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Table of Contents

Executive Summary

The Heavy Duty Truck Engine Program at Cummins embodied three significant development phases. All phases of work strove to demonstrate a high level of diesel engine efficiency in the face of increasingly stringent emission requirements. Concurrently, aftertreatment system development and refinement was pursued in support of these efficiency demonstrations.

The program's first phase focused on the demonstration in-vehicle of a high level of heavy duty diesel engine efficiency (45% Brake Thermal Efficiency) at a typical cruise condition while achieving composite emissions results which met the 2004 U.S. EPA legislated standards. With a combination of engine combustion calibration tuning and the development and application of Urea-based SCR and particulate aftertreatment, these demonstrations were successfully performed by Q4 of 2002.

The second phase of the program directed efforts towards an in-vehicle demonstration of an engine system capable of meeting 2007 U.S. EPA legislated emissions requirements while achieving 45% Brake Thermal Efficiency at cruise conditions. Through further combustion optimization, the refinement of Cummins' Cooled EGR architecture, the application of a high pressure common rail fuel system and the incorporation of optimized engine parasitics, Cummins Inc. successfully demonstrated these deliverables in Q2 of 2004.

The program's final phase set a stretch goal of demonstrating 50% Brake Thermal Efficiency from a heavy duty diesel engine system capable of meeting 2010 U.S. EPA legislated emissions requirements. Cummins chose to pursue this goal through further combustion development and refinement of the Cooled EGR system architecture and also applied a Rankine cycle Waste Heat Recovery technique to convert otherwise wasted thermal energy to useful power. The engine and heat recovery system was demonstrated to achieve 50% Brake Thermal Efficiency while operating at a torque peak condition in second quarter, 2006. The 50% efficient engine system was capable of meeting 2010 emissions requirements through the application of NOx and particulate matter reduction techniques proven earlier in the program.

The work embodied within this final report is the result of efforts by many talented individuals whose contributions and achievements would not have been possible without the Joint Agreement's support. This work has helped to firmly found heavy duty diesel technology as a fundamental power source well into 21st century. Cummins Inc. looks forward to a continued relationship with the U.S. Department of Energy in the successful pursuit of ever more effective and efficient diesel engine technology.

Phase I – Demonstration of 45% Brake Thermal Efficiency while achieving 2002 Emissions Levels

Phase I Introduction

The first major development phase of the program was focused on the demonstration of 45% Brake Thermal Efficiency while meeting 2004 emissions levels. Exploration and development of Urea-based, SCR aftertreatment for NOx reduction and filtration aftertreatment for particulate matter reduction was a primary focus during this development phase. Engine and aftertreatment development culminated with an on-vehicle demonstration of a 45% Brake Thermal Efficiency engine with aftertreatment. In pursuit of this goal, an optimized drivetrain concept was explored that sought to maintain a lower engine speed at a cruise condition. Cummins successfully achieved these demonstrations by Q4, 2002.

Base engine optimization centered on the refinement of engine tuning to achieve 45% Brake Thermal Efficiency at the cruise condition. In pursuit of this goal, engine-out NOx emissions were allowed to reach 8 gm/bhp-hr NOx as it was expected that Urea-based SCR aftertreatment would reach at least 70% reduction efficiency. The system (engine and aftertreatment combination) BSNOx performance was targeted at 2.5 gm/bhp-hr. Engine-out smoke levels were limited to 1gm/bhp-hr (BSDPM) with the expectation that particulate filter aftertreatment would achieve at least 90% effectiveness. The engine's combustion system did not incorporate exhaust gas recirculation (EGR). The engine fuel system was a Cummins High Pressure Injection (HPI) system utilizing direct, cam-driven injection actuation and pressure generation. An engine cam and injector recipe was defined during the development program that achieved 45% Brake Thermal Efficiency at the cruise point.

Urea-SCR aftertreatment development began by using available hardware and technology. Bosch urea injection systems and Siemens catalysts were initially employed. During the effort, a Cummins controller was developed which better optimized aftertreatment operation to match the diesel engine performance. Using the Cummins controller, greater than 80% BSNOx reduction was achieved.

