Final Report Certification
for
CRADA Number NFE-07-00722

Between

UT-Battelle, LLC

and

Delphi Automotive Systems, LLC
(Participant)

Instructions:

Mark the appropriate statement in 1a or 1b below with an 'IX.' Refer to the articles in the CRADA terms and conditions governing the identification and marking of Protected CRADA Information (PCI).

If no PCI is identified, the report will be distributed without restriction. If PCI is identified, the report distribution will be limited in accordance with the CRADA terms and conditions governing release of data. In all cases items 2 and 3 must be true. That is, the report cannot contain Proprietary Information and a disclosure must be filed prior to release of the report.

This certification may either be made by using this form or may be made on company letterhead if the Participant desires. A faxed copy of this completed form is acceptable.

The following certification is made for the subject final report:

1. (a) ☐ The final report contains information that qualifies as "Protected CRADA Information" (PCI). The PCI legend is printed on the report cover, and the PCI is clearly identified.

OR

(b) ☒ The final report does not contain "Protected CRADA Information." The "Approved for Public Release" legend is printed on the report cover.

2. The final report does not contain Proprietary Information.

3. By the signature below, the Participant has no objection to the public distribution of the final report due to patentable information.

For the Participant:

[signature] Brown
(Name)

Executive Director & Chief Technologist
(Title)

Feb 22, 2011
(Date)

ORNL-851 (9/2007)

OAK RIDGE
NATIONAL LABORATORY

MANAGED BY UT-BATTELLE
FOR THE DEPARTMENT OF ENERGY

NFE-07-00722

ETSD

CRADA Final Report
For
CRADA Number NFE-07-00722

Enabling High Efficiency Ethanol Engines

Jim Szybist
Oak Ridge National Laboratory

Keith Confer
Delphi Automotive Systems

Prepared by
Oak Ridge National Laboratory
Oak Ridge, TN 37831
managed by
UT-BATTELE, LLC
for the
U.S. Department of Energy
under contract DE-AC05-00OR2225

Approved for
Public Release

UT-BATTELLE

ORNL-27 (4-00)

DOCUMENT AVAILABILITY

Reports produced after January 1, 1996, are generally available free via the U.S. Department of Energy (DOE) Information Bridge.

Web site http://www.osti.gov/bridge

Reports produced before January 1, 1996, may be purchased by members of the public from the following source.

National Technical Information Service
5285 Port Royal Road
Springfield, VA 22161
Telephone 703-605-6000 (1-800-553-6847)
TDD 703-487-4639
Fax 703-605-6900
E-mail info@ntis.fedworld.gov
Web site http://www.ntis.gov/support/ordernowabout.htm

Reports are available to DOE employees, DOE contractors, Energy Technology Data Exchange (ETDE) representatives, and International Nuclear Information System (INIS) representatives from the following source.

Office of Scientific and Technical Information
P.O. Box 62
Oak Ridge, TN 37831
Telephone 865-576-8401
Fax 865-576-5728
E-mail reports@adonis.osti.gov
Web site http://www.osti.gov/contact.html

Abstract

Delphi Automotive Systems and ORNL established this CRADA to explore the potential to improve the energy efficiency of spark-ignited engines operating on ethanol-gasoline blends. By taking advantage of the fuel properties of ethanol, such as high compression ratio and high latent heat of vaporization, it is possible to increase efficiency with ethanol blends. Increasing the efficiency with ethanol-containing blends aims to remove a market barrier of reduced fuel economy with E85 fuel blends, which is currently about 30% lower than with petroleum-derived gasoline. The same or higher engine efficiency is achieved with E85, and the reduction in fuel economy is due to the lower energy density of E85. By making ethanol-blends more efficient, the fuel economy gap between gasoline and E85 can be reduced.

In the partnership between Delphi and ORNL, each organization brought a unique and complementary set of skills to the project. Delphi has extensive knowledge and experience in powertrain components and subsystems as well as overcoming real-world implementation barriers. ORNL has extensive knowledge and expertise in non-traditional fuels and improving engine system efficiency for the next generation of internal combustion engines. Partnering to combine these knowledge bases was essential towards making progress to reducing the fuel economy gap between gasoline and E85.

ORNL and Delphi maintained strong collaboration throughout the project. Meetings were held regularly, usually on a bi-weekly basis, with additional reports, presentations, and meetings as necessary to maintain progress. Delphi provided substantial hardware support to the project by providing components for the single-cylinder engine experiments, engineering support for hardware modifications, guidance for operational strategies on engine research, and hardware support by providing a flexible multi-cylinder engine to be used for optimizing engine efficiency with ethanol-containing fuels.

1. Statement of Objectives

- Quantify the achievable efficiency benefits of higher compression ratio in a direct-injection spark-ignited engine compared to an OEM compression ratio
- Develop valvetrain strategies to mitigate knocking with conventional lower-octane gasoline in order to maintain with these fuels
- Demonstrate that by using advanced valvetrain strategies, it is possible to optimize an engine for E85 without sacrificing efficiency during gasoline operation compared to the original OEM compression ratio
- Quantify the particle emissions of gasoline and ethanol blends using multiple valvetrain and engine fueling configurations

2. Benefits to the Funding DOE Office's Mission

A key strategy in DOE's mission to reduce the consumption of imported petroleum is direct replacement of this fuel with domestic renewable sources of liquid fuel for the transportation sector. This is not only a goal, but is a requirement of the Energy Independence and Security Act (EISA) of 2007 [1] which requires that production of bio-derived fuels increase more than 7 fold from their 2007 levels by 2020. Ethanol is the domestic renewable fuel that will account for the majority of the bio-derived fuels meeting this requirement, and there has been a dramatic increase in the use of fuel ethanol in the United States in the past decade, as shown in Figure 1. The ethanol consumption in 2008, 221,637 thousand barrels, was equivalent to 6.7% of the volume of gasoline sold [2]. Thus, production and consumption of fuel ethanol will almost certainly continue to increase rapidly in an effort to comply with EISA.

