Report from the Workshop on

Research Needs Related to CIDI and SIDI Fuel Injection Systems

Sponsored by

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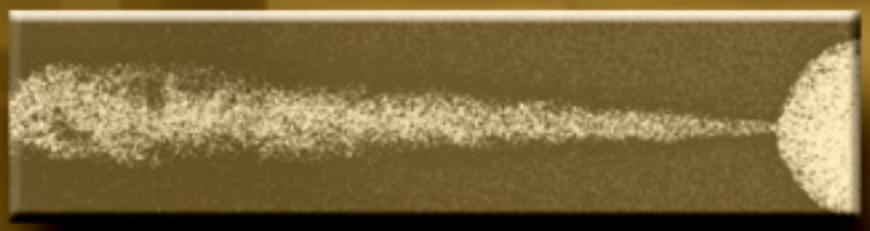

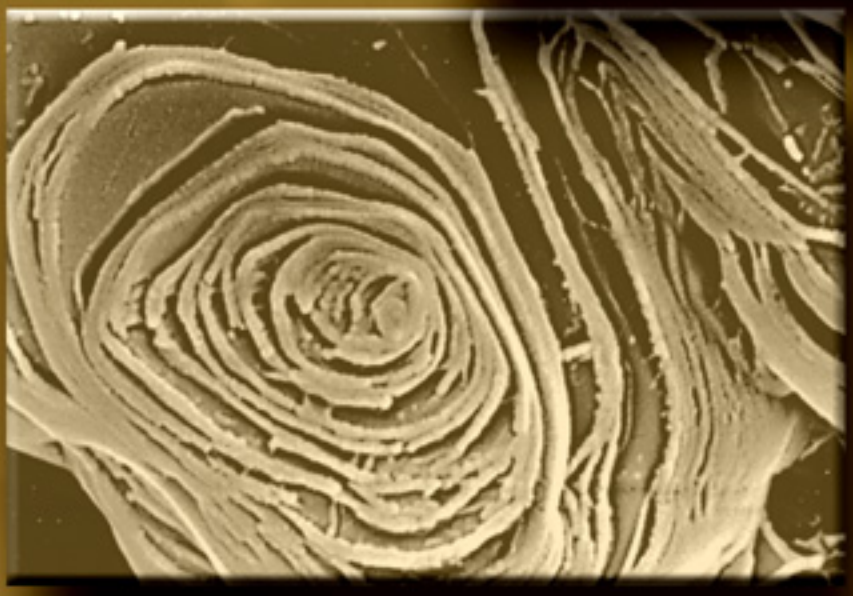

RESEARCH NEEDS RELATED TO FUEL INJECTION SYSTEMS IN CIDI AND SIDI ENGINES

Sponsored by
U.S. Department of Energy
Energy Efficiency and Renewable Energy
Office of Transportation Technologies

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Acknowledgments

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Light-Duty CIDI
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EXECUTIVE SUMMARY

Increasing the fuel economy and reducing the emissions of future vehicles will depend upon introducing new technologies for the fuel system, the fuel, and the after-treatment system, all of which must be treated with a coordinated systems approach. This document focuses on research needs related to the fuel systems of compression-ignition, direct-injection (CIDI) engines and spark-ignition, direct-injection (SIDI) engines. Fuel efficiencies related to direct-injection engines are important to both the Office of Advanced Automotive Technologies (OAAT) for its goal of developing an affordable advanced automotive piston-engine technology for emission-compliant passenger cars with 80 mpg fuel economy, and the Office of Heavy Vehicle Technologies (OHVT) for its goal of developing the enabling technology for a Class 7-8 truck with a fuel efficiency of 10 mpg at 65 mph and that will meet prevailing emission standards when using either diesel or liquid alternate fuel.

This document is based on input from industry that was presented at a workshop at Argonne National Laboratory on February 28-March 2, 2001, and on discussions with key industrial people before that workshop.