Particulate aftertreatment development began using filtration media from Englehard but transitioned to Fleetguard-Nelson media later in the program. A more detailed description of the development of the Particulate filter is presented in the Aftertreatment Development section of this report.

The optimized drivetrain studied during the program utilized an advanced Eaton Autoshift transmission. The transmission was built with closely-ranged gears which would be automatically selected by the transmission controller during operation. The control logic sought to maintain a more constant engine speed during cruise operation that would significantly increase the time the engine spent in its most efficient operating range.

The optimized drivetrain, aftertreatment system and optimized engine were installed into an International 9200i vehicle during 2002 and successfully demonstrated to achieve high efficiency during on-highway operation.

The development work performed in this program laid a foundation for work in later program phases. Simultaneous to the Phase I effort, Cummins was developing a Cooled Exhaust Gas Recirculation (CEGR) concept which was targeted toward achieving 2004 emissions without aftertreatment. The combustion optimization performed during this program had a significant effect on the development of the commercial products which were subsequently introduced.

Urea-SCR aftertreatment developed during this program was largely set aside after the Phase I demonstrations were completed. Cummins found that for its 2007 product development goals (and for Phase IIA goals), the need for NOx reduction aftertreatment was unnecessary in their heavy duty product line.

Particulate aftertreatment developed during Phase I continued to play a significant role in Phase IIA and B program phases. This technology continued to serve as a fundamental aftertreatment feature for the following program phases.

Optimized drivetrain development carried forward beyond the Phase I portion of the program and was further explored during Phase IIA. During Phase I, the system development between engine and drivetrain was demonstrated to achieve significant efficiency benefits and emphasized the need for close coordination during the development of these complimentary systems.

Phase I Discussion and Conclusions

The Phase I portion of the Heavy Duty Truck Engine program achieved its goals with the demonstration of efficient engine and effective aftertreatment systems. Combined engine and driveline performance was also optimized to achieve significant efficiency benefits on-highway.

Base engine development utilizing existing engine technology achieved 45% Brake Thermal Efficiency at the engine cruise point. This efficiency was demonstrated both in the test cell as well as in-vehicle. Base engine development focused on a cam-injector combination that would achieve the program efficiency.

Optimized drivetrain integration was explored during this program phase and resulted in a successful demonstration of the efficiency advantage to be gained through closely coordinated development of the engine and drivetrain systems.

Aftertreatment development drove Urea-SCR aftertreatment system refinement and application into the heavy duty diesel engine system. The program achieved an effective and efficient Urea-based NOx reduction system which demonstrated better than an 80% BSNOx reduction efficiency. The system was demonstrated both in the test cell and in-vehicle. An optimized controller was developed which worked well with available urea injection and aftertreatment (catalyst) technology. A significant amount of effort was made to test this system in a number of vehicle operating environments. A number of significant technical issues with the incorporation and operation of a Urea-based SCR aftertreatment system were experienced and overcome.

Particulate aftertreatment was extensively explored during this program phase with the achievement of better than 90% reduction efficiency achieved. The application of PM reduction technology was adopted into nearly all future Cummins products. Particulate aftertreatment development for Phase I and the rest of the program is more fully described in the Aftertreatment System Development portion of this report.

Phase IIA – Demonstration of 45% Brake Thermal Efficiency while achieving 2007 Emissions Levels

Phase IIA Introduction

The Phase IIA portion of the Heavy Duty Truck Engine Program again focused on the achievement of 45% Brake Thermal Efficiency from an engine system. Emissions goals were set to meet 2007 U.S. EPA legislated levels. The 2007 levels were significantly more difficult to reach with a further 50% reduction in BSNOx emissions.