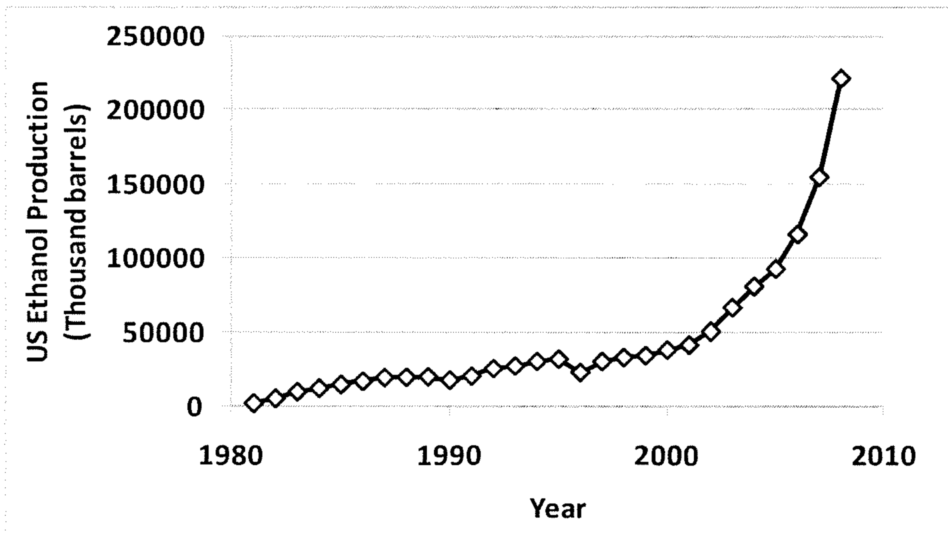

Figure 1. Ethanol production in the United States. Data from the US Energy Information Administration [2].

Two legal forms of ethanol fuel blends are currently sold in the US: E10 and E85, although E15 is currently under consideration. E10, which is nominally 10 vol% ethanol blended with gasoline or gasoline blendstock, can be used in all gasoline vehicles. E85, which can contain nominally from 70 to 85 vol% ethanol [3], is only compatible with Fuel Flexible Vehicles (FFVs). For a more complete assessment of ethanol compatibility, see reference [4]. Approximately 99% of the fuel ethanol sold in the US is in the form of E10, and even if all the gasoline sold in the US contains 10% ethanol, the goals of EISA cannot be met [4]. Thus, the US Department of Energy (DOE) has an interest in increasing the amount of E85 consumed.

One of the market barriers associated with increased consumer use of E85 is reduced fuel economy compared to gasoline. Ethanol blends do not operate any less efficiently than gasoline;

the reduced fuel economy for E85 and other ethanol-gasoline blends can be attributed to lower energy content on both a mass and volumetric basis. The energy content of E85 is approximately 32% lower than gasoline on a mass basis. This project aims to directly address this market barrier by reducing the fuel economy gap between gasoline and E85 by increasing the thermal efficiency of E85 in an effort to make it more acceptable to consumers.

3. Technical Discussion of Work Performed by All Parties

Year 1.

One of the most widely-known methods of increasing the thermal efficiency of spark-ignition engines is to increase the compression ratio. Compression ratio is relatively low in most gasoline-optimized engines to prevent engine-knock. Ethanol and ethanol blends have a higher octane rating than gasoline, allowing compression ratio to be increased without knock. This allows them to realize the greater thermal efficiency potential of higher compression ratio, unlike gasoline which is prone to knocking.

A study was undertaken at ORNL using a 2-cylinder variable compression ratio engine to quantify the extent that compression ratio could be increased with ethanol blends before being limited by either engine knock or before the increased friction of higher compression ratio negated the benefits of a higher indicated thermal efficiency. The study was focused on knock-prone conditions, namely low engine speed and high load (wide-open throttle).

After it was initiated, this initial experimental effort could not be completed because the 2-cylinder variable compression ratio engine being used experienced a catastrophic failure. The prolonged engine operation at high engine load caused the crankshaft in the prototype engine to fail, destroying a series of custom-made engine components. It was decided that repair of the engine would not be feasible on a time or economic standpoint. A decision was made to accomplish the goals of this initial study in a different engine platform during the second year of the CRADA.

Year 2.

During the second year of the project we succeeded in experimentally determining the extent that compression ratio could be increased in a spark-ignition engine with ethanol fuel blends, and the potential impact that it would have on reducing the fuel economy gap between gasoline and E85. This study was performed on a new single-cylinder engine platform at ORNL equipped with a Sturman hydraulic variable valve actuation (VVA) valvetrain, as shown in Figure 2. To change compression ratio, Delphi provided a series of custom pistons with compression ratios ranging from the OEM configuration of 9.2 up to 13.5, allowing a total of 5 different compression ratio configurations. The highest compression ratio configuration was inoperable due to ignitibility problems.

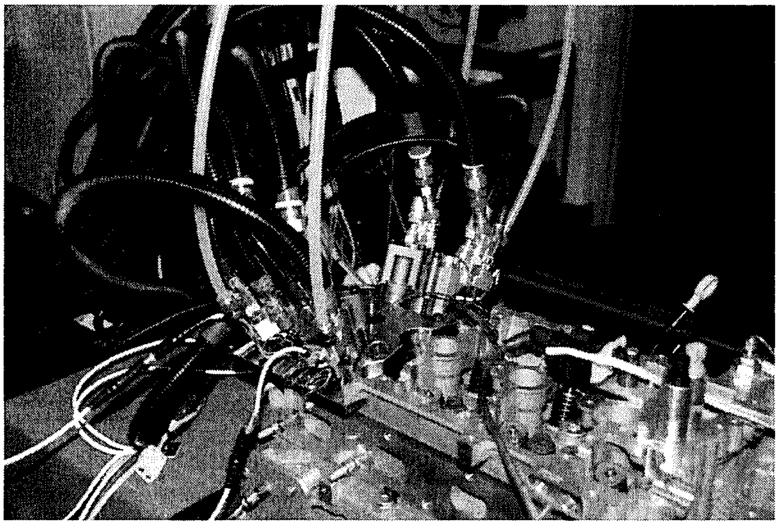

Figure 2. ORNL single-cylinder research engine equipped with a hydraulic variable valve actuation system.

Figure 3 shows thermal efficiency, power, and fuel consumption at the same operating condition for the production compression ratio configuration for a series of ethanol blend levels. As ethanol content increases, thermal efficiency and power both increase. However, the higher thermal efficiency for ethanol blends is not sufficient to offset the lower energy density compared to gasoline. Thus, the fuel consumption shows a substantial increase with ethanol-containing fuels.

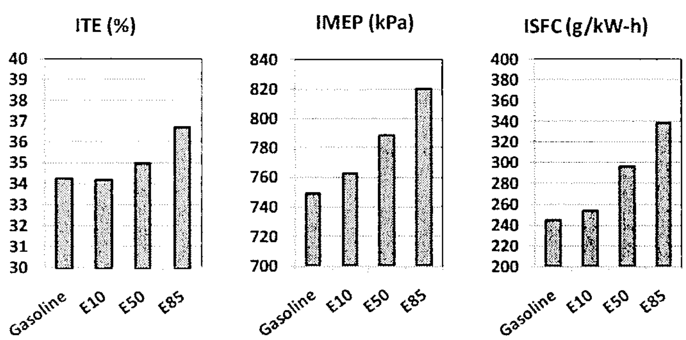

Figure 3. Thermal efficiency (ITE, %), power (IMEP, kPa), and fuel consumption (ISFC, g/kW-h) at 1500 rpm, 80 kPa intake manifold pressure, and spark timing for best torque. OEM compression ratio of 9.2, and spark advance is not knock-limited for any fuel.

