations.

CHAPTER 6: Benefits to Ratepayers

Transient plasma ignition systems will benefit California's ratepayers by accelerating a transition to lower emission gas engines from diesel for use in heavy-duty vehicles. Combusting gas in engines produces 23 percent fewer CO_2 emissions than the combustion of diesel fuel; however, gas engines are less efficient than diesel engines, offsetting some of the CO_2 emission reductions. If future gas engines are made more efficient, gas will be even more favorable from a CO_2 standpoint compared to diesel. Turbocharging and increasing compression ratio are two strategies to improve the efficiency of gas engines; however, both necessitate improved ignition systems such as the one developed through this project.

Heavy-duty gas vehicles are currently available in limited quantity and hence are higher priced compared to conventional diesel vehicles. Performance improvements from transient plasma ignition can help accelerate adoption of gas vehicles and achieve sufficient cost and volume scales to better compete with diesel. If gas engines can be improved to within 10 percent of the efficiency of diesels for Class 8 heavy-duty vehicles, fuel savings will translate to about \$6,500 saved and 7,660 pounds of CO_2 emission reductions per year per vehicle. If just 10 percent of the 1,720,000 registered Class 8 vehicles nationwide transitioned to gas engines, the annual savings would be \$1.1 billion per year and CO_2 emissions would be reduced by 1.3 billion pounds per year. California would see annual fuel cost savings of \$82 million and 97 million pounds of CO_2.

TPS aims to collaborate with a commercial ignition systems (or engine) manufacturer to get the current design commercially ready, by advancing it through manufacturer design and production process validation. By demonstrating that this technology is commercially viable, the significant benefit to ratepayers will be the actual adoption of advanced ignition technology by heavy-duty gas vehicle OEMs. This will be another tool as part of many solutions to reduce CO_2 emissions from the transportation sector.

LIST OF ACRONYMS

Term	**Definition**
ATC	amplitude to time
BTE	brake thermal efficiency
CEC	California Energy Commission
CH_4	Methane
CO	carbon monoxide
CO_2	carbon dioxide
CWI	Cummins Westport Inc.
DC	direct current
EGR	Exhaust Gas Recirculation
GHG	greenhouse gas
kHz	Kilohertz
kV	Kilovolt
Nm	Newton meters
NOx	Oxides of nitrogen
OEM	Original equipment manufacturer
PCB	Printed circuit board
PM	Particulate matter
RPM	Revolutions Per Minute
TPI	Transient plasma ignition
TPS	Transient Plasma Systems, Inc.
V	Volt
VDC	volts of direct current

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