An extensive engine and aftertreatment architecture selection process was pursued which led to the selection of an engine equipped with Cooled Exhaust Gas Recirculation (EGR), a high pressure, common rail fuel system, and particulate aftertreatment. The use of NOx reduction aftertreatment was avoided through optimization of in-cylinder combustion and air handling. Control system development focused on EGR measurement and manipulation along with controls for optimum performance from the new fuel system.

The 1.2 gm BSNOx emissions limit required a significant amount of EGR which slightly deteriorated the engine's thermal efficiency. Much of this efficiency loss was mitigated through intelligent combustion control and hardware optimization. The fuel system choice allowed significantly higher injection pressures with flexible timing and injection rate shaping strategies. A variable geometry turbocharger was also introduced to allow finer control over fresh air and EGR flow. In addition, optimized parasitics were studied and demonstrated to contribute a small amount of benefit at the cruise point. A demonstration of 2007 emissions capability while achieving 45% BTE was performed during Q2, 2004. The engine system employed in this demonstration was also installed and operated in-vehicle to demonstrate the practical application of the combination of technologies employed.

Aftertreatment development continued to be a part of the Phase IIA demonstration. Effective and efficient Particulate Aftertreatment was a prime focus of the heavy duty engine recipe. A detailed description of the effort made to achieve a robust particulate filter is described in the Aftertreatment System Development section of this report.

Phase IIA – Discussion and Conclusions

The Phase IIA portion of the Heavy Duty Truck Engine program at Cummins explored a number of new technologies in pursuit of the 45% Brake Thermal Efficiency goal while achieving 2007 emissions from their heavy duty, ISX engine.

Advanced combustion, mainly focusing on LQHCCI combustion techniques, was extensively explored in modeling, single cylinder and multi-cylinder research. Ultimately, this advanced combustion technique proved to require more research and development than could be accomplished in time to support the program's demonstration timeline. The combustion research justified the move to higher injection pressures however and the creation and an advanced, common rail, high pressure fuel system was applied for this demonstration. The flexibility of this fuel system allowed the investigation of rate shaping and multiple injection event combustion. Also, the fuel system was capable of much higher injection pressure which was key to achieving the NOx and PM emissions levels.

A significantly higher flow rate of EGR than previously used was found to be required to meet NOx emissions. This posed significant challenges to the engine's air handling and cooling package. Studies were made of optimized cooling techniques and performance with optimized EGR cooing was demonstrated to achieve higher efficiency. Air handling to move, cool, mix, and measure this greater amount of EGR was developed to an effective level.

Aftertreatment development for Phase IIA focused on particulate matter reduction in the combustion process and efficient regeneration of the aftertreatment media. A discussion of the aftertreatment development is contained in the Aftertreatment Development section of this report.

Also in support of improved engine efficiency, optimized parasitics were studied. An electric water pump was obtained and tested and a variable flow lube pump was studied. Both optimized parasitics offered efficiency improvements but at the cruise point, their contribution was fractional and therefore did not justify further development. They did, however, add to the bottom line in the pursuit of the 45% efficiency goal. The electric water pump system was operated on-vehicle and in test cell.

The Phase IIA portion of the program continued the drive to maintain or improve engine efficiency in the face of increasingly stringent emission requirements. It also laid foundations for further work in the program's final phase.

Phase IIB – Demonstration of 50% Brake Thermal Efficiency while achieving 2010 Emissions Levels

Phase IIB Introduction

The HDTE Program's final phase focused efforts toward the demonstration goal of a maximum of 50% Brake Thermal Efficiency (BTE) from a heavy duty diesel engine capable of achieving 2010 U.S. EPA Legislated emissions. As in the previous program phase, the BSNOx emission requirement was significantly more challenging. The 0.2 gm/bhp-hr limit was more than an 80% reduction from the previous 1.2 gm/bhp-hr level.

To achieve these goals, an intensive effort was made to identify efficient and effective combustion techniques which would achieve the lowest NOx emission levels possible while simultaneously meeting the stringent Particulate Matter emission level. Several techniques were explored including HCCI, PCCI, and advanced diffusion burn combustion. In support of this advanced combustion development, variable valve actuation was explored both through modeling and simulation as well as in hardware developed for use on Single Cylinder Engines (SCE) and on multi-cylinder engines.