For E50 and E85, fuels that are not knock-limited, efficiency and power continue to increase with increases in compression ratio. However, in order to maintain compatibility at high compression ratio with fuels that are prone to knocking, such as gasoline and E10, changes in operating conditions are required. Early and late intake valve closing operating strategies were used to de-rate the engine at these conditions as a method of mitigating knock with a minimal efficiency penalty, or even an efficiency increase. This result is demonstrated in Figure 4, which compares maximum load at 1500 rpm for E85 and gasoline as a function of compression ratio.

Thermal efficiency increases for both fuels as compression ratio increases, but the increases for E85 are much higher. Engine power, however, increases for E85 but decreases for gasoline. The net effect is that under these conditions, the fuel economy gap between E85 and gasoline can be reduced by about 20%.

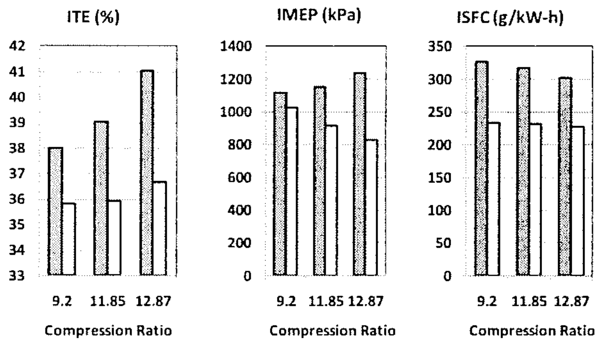

Figure 4. Comparison of engine performance of E85 (▩) and gasoline (□) at 1500 rpm and maximum load.

Complete details of this study are presented in reference [5], presented at the 2010 SAE World Congress. Jim Szybist was given the *SAE Award for Outstanding Oral Presentation* while presenting this material. This work was also presented at two additional forums [6, 7].

Year 3.

As part of this CRADA activity, ORNL added a multi-cylinder spark-ignited multi-cylinder engine equipped with custom pistons for a high compression ratio and a cam-based VVA valvetrain. The modifications to the valvetrain were performed by the CRADA partner Delphi, and include a 2-step cam profile and a high authority cam phasing. Together, this flexible valvetrain allows the engine to be operated without throttling for a large portion of the engine map as well as de-rate the effective compression ratio to mitigate engine knock with gasoline. These features make this engine a highly versatile research platform, ideal for optimizing the engine for operation with ethanol fuel blends. The multi-cylinder engine currently installed in ORNL engine cell 7 is pictured in Figure 5.

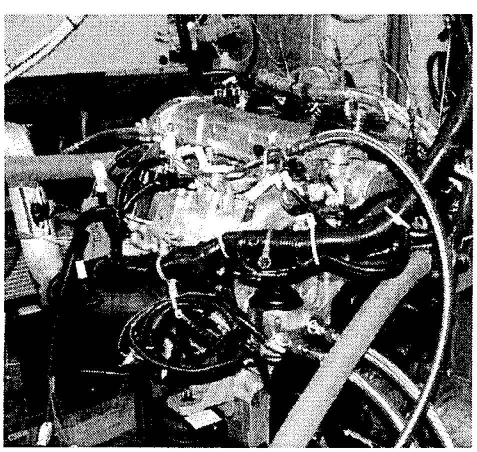

Figure 5. Multi-cylinder spark-ignited engine installed in ORNL engine cell 7, equipped with high compression ratio pistons and a flexible cam-based valvetrain.

Once installed at ORNL, the engine was used to characterize particle emissions with gasoline and ethanol blends. Regulations for total number particle emissions are currently in place for diesel engines in Europe, but additional regulations are under consideration for gasoline engines in both Europe and in the United States. Regulators appear to be moving towards a total particle number regulation rather than a mass-based regulation because emissions of small particles contribute very little to mass emissions, but are a major concern for respiratory health. Coincidentally, direct-injection gasoline engines allow for higher efficiency, but increase particle emissions compared to port-fuel injected engines. Thus, there is a motivation to gain an understanding of the conditions under which particles are formed, and the tendency of different fuels to form those emissions.

The study included three fueling strategies: single injection GDI, multiple injection GDI (m-GDI), and port fuel injection (PFI). The engine breathing strategies include conventional throttled operation as well as two unthrottled methods of operation: early intake valve closing (EIVC) and late intake valve closing (LIVC). The three fuel blends that were investigated include conventional gasoline, E20 and E85. The particle emissions from the engine were being characterized both with filter smoke number (FSN) and with a scanning mobility particle sizer (SMPS).

Results show clear differences in particle emissions from the three different fueling strategies. Figure 6 shows FSN particle emissions as a function of the start of injection timing for GDI and m-GID fueling. PFI FSN is shown below as a line. It can be seen that at the most advanced start of injection timing (320 deg before TDC) the GDI fueling strategy had higher smoke emissions than m-GDI. This is thought to be a result of reduced fuel impingement on the piston with the m-GDI strategy. At the most retarded start of injection timing (200 deg before TDC), the GDI fueling strategy had lower smoke emissions than the m-GDI strategy. This is thought to be a result of inadequate mixing of the fuel and air for the m-DGI spray. The fuel injection timing that results in the lowest smoke emissions shows there is comparable smoke levels for all three fueling strategies.

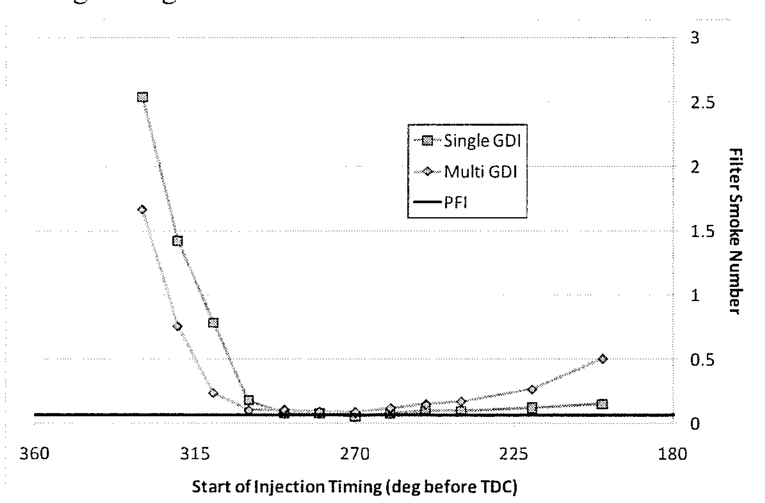

Figure 6. Filter smoke number as a function of the start of injection timing for the three different fueling strategies under early intake valve closing conditions at 1500 rpm, 8 bar net IMEP.