To satisfy future fuel economy and emission requirements, fuel systems for CIDI engines should incorporate the following new features:

- Rate shaping and multiple injections
- Higher pressures
- Variable pressures
- Smaller spray holes
- Variable-orifice geometry
- Closed-loop control
- Ability to inject lube oil
- Improved durability and reliability
- Low cost

Technical barriers to achieving those features include

- Inadequate models
- Manufacturing technology
- Measurement techniques
- Speed of actuators
- Sulfur contamination of after-treatment devices
- Seizure and wear
- Structural integrity
- Lack of sensors for measuring critical parameters
- Unknown future requirements

Desired features for future SIDI fuel systems include the following:

- Higher pressures
- Better atomization
- Control of spray penetration
- Operating flexibility
- Lower cost

Technical barriers to achieving those features include

- Inadequate models
- Fuel-injector deposits
- Unburned hydrocarbon and soot emissions
- Parasitic losses
- Durability of after-treatment devices
- Friction, wear, and corrosion
- Lack of real-time feedback control system

Recommended research areas for **light-duty CIDI** fuel systems are:

- *Spray and Combustion Fundamentals.* Includes studies of injection rate control, higher injection pressure, and other factors that control the spray and combustion.
- *Control Strategies.* Includes a number of the topics on spray and combustion fundamentals, plus the use of sensors and the role of exhaust gas recirculation in conjunction with multiple injections.
- *Alternative Injection Methods.* Lower-pressure injection systems based on other technologies such as electrothermal, electrostatics, or ultrasonics.
- *Advanced Design Concepts.* These cover many of the topics on spray and combustion fundamentals, plus an evaluation of variable-orifice technology.
- *Fuels and Tribology.* Study of the effects of fuel properties on durability of injection systems, including wear, corrosion, injector plugging, and deposit formation.
- *Modeling/Simulation.* Developing improved models of spray, including spray formation in noncircular orifices and multiphase spray.
- *Advanced Diagnostics and Instrumentation.* Developing new or improved devices to measure the performance of injector systems in support of manufacturing, development, and modeling.
- *Manufacturing and Materials.* Exploring the use of high-strength materials and advanced manufacturing techniques to miniaturize nozzles.

The following areas of research were recommended for future **SIDI** fuel systems:

- *Injector Design.* Various techniques for atomizing the fuel, faster actuators, variable-orifice injectors, and rate shaping.
- *Combustion.* Gaining a better understanding of the factors that control production of various pollutants and development of a system to detect misfire.
- *Deposits.* Developing a better fundamental understanding of the factors that affect the formation of deposits, ways to prevent deposits, and a standardized test for qualifying the resistance of a system to damage from deposits.
- *Modeling.* Improved models for spray, wall/fuel interactions, and combustion of air/fuel mixtures.
- *Fuels.* Additives for control of deposits, and on-board removal of sulfur, biofuels, and synthetic fuels.
- *Materials.* Development of coatings to resist wear and corrosion associated with new fuels and additives to resist formation of deposits.
- *Parasitics.* Reduction of parasitic energy losses in the low-pressure intake pump, high-pressure engine-drive pump, and air pump.
- *System Integration.* Investigation of stratified and lean-homogeneous air-guided, jet-guided, and wall-guided systems.

Five research areas were recommended for **heavy-duty CIDI** systems:

- *Manufacturing.* Low-cost ultra-precision manufacturing processes and low-cost methods for producing ultra-small holes.
- *Materials.* Desired properties include higher fatigue strength; higher stiffness; lower density; improved resistance to corrosion, particulate erosion, and cavitation; and improved piezoelectric performance. Also included under this topic are materials that are resilient to fuels with varying levels of lubricity.
- *Advanced Concepts.* Alternatives to higher pressures for atomization, variable-orifice geometries, novel combustion systems such as HCCI (homogeneous charge compression ignition), full rate-shape control, improved solenoids, and exhaust-pipe fuel injection for supplying a reductant.
- *Fundamental Understanding.* Developing improved models for atomization, flow in the injector, and combustion, plus a technique for measuring very small quantities of fuel in a single stroke.
- *Sensors for Real-Time Feedback.* Low-cost, reliable sensors are needed to measure cylinder pressure, injection pressure, needle position, and fuel quality.