The high pressure, common rail fuel system employed during Phase IIA was further developed and tested on single cylinder and multi-cylinder engines. Peak injection pressures passed 2400 bar.

The base engine architecture pursued in this portion of the program carried on the Cooled EGR method developed previously. This architecture required additional Cooled EGR to achieve the ultra-low NOx emission goal. To mitigate the additional heat rejection additional EGR would present, several optimized cooling strategies were explored and effective methods to provide adequate charge mass cooling for efficient combustion were identified.

To achieve the program's goal of 50% BTE, methods were explored to recover and convert to useful power otherwise wasted heat energy from the ISX engine. A Rankine Cycle system was identified as the most effective method to achieve a significant increase in BTE. The Rankine Cycle system employed in this program recovered thermal energy from the engine's Jacket Water, Charge Air, Exhaust and EGR streams and converted that energy to electricity. The electricity generated, less parasitic losses, was included in the engine's brake power output.

Phase IIB Discussion and Conclusions

The Phase IIB portion of the HDTE program achieved its goal of demonstrating a heavy duty diesel engine system achieving 2010 U.S. EPA Legislated emissions.

Effective techniques to achieve ultra-low emissions of NOx and Particulate Matter in-cylinder were found which met the program's emissions requirements. The Program's goal of demonstrating an engine capable of 2010 U.S. EPA Legislated emissions while achieving 50% Brake Thermal Efficiency was also met during second quarter, 2006.

Advanced combustion techniques explored included HCCI, PCCI, and diffusion burn combustion with variable valve actuation and multi-pulse, high pressure fuel injection. Fuel injection pressures exceeded 2400 bar and drove new developments in fuel pressure generation and actuation techniques. The most effective method for efficient and clean combustion across the engine's operating map continued to rely on traditional diffusion-burn techniques but portions of the engine's operating map were developed which utilized homogeneous (HCCI) and pre-mixed charge (PCCI) combustion methods. Steady state combustion was demonstrated which met the target limits of emissions. Engine efficiency was only slightly degraded from previous demonstrations due to the additional EGR required to mitigate emissions of NOx. Particulate emissions were effectively kept within the operating limits of developed Robust Particulate Filters (see section on Aftertreatment Development for NOx and Particulate Emissions) through the combination of effective air handling and combustion techniques.

The 50% BTE demonstration goal was met through the development and application of a Rankine Cycle Heat Recovery system which captured and converted to electricity otherwise wasted thermal energy from the engine's Jacket Water, Charge Air, Exhaust, and EGR streams. A combined-cycle, BTE of 50% was demonstrated from an engine capable of 2010 U.S. EPA legislated emissions assuming the application of previously demonstrated (see Phase I Discussion) Urea-based SCR NOx and Particulate Aftertreatment. The Waste Heat Recovery system demonstrated under this program effectively laid the foundation for further waste energy utilization development for heavy duty engines at Cummins Inc.

Aftertreatment Development Summary

Aftertreatment system development at Cummins under the Heavy Duty Truck Engine (HDTE) Program explored a number of new technologies and their application to Cummins' heavy duty diesel engines.

Urea-based SCR aftertreatment for NOx reduction was explored under the program's Phase I effort. A more complete description of that effort is included in the Phase I portion of this report. The effort began using available, lab-based technology and developed it into a viable system for use on-vehicle. An effective system was demonstrated on-vehicle during the Phase I effort.

In addition to Urea-based SCR aftertreatment, development of a Robust Particulate Filter also occurred. The combination of a Diesel Oxidation Catalyst (DOC) placed upstream of a Particulate Filter element achieved the 'Robust' feature of the system allowing it to be operated on-vehicle in almost any duty cycle. The heat from the DOC provided the Particulate Filter with the energy required to completely reduce soot to unregulated, carbon-based emissions (CO and CO2). To withstand the thermal cycling imposed by the DOC, significant effort was put into insuring that particulate filters were mechanically sound and robust to thermal stresses. Intensive modeling and analysis was performed to identify areas of thermal degradation and a number of significant improvements were identified which improved the manufacture of the filter element.