SMPS results shown in Figure 7 provide additional insight into the particle emissions under the different fueling strategy conditions. The GDI fueling strategy produces the most emissions at all particle sizes at the earliest fuel injection timing, whereas the m-GDI strategy produces the highest particle emissions at the latest fuel injection timing. At the intermediate timing, all strategies produce low particle emissions, with the PFI still being the lowest. It is also interesting that GDI engines, unlike diesel engines, produce a very broad range of particles from 10 nm to over 100 nm.

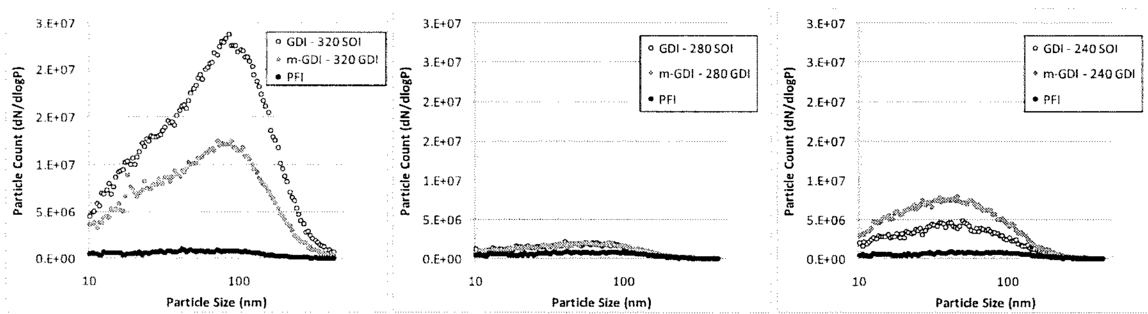

Figure 7. SMPS particle size distributions for GDI, m-GDI and PFI fueling at three different start-of-injection timings under early intake valve closing conditions at 1500 rpm, 8 bar IMEP.

Significant differences in particle emissions were also observed with fuel type. Figure **8** shows particle emissions from conventional gasoline, E20 and E85. At this condition, E20 produced the highest concentration of particle emissions, followed by conventional gasoline and E85. The differences between conventional gasoline and E20 were dependent on the fueling and breathing strategy, with E20 producing highest particle emission under some conditions and conventional gasoline producing the highest emissions at other conditions. At all cases, however, E85 produced by far the lowest concentration of particle emissions. Thus E85, and likely other high-level ethanol blends, appear to be one methodology to reduce particle emissions from direct-injected spark-ignition engines.

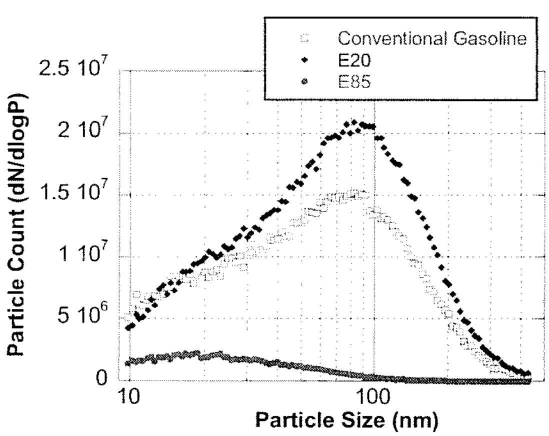

Figure 8. Particle emissions for conventional gasoline, E20 and E85 under throttled operation at 1500 rpm, 8 bar IMEP, and a fuel injection timing of 320 CA BTDC.

4. Subject Inventions

No Inventions were filed under this CRADA.

5. Commercialization Possibilities

No new product was developed as a direct result of this CRADA project. However, this product aided Delphi in the development of its 2-step valvetrain technology, which is a production-intent system that they are marketing to vehicle manufacturers.

6. Plans for Future Collaborations

Participants in his CRADA are continuing to collaborate in the form of a CRADA project to expand the operating range of robust HCCI combustion. Discussions for additional collaboration will continue as research needs and opportunities present themselves.

7. Conclusions

A successful CRADA project was conducted to explore methods of removing market barriers to more widespread E85 consumption in the United States. The team member from ORNL and Delphi each brought a unique set of complementary skills to the project, and progress was made in reducing the fuel economy gap between E85 and conventional gasoline by up to 20% by using a higher compression ratio configuration and using unconventional valve strategies. We also showed that the fuel economy gap reduction could be accomplished solely through the increase in efficiency of E85, and that the efficiency of conventional gasoline was not reduced compared to the OEM compression ratio configuration.

ORNL added a new highly flexible multi-cylinder engine platform during the course of this project. The engine is equipped with a high compression ratio configuration and includes a flexible cam-based valvetrain, ideal for ethanol optimization. The modifications and engine break-in were performed by the CRADA partners, Delphi. The engine will remain at ORNL after the completion of this CRADA.

Finally, progress was made towards understanding particle emissions from direct-injection spark-ignited engines when operated with several different breathing strategies and with multiple ethanol fuel blends. Optimization of fuel injection timing is essential to minimize particle emissions, and the engine breathing and fueling strategies can also impact particle emissions. A large reduction in particle emissions was observed with E85 fuel compared to conventional gasoline and E20.

ORNL maintained a good working relationship throughout the project and the same team members continue to collaborate under a different CRADA agreement focused on HCCI combustion. The two organizations will continue to explore new opportunities for collaboration as opportunities present themselves.

8. References

1. One Hundred Tenth Congress of the United States of America. Energy Independence and Security Act. 2007. URL: http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_bills&docid=f:h6enr.txt.pdf. Accessed on September 10, 2009.

2. United States Energy Information Association, Official ethanol consumption statistics. URL: http://tonto.eia.doe.gov/dnav/pet/pet_pnp_oxy_dc_nus_mbbl_a.htm. Accessed on September 4, 2009.

3. ASTM D 5798-09b. "Standard Specification for Fuel Ethanol (Ed75-Ed85) for Automotive Spark-Ignition Engines." ASTM International, 2009.

4. R. Bechtold, J.F. Thomas, S.P. Huff, J.P. Szybist, T.J. Theiss, B.H. West, M. Goodman, T.A. Timbario. Technical Issues Associated with the Use of Intermediate Ethanol Blends (>E10) in the U.S. Legacy Fleet: Assessment of Prior Studies." Oak Ridge National Laboratory Technical Report, August 2007, ORNL/TM-2007/37. URL: https://portal.ornl.gov/sites/apps/PTS/PtsDocs/Publication%207767.pdf. Accessed on September 14, 2009.

5. Szybist, J. M. Foster, W. Moore, K. Confer, A. Youngquist and R. Wagner. "Investigation of Knock Limited Compression Ratio of Ethanol Gasoline Blends." Society of Automotive Engineers, 2010, Technical Paper 2010-01-0619.