Efficient and effective use of the DOC was developed under this program with intensive modeling, analysis, and experimentation conducted to identify techniques which would balance the need for hydrocarbon addition to exhaust streams with the capacity of the filter element. Mitigation of 'uncontrolled regeneration' was effectively achieved. A great deal of in-vehicle testing was performed to gather real-world test data from a variety of duty cycles so that a clean and regenerated filter could always be insured.

Particulate Filter aftertreatment development under the HDTE Program at Cummins Inc. carried the technology from the lab to the vehicle and demonstrated the technology in a number of applications.

NOx adsorber development at Cummins under the Program explored a great number of materials and methods to achieve an effective aftertreatment system. A purpose-built, Mobile Emissions Research Laboratory (Cummins' MERLin vehicle) was built for the purpose of studying various aftertreatment techniques. Combinations of NOx adsorbers with SOx traps and robust particulate filters were extensively studied and effective methods were found to mitigate Sulfur poisoning, reduce precious metal loading, and regeneration sintering. NOx adsorber technology continues to be studied to improve its robustness in applications to heavy duty diesel engines.

Electrostatic Oil Droplet Separation Crankcase Ventilation

Introduction

Crankcase Ventilation and its improvement was a part of this program's development as 2007 EPA rules dictated that direct venting of crankcase vapors to the atmosphere would be prohibited. Achieving overall emissions capability during the Phase IIA portion of the program required Cummins to address this emissions source.

Quantification of crankcase generated PM during an FTP cycle on a 6BT engine revealed that crankcase generated levels were on the order of 0.01 g/bhp*hr. Further quantification of blowby during an EPA certification cycle showed that blowby emissions could account for up to 120% of the 0.01 g/hp-hr Particulate limit for 2007 emissions. This indicated the need for a crankcase ventilation filter.

Cummins chose to investigate a Closed Crankcase Ventilation system that incorporated an Electrostatic filter. When the program initiated, standard filtration and separation technologies weren't yet capable of meeting the 2007 emissions standards. Electrostatic filtration was expected to provide effective and durable blowby emissions control while satisfying crankcase ventilation needs.

A thorough understanding of crankcase ventilation test methods and how to evaluate the contribution of blow-by to the overall particulate matter was achieved during this program.

Ultimately, passive filtration technology 'caught up' during the investigation and eventually displaced the electrostatic filter concept as a viable design choice due to cost and reliability issues.

HDTE Report Summary

The Heavy Duty Truck Engine Program at Cummins Inc., begun in 2000 and ended in 2006, fostered a tremendous amount of technological innovation which has maintained the traditionally high brake thermal efficiency of heavy duty diesel engines in the face of increasingly stringent emissions requirements.

At the program's outset, regulated emissions of NOx were at the 6 gm BSNOx level and Particulate Matter Emissions were unregulated. The program's first phase sought to demonstrate greater than a 50% reduction in NOx emissions (2.5 gm BSNOx target) and a 90% reduction in BSDPM. The program successfully carried out these dramatic emission reductions while simultaneously demonstrating 45% Brake Thermal Efficiency from the base engine. This level of engine fuel efficiency was achieved through a successful refinement of cam-driven fuel injection and air handling combined with an effective application of aftertreatment system technology.

The program's first phase initiated an aftertreatment development plan which identified, refined, and delivered to demonstration the first Urea-based SCR NOx aftertreatment system Cummins Inc. had ever worked with for a heavy duty engine application. The development to achieve a successful on-vehicle demonstration resulted in a refined NOx reduction system that exceeded modeled performance and performed well in a number of operating environments and duty cycles.