6. Szybist, J. M. Foster, W. Moore, K. Confer, A. Youngquist and R. Wagner. "Enabling High-Efficiency Ethanol Engines." Presented at the AEC/HCCI Working Group Meeting, Sandia National Laboratory, February 25, 2010.

7. Szybist, J., B. Bunting, S. Sluder, K. Cho, R. Wagner, D. Edwards, and S. Daw. "*Non Petroleum Based Fuel Effects on Advanced Combustion*" Presented at the 2010 DOE Vehicle Technologies Program Annual Merit Review, Presentation Number FT008.

OAK RIDGE
NATIONAL LABORATORY

MANAGED BY UT-BATTELLE
FOR THE DEPARTMENT OF ENERGY

NFE-07-00722

ETSD

CRADA Final Report
For
CRADA Number NFE-07-00722

Enabling High Efficiency Ethanol Engines

Jim Szybist
Oak Ridge National Laboratory

Keith Confer
Delphi Automotive Systems

Prepared by
Oak Ridge National Laboratory
Oak Ridge, TN 37831
managed by
UT-BATTELE, LLC
for the
U.S. Department of Energy
under contract DE-AC05-00OR2225

Approved for
Public Release

UT-BATTELLE

ORNL-27 (4-00)

Abstract

Delphi Automotive Systems and ORNL established this CRADA to explore the potential to improve the energy efficiency of spark-ignited engines operating on ethanol-gasoline blends. By taking advantage of the fuel properties of ethanol, such as high compression ratio and high latent heat of vaporization, it is possible to increase efficiency with ethanol blends. Increasing the efficiency with ethanol-containing blends aims to remove a market barrier of reduced fuel economy with E85 fuel blends, which is currently about 30% lower than with petroleum-derived gasoline. The same or higher engine efficiency is achieved with E85, and the reduction in fuel economy is due to the lower energy density of E85. By making ethanol-blends more efficient, the fuel economy gap between gasoline and E85 can be reduced.

In the partnership between Delphi and ORNL, each organization brought a unique and complementary set of skills to the project. Delphi has extensive knowledge and experience in powertrain components and subsystems as well as overcoming real-world implementation barriers. ORNL has extensive knowledge and expertise in non-traditional fuels and improving engine system efficiency for the next generation of internal combustion engines. Partnering to combine these knowledge bases was essential towards making progress to reducing the fuel economy gap between gasoline and E85.

ORNL and Delphi maintained strong collaboration throughout the project. Meetings were held regularly, usually on a bi-weekly basis, with additional reports, presentations, and meetings as necessary to maintain progress. Delphi provided substantial hardware support to the project by providing components for the single-cylinder engine experiments, engineering support for hardware modifications, guidance for operational strategies on engine research, and hardware support by providing a flexible multi-cylinder engine to be used for optimizing engine efficiency with ethanol-containing fuels.

1. Statement of Objectives

- Quantify the achievable efficiency benefits of higher compression ratio in a direct-injection spark-ignited engine compared to an OEM compression ratio
- Develop valvetrain strategies to mitigate knocking with conventional lower-octane gasoline in order to maintain with these fuels
- Demonstrate that by using advanced valvetrain strategies, it is possible to optimize an engine for E85 without sacrificing efficiency during gasoline operation compared to the original OEM compression ratio configuration
- Quantify the particle emissions of gasoline and ethanol blends using multiple valvetrain and engine fueling configurations

2. Benefits to the Funding DOE Office's Mission

A key strategy in DOE's mission to reduce the consumption of imported petroleum is direct replacement of this fuel with domestic renewable sources of liquid fuel for the transportation sector. This is not only a goal, but is a requirement of the Energy Independence and Security Act (EISA) of 2007 [1] which requires that production of bio-derived fuels increase more than 7 fold from their 2007 levels by 2020. Ethanol is the domestic renewable fuel that will account for the majority of the bio-derived fuels meeting this requirement, and there has been a dramatic increase in the use of fuel ethanol in the United States in the past decade, as shown in Figure 1. The ethanol consumption in 2008, 221,637 thousand barrels, was equivalent to 6.7% of the volume of gasoline sold [2]. Thus, production and consumption of fuel ethanol will almost certainly continue to increase rapidly in an effort to comply with EISA.

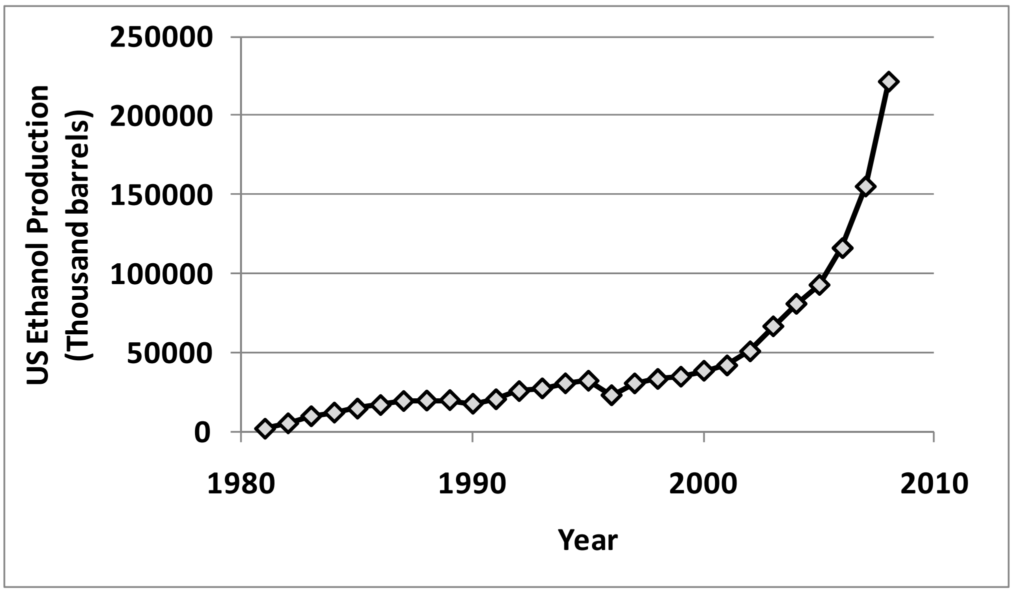

Figure 1. Ethanol production in the United States. Data from the US Energy Information Administration [2].

Two legal forms of ethanol fuel blends are currently sold in the US: E10 and E85, although E15 is currently under consideration. E10, which is nominally 10 vol% ethanol blended with gasoline or gasoline blendstock, can be used in all gasoline vehicles. E85, which can contain nominally from 70 to 85 vol% ethanol [3], is only compatible with Fuel Flexible Vehicles (FFVs). For a more complete assessment of ethanol compatibility, see reference [4]. Approximately 99% of the fuel ethanol sold in the US is in the form of E10, and even if all the gasoline sold in the US contains 10% ethanol, the goals of EISA cannot be met [4]. Thus, the US Department of Energy (DOE) has an interest in increasing the amount of E85 consumed.

One of the market barriers associated with increased consumer use of E85 is reduced fuel economy compared to gasoline. Ethanol blends do not operate any less efficiently than gasoline;

the reduced fuel economy for E85 and other ethanol-gasoline blends can be attributed to lower energy content on both a mass and volumetric basis. The energy content of E85 is approximately 32% lower than gasoline on a mass basis. This project aims to directly address this market barrier by reducing the fuel economy gap between gasoline and E85 by increasing the thermal efficiency of E85 in an effort to make it more acceptable to consumers.

3. Technical Discussion of Work Performed by All Parties

Year 1.

One of the most widely-known methods of increasing the thermal efficiency of spark-ignition engines is to increase the compression ratio. Compression ratio is relatively low in most gasoline-optimized engines to prevent engine-knock. Ethanol and ethanol blends have a higher octane rating than gasoline, allowing compression ratio to be increased without knock. This allows them to realize the greater thermal efficiency potential of higher compression ratio, unlike gasoline which is prone to knocking.

A study was undertaken at ORNL using a 2-cylinder variable compression ratio engine to quantify the extent that compression ratio could be increased with ethanol blends before being limited by either engine knock or before the increased friction of higher compression ratio negated the benefits of a higher indicated thermal efficiency. The study was focused on knock-prone conditions, namely low engine speed and high load (wide-open throttle).

After it was initiated, this initial experimental effort could not be completed because the 2-cylinder variable compression ratio engine being used experienced a catastrophic failure. The prolonged engine operation at high engine load caused the crankshaft in the prototype engine to fail, destroying a series of custom-made engine components. It was decided that repair of the engine would not be feasible on a time or economic standpoint. A decision was made to accomplish the goals of this initial study in a different engine platform during the second year of the CRADA.

Year 2.

During the second year of the project we succeeded in experimentally determining the extent that compression ratio could be increased in a spark-ignition engine with ethanol fuel blends, and the potential impact that it would have on reducing the fuel economy gap between gasoline and E85. This study was performed on a new single-cylinder engine platform at ORNL equipped with a Sturman hydraulic variable valve actuation (VVA) valvetrain, as shown in Figure 2. To change compression ratio, Delphi provided a series of custom pistons with compression ratios ranging from the OEM configuration of 9.2 up to 13.5, allowing a total of 5 different compression ratio configurations. The highest compression ratio configuration was inoperable due to ignitibility problems.

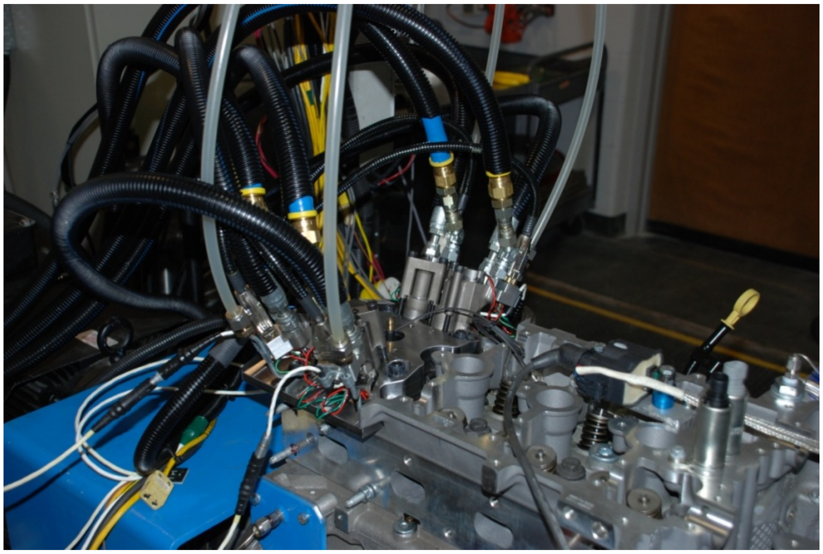

Figure 2. ORNL single-cylinder research engine equipped with a hydraulic variable valve actuation system.

Figure 3 shows thermal efficiency, power, and fuel consumption at the same operating condition for the production compression ratio configuration for a series of ethanol blend levels. As ethanol content increases, thermal efficiency and power both increase. However, the higher thermal efficiency for ethanol blends is not sufficient to offset the lower energy density compared to gasoline. Thus, the fuel consumption shows a substantial increase with ethanol-containing fuels.

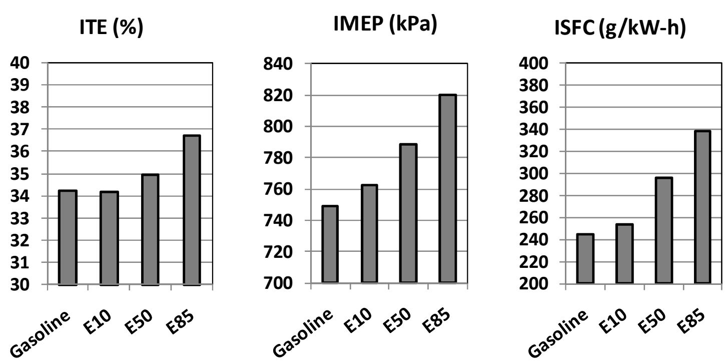

Figure 3. Thermal efficiency (ITE, %), power (IMEP, kPa), and fuel consumption (ISFC, g/kW-h) at 1500 rpm, 80 kPa intake manifold pressure, and spark timing for best torque. OEM compression ratio of 9.2, and spark advance is not knock-limited for any fuel.

For E50 and E85, fuels that are not knock-limited, efficiency and power continue to increase with increases in compression ratio. However, in order to maintain compatibility at high compression ratio with fuels that are prone to knocking, such as gasoline and E10, changes in operating conditions are required. Early and late intake valve closing operating strategies were used to de-rate the engine at these conditions as a method of mitigating knock with a minimal efficiency penalty, or even an efficiency increase. This result is demonstrated in Figure 4, which compares maximum load at 1500 rpm for E85 and gasoline as a function of compression ratio.

Thermal efficiency increases for both fuels as compression ratio increases, but the increases for E85 are much higher. Engine power, however, increases for E85 but decreases for gasoline. The net effect is that under these conditions, the fuel economy gap between E85 and gasoline can be reduced by about 20%.