The program's first phase also initiated particulate matter aftertreatment development which carried on through the rest of the program. The 'Robust Particulate Filter', first applied to the Phase I deliverable, was continually refined and improved to the point where it essentially graduated from an experimental technology to a device ready for production. Robust Particulate Filters have become an essential part of many of Cummins Inc.'s product architectures. Greater than 90% effectiveness is routinely expected from these devices and their longevity in-application matches the life of the engine they're applied to.

The Program's second Phase (IIA) required the demonstration of 45% Brake Thermal Efficiency at a typical cruise point operating condition while meeting 2007 emissions requirements. The level of PM emission didn't change but BSNOx emissions were again reduced by more than 50% to a 1.2 gm BSNOx limit. Cummins approached this second significant reduction in BSNOx emissions without any NOx aftertreatment. The goal was to reach the 1.2 gm limits entirely in-cylinder. Meeting the BTE goal in this manner was a significant technical challenge.

For Phase IIA, combustion technology and development moved away from the architecture employed during the program's first phase and included several significant upgrades. Cooled Exhaust Gas Recirculation (EGR) was introduced along with flexible, high-pressure, common rail fuel systems. The second 50% reduction in BSNOx emissions targets drove the need to reduce combustion temperatures by reducing the O2 fraction in the combustion charge mass. The addition of EGR to the intake charge required that optimized cooling strategies be studied and effective cooling means were found which allowed high engine efficiency to continue to exist in the heavy duty engine platform. High pressure injection offered improved combustion with lower PM emissions at the reduced O2 levels in-cylinder. We explored the flexibility offered by multiple injections and injection rate-shaping.

As a means to further supplement efficiency reductions caused by the reduced NOx emission requirement, we explored optimized engine parasitics including electric water pumps and variable flow oil pumps. These devices offered fractional improvements to brake thermal efficiency at our target cruise point demonstration but clearly offered greater benefits depending on the engine duty cycle and the amount of time it spent at other than traditional cruise-point engine speeds.

Utilizing an optimized combustion system and EGR cooling system with the reduced level of parasitic load, Cummins successfully met the Phase IIA deliverables by demonstrating an engine system capable of meeting 2007 emissions requirements and achieving 45% Brake Thermal Efficiency at cruise. Cummins demonstrated this efficiency in a test cell and demonstrated the engine system in-vehicle during the first half of 2004.

As the program moved on to its final phase (IIB), the BSNOx emission goal was again reduced significantly – this time by more than 80% to an 0.2 gm BSNOx limit. Particulate Matter emissions remained unchanged at 0.1 gm BSDPM. Simultaneously, the Brake Thermal Efficiency demonstration goal increased to a 50% target. Cummins again approached the Program's NOx emissions goal without requiring NOx aftertreatment.

Cummins further refined its Cooled EGR architecture to significantly increase the amount of EGR mass flow while maintaining an intake manifold temperature target that would allow NOx-clean combustion. A number of optimized cooling strategies were considered. By the program's closure, no one optimized cooling technique had been clearly identified as a 'take forward' concept but several capable choices were available.

Cummins demonstrated U.S. EPA Legislated emissions capability to 2010 limits with its ISX engine without NOx aftertreatment in the fourth quarter of 2005.

To achieve the 50% Brake Thermal Efficiency goal, a Rankine Cycle waste heat recovery system was devised and applied to the engine. The Rankine Cycle, during engine operation at approximately 1200 rpm and 1650 ft-lbf of torque, provided an extra 57 Hp of electrical power to the engine's own brake power thereby reaching the 50% BTE goal. The base engine was capable of 2007 emissions but the assumed application of effective BSNOx aftertreatment in the form of the previously demonstrated Urea-based SCR NOx reduction with Robust Particulate Filtration allowed the 2010 emissions goal to be met. The 50% BTE goal was demonstrated in May of 2006. This demonstration was the last significant goal for the Program.