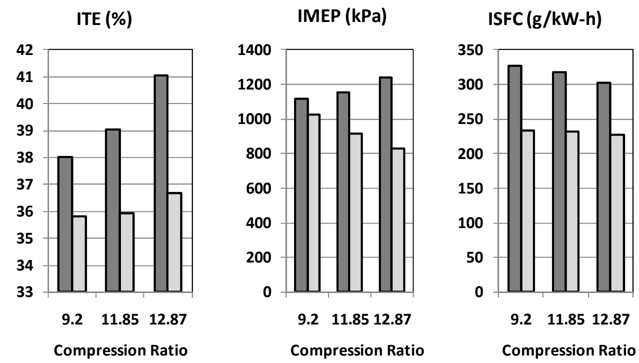

Figure 4. Comparison of engine performance of E85 (■) and gasoline (□) at 1500 rpm and maximum load.

Complete details of this study are presented in reference [5], presented at the 2010 SAE World Congress. Jim Szybist was given the *SAE Award for Outstanding Oral Presentation* while presenting this material. This work was also presented at two additional forums [6, 7].

Year 3.

As part of this CRADA activity, ORNL added a multi-cylinder spark-ignited multi-cylinder engine equipped with custom pistons for a high compression ratio and a cam-based VVA valvetrain. The modifications to the valvetrain were performed by the CRADA partner Delphi, and include a 2-step cam profile and a high authority cam phasing. Together, this flexible valvetrain allows the engine to be operated without throttling for a large portion of the engine map as well as de-rate the effective compression ratio to mitigate engine knock with gasoline. These features make this engine a highly versatile research platform, ideal for optimizing the engine for operation with ethanol fuel blends. The multi-cylinder engine currently installed in ORNL engine cell 7 is pictured in Figure 5.

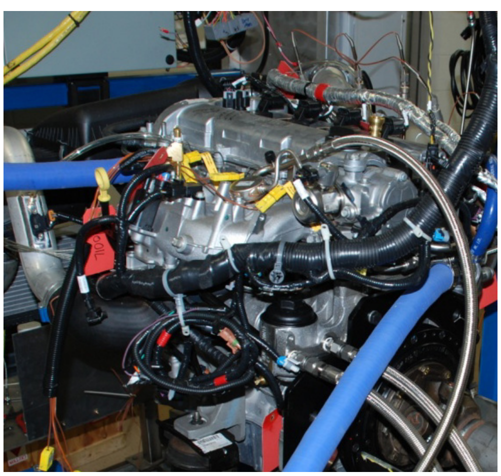

Figure 5. Multi-cylinder spark-ignited engine installed in ORNL engine cell 7, equipped with high compression ratio pistons and a flexible cam-based valvetrain.

Once installed at ORNL, the engine was used to characterize particle emissions with gasoline and ethanol blends. Regulations for total number particle emissions are currently in place for diesel engines in Europe, but additional regulations are under consideration for gasoline engines in both Europe and in the United States. Regulators appear to be moving towards a total particle number regulation rather than a mass-based regulation because emissions of small particles contribute very little to mass emissions, but are a major concern for respiratory health. Coincidentally, direct-injection gasoline engines allow for higher efficiency, but increase particle emissions compared to port-fuel injected engines. Thus, there is a motivation to gain an understanding of the conditions under which particles are formed, and the tendency of different fuels to form those emissions.

The study included three fueling strategies: single injection GDI, multiple injection GDI (m-GDI), and port fuel injection (PFI). The engine breathing strategies include conventional throttled operation as well as two unthrottled methods of operation: early intake valve closing (EIVC) and late intake valve closing (LIVC). The three fuel blends that were investigated include conventional gasoline, E20 and E85. The particle emissions from the engine were being characterized both with filter smoke number (FSN) and with a scanning mobility particle sizer (SMPS).

Results show clear differences in particle emissions from the three different fueling strategies. Figure 6 shows FSN particle emissions as a function of the start of injection timing for GDI and m-GID fueling. PFI FSN is shown below as a line. It can be seen that at the most advanced start of injection timing (320 deg before TDC) the GDI fueling strategy had higher smoke emissions than m-GDI. This is thought to be a result of reduced fuel impingement on the piston with the m-GDI strategy. At the most retarded start of injection timing (200 deg before TDC), the GDI fueling strategy had lower smoke emissions than the m-GDI strategy. This is thought to be a result of inadequate mixing of the fuel and air for the m-DGI spray. The fuel injection timing that results in the lowest smoke emissions shows there is comparable smoke levels for all three fueling strategies.

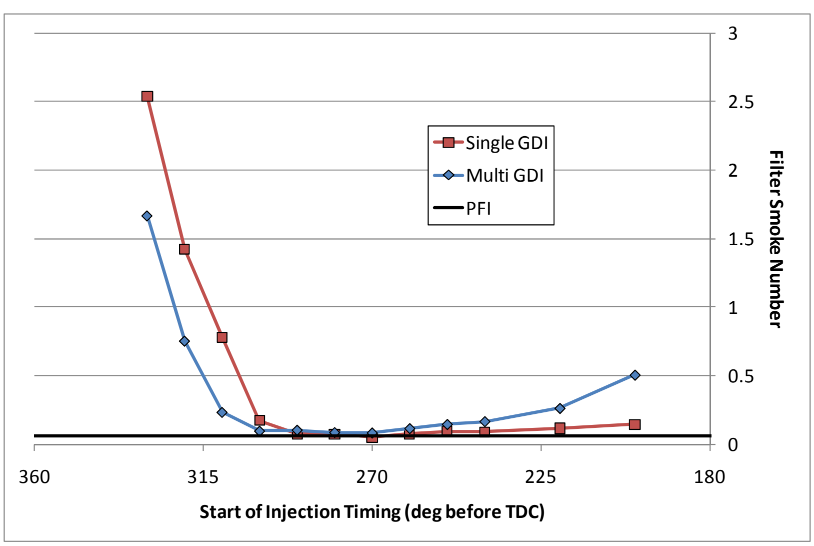

Figure 6. Filter smoke number as a function of the start of injection timing for the three different fueling strategies under early intake valve closing conditions at 1500 rpm, 8 bar net IMEP.

SMPS results shown in Figure 7 provide additional insight into the particle emissions under the different fueling strategy conditions. The GDI fueling strategy produces the most emissions at all particle sizes at the earliest fuel injection timing, whereas the m-GDI strategy produces the highest particle emissions at the latest fuel injection timing. At the intermediate timing, all strategies produce low particle emissions, with the PFI still being the lowest. It is also interesting that GDI engines, unlike diesel engines, produce a very broad range of particles from 10 nm to over 100 nm.