During the HDTE Program, Cummins Inc. conducted advanced research on virtually every aspect of its heavy duty ISX engine. The contributions by many talented and dedicated individuals in these pursuits led to the successful demonstration of the Program's goals. The integration of a variety of new and often unproven technologies was effectively achieved. The high efficiency of the heavy duty diesel engine was maintained in the face of over a 95% reduction in NOx and a 90% reduction in Particulate Matter emissions. The high level goals of the Program were met and many of the technologies developed in its course will be carried forward into production programs which will ultimately benefit the consumer and the Nation.

Acronyms, Abbreviations, and Other Definitions

A/F	Air to Fuel ratio
APCRS	Advanced Production Common Rail System
AREA	Advanced Reciprocating Engine System
Bhp	Brake horse power
BSDPM	Brake Specific Diesel Particulate Matter
BSHC	Brake Specific Hydrocarbon Emissions
BSNOx	Brake Specific Nitrous Oxide Emissions
BTE	Brake Thermal Efficiency
^oC	Degree Centigrade
CA	Crank Angle
CAD	Crank Angle Degrees
CAPS	Cummins Advanced Pressure System
CFD	Computational Fluid Dynamics
CFR	Critical Functional Response
CO	Carbon Monoxide
COS	Carbonyl Sulfide
CRPT	Cummins Rapid Prototyping Tool for controls
CSF	Catalyzed Soot Filter
CST	Close Shift Transmission (Eaton)
CVS	Constant Volume Sampling
CVT	Continuously Variable Transmission
Cybertruck	Cummins' Controller/Engine-In-Loop vehicle simulation tool
DFSS	Design for Six Sigma
DOC	Diesel Oxidation Catalyst
DOE	Design of Experiments
DPF	Diesel Particulate Filter
ECM	Engine Control Module
EDC	Electro Discharge
EGR	Exhaust Gas Recirculation
Enforcer	Cummins' 2002 15 liter HD engine
EPSII	Fleetguard exhaust filter media
FGN	Fleetguard Nelson
FMEA	Failure Mode Effect Analysis
ft^3	Cubic feet
g	Gram
GIMEP	Gross Indicated Mean Effective Pressure
GT-Power	Cycle simulation software
HC	Hydrocarbon(s)
HD	Heavy-duty
HDT	Heavy-duty Truck
hp	Horse power
HPCR	High Pressure Common Rail
hr	Hour

HVPS	High Voltage Power Supply
Hz	Hertz (cycles per second)
H_2O	Water
H_2S	Hydrogen Sulfide
IMP	Intake Manifold Pressure
IMT	Intake Manifold Temperature
ISB	Cummins' 5.9 liter MD engine
ISX	Cummins' 15 liter HD engine
IVS	In-Vehicle System (CRPT)
J1939	Standardized electronic communication port
HCCI	Homogenous Charge Compression Ignition (Diesel Cycle)
LQR	Linear Quadratic Regulator
MatLab	Engineering math software
MD	Medium-duty
MERLin	Mobile Emission Research Laboratory
Modest	Engine system simulation software
ms	Millisecond
NAC	NOx Adsorber Catalyst
NOX	Oxides of Nitrogen
O_2	Oxygen
PCCI	Partial homogeneous Charge Compression Ignition
PM	Particulate Matter
Pt	Platinum
QFD	Quality Function Deployment
Rpm	Revolutions Per Minute
Psi	Pound per square foot
RPF	Robust Particulate Filter
RPN	Risk Priority Number
RTS	Real Time Station (CRPT)
SCR	Selective Catalytic Reduction
SCRT	Selective Catalytic Reduction Trap
SiC	Silicon Carbide
Simulink	Dynamic simulation software
SOX	Oxides of Sulfur
SrSCO NO_X^{TM}	Sulfur resistant SunLaw Carbon Monoxide and Nitrogen Oxide, NO_X adsorber system
T2000	Class 8 Heavy-duty truck model manufactured by Kenworth
T300	Medium-duty truck model (Kenworth) (MERLin)
TDFSS	Technology Design for Six-Sigma
VMS	Vehicle Mission Simulation
VVA	Variable Valve Actuation
VVT	Variable Valve Technology
WET	Winter Express Test