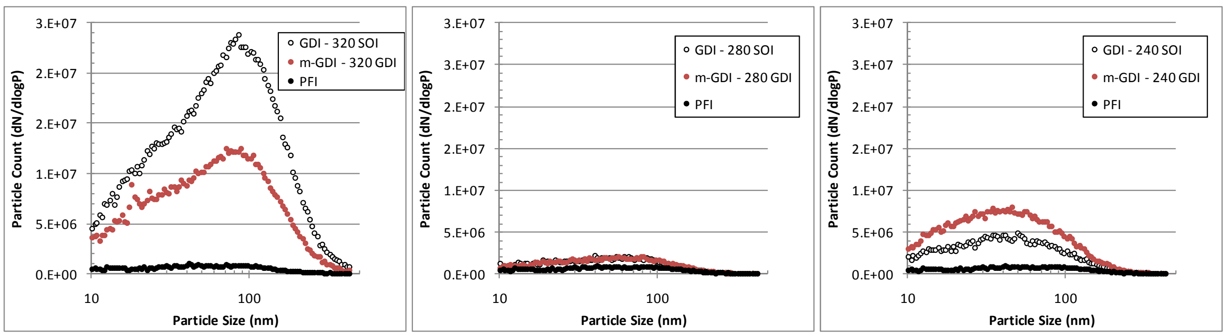

Figure 7. SMPS particle size distributions for GDI, m-GDI and PFI fueling at three different start-of-injection timings under early intake valve closing conditions at 1500 rpm, 8 bar IMEP.

Significant differences in particle emissions were also observed with fuel type. Figure **8** shows particle emissions from conventional gasoline, E20 and E85. At this condition, E20 produced the highest concentration of particle emissions, followed by conventional gasoline and E85. The differences between conventional gasoline and E20 were dependent on the fueling and breathing strategy, with E20 producing highest particle emission under some conditions and conventional gasoline producing the highest emissions at other conditions. At all cases, however, E85 produced by far the lowest concentration of particle emissions. Thus E85, and likely other high-level ethanol blends, appear to be one methodology to reduce particle emissions from direct-injected spark-ignition engines.

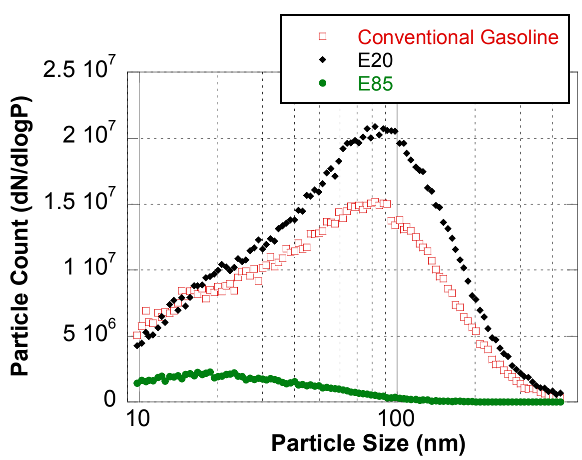

Figure 8. Particle emissions for conventional gasoline, E20 and E85 under throttled operation at 1500 rpm, 8 bar IMEP, and a fuel injection timing of 320 CA BTDC.

4. Subject Inventions

No Inventions were filed under this CRADA.

5. Commercialization Possibilities

No new product was developed as a direct result of this CRADA project. However, this product aided Delphi in the development of its 2-step valvetrain technology, which is a production-intent system that they are marketing to vehicle manufacturers.

6. Plans for Future Collaborations

Participants in his CRADA are continuing to collaborate in the form of a CRADA project to expand the operating range of robust HCCI combustion. Discussions for additional collaboration will continue as research needs and opportunities present themselves.

7. Conclusions

A successful CRADA project was conducted to explore methods of removing market barriers to more widespread E85 consumption in the United States. The team member from ORNL and Delphi each brought a unique set of complementary skills to the project, and progress was made in reducing the fuel economy gap between E85 and conventional gasoline by up to 20% by using a higher compression ratio configuration and using unconventional valve strategies. We also showed that the fuel economy gap reduction could be accomplished solely through the increase in efficiency of E85, and that the efficiency of conventional gasoline was not reduced compared to the OEM compression ratio configuration.

ORNL added a new highly flexible multi-cylinder engine platform during the course of this project. The engine is equipped with a high compression ratio configuration and includes a flexible cam-based valvetrain, ideal for ethanol optimization. The modifications and engine break-in were performed by the CRADA partners, Delphi. The engine will remain at ORNL after the completion of this CRADA.

Finally, progress was made towards understanding particle emissions from direct-injection spark-ignited engines when operated with several different breathing strategies and with multiple ethanol fuel blends. Optimization of fuel injection timing is essential to minimize particle emissions, and the engine breathing and fueling strategies can also impact particle emissions. A large reduction in particle emissions was observed with E85 fuel compared to conventional gasoline and E20.

ORNL maintained a good working relationship throughout the project and the same team members continue to collaborate under a different CRADA agreement focused on HCCI combustion. The two organizations will continue to explore new opportunities for collaboration as opportunities present themselves.

8. References

1. One Hundred Tenth Congress of the United States of America. Energy Independence and Security Act. 2007. URL: http://frwebgate.access.gpo.gov/cgi-bin/getdoc.cgi?dbname=110_cong_bills&docid=f:h6enr.txt.pdf. Accessed on September 10, 2009.

2. United States Energy Information Association, Official ethanol consumption statistics. URL: http://tonto.eia.doe.gov/dnav/pet/pet_pnp_oxy_dc_nus_mbbl_a.htm. Accessed on September 4, 2009.

3. ASTM D 5798-09b. "Standard Specification for Fuel Ethanol (Ed75-Ed85) for Automotive Spark-Ignition Engines." ASTM International, 2009.

4. R. Bechtold, J.F. Thomas, S.P. Huff, J.P. Szybist, T.J. Theiss, B.H. West, M. Goodman, T.A. Timbario. Technical Issues Associated with the Use of Intermediate Ethanol Blends (>E10) in the U.S. Legacy Fleet: Assessment of Prior Studies." Oak Ridge National Laboratory Technical Report, August 2007, ORNL/TM-2007/37. URL: https://portal.ornl.gov/sites/apps/PTS/PtsDocs/Publication%207767.pdf. Accessed on September 14, 2009.

5. Szybist, J. M. Foster, W. Moore, K. Confer, A. Youngquist and R. Wagner. "Investigation of Knock Limited Compression Ratio of Ethanol Gasoline Blends." Society of Automotive Engineers, 2010, Technical Paper 2010-01-0619.

6. Szybist, J. M. Foster, W. Moore, K. Confer, A. Youngquist and R. Wagner. "Enabling High-Efficiency Ethanol Engines." Presented at the AEC/HCCI Working Group Meeting, Sandia National Laboratory, February 25, 2010.

7. Szybist, J., B. Bunting, S. Sluder, K. Cho, R. Wagner, D. Edwards, and S. Daw. "*Non Petroleum Based Fuel Effects on Advanced Combustion*" Presented at the 2010 DOE Vehicle Technologies Program Annual Merit Review, Presentation Number FT008.