Most of the recommended research topics are within five areas, each of which is relevant to light-duty CIDI, heavy-duty CIDI, and SIDI fuel systems:

- Modeling and simulation of spray and combustion
- Manufacturing technologies for small holes and ultraprecision machining
- Materials and coatings to resist fatigue, wear, and corrosion
- Sensors and controls
- Development of advanced, non-traditional strategies for fuel injection.

INTRODUCTION

Fuel systems in vehicles play an important role in determining the fuel efficiency and level of emissions. Therefore, they are of interest to both the Office of Advanced Automotive Technologies (OAAT) and the Office of Heavy Vehicle Technologies (OHVT) within the Office of Transportation Technologies (OTT) in the U.S. Department of Energy (DOE). The goal of OAAT is to investigate, develop, and validate technologies that will enable automobiles and other vehicles to have greater fuel economy, fuel flexibility, and lower emissions without sacrificing other attributes such as price, comfort, and safety. The mission of OHVT is to conduct, in collaboration with industrial partners from the heavy-vehicle industry, customer-focused national programs to investigate and develop technologies that will enable vehicles to be more energy efficient and capable of using alternative fuels while simultaneously reducing emissions. Current and pending emissions regulations are placing a great deal of urgency on the development of new technologies, because current technologies are not capable of meeting future requirements.

Direct-injection engines are seen as a key element in improved efficiency. Both compression-ignition direct-injection (CIDI) engines and spark-ignition direct-injection (SIDI) engines are being considered for automobiles, while CIDI engines appear to be the primary choice for heavy-duty vehicles.

To meet future requirements, it will be necessary to consider the fuel, the after-treatment system, and the fuel system together as a larger system. For example, after-treatment devices may require special fuels that may have lower lubricity, which, in turn, will affect the design of the fuel system. Although the fuel system for any vehicle must be designed with both the after-treatment system and the fuel in mind, fuel systems could be improved in a number of generic ways that are applicable to almost any fuel or after-treatment technology.

This document summarizes the nature of the research needed to develop the technologies needed for SIDI engines, light-duty CIDI engines, and heavy-duty CIDI engines. The contents are based on input from industry that was presented at a workshop held at Argonne National Laboratory on February 28-March 2, 2001, and on discussions with key industrial people before that workshop.

The workshop opened with a series of presentations that outlined the goals of DOE and the perspectives of various segments of industry, including automotive OEMs, diesel-engine manufacturers, fuel-system suppliers, engineering/design firms, and fuel suppliers. Following the presentations, three simultaneous breakout sessions were held to further define the technical needs and research topics that would be appropriate for DOE support. Each breakout session focused on one of the following three areas: light-duty CIDI, SIDI, and heavy-duty CIDI.

The agenda for the workshop is in Appendix A, the presentations are in Appendix B, and the attendance list is in Appendix C.

GOALS AND CHALLENGES

OAAT

One of OAAT's primary goals is to develop, in support of the Partnership for a New Generation of Vehicles (PNGV), an affordable, advanced automotive piston-engine technology for application in emission-compliant passenger cars with fuel economy of 80 miles per gallon (mpg). Specific performance and cost targets are listed in Table 1 for 2002 and 2004, along with tentative targets for 2007 [(1)].

Table 1 - Technical Targets for 80-mpg PNGV Vehicle

Characteristics	***2002***	***2004***	***2007***
Best brake thermal efficiency[a] (%)	44	45	46
Best full load thermal efficiency[b] (%)	42	43	44
Displacement power density[c] (kW/L)	42	45	47
Specific power (W/kg)	590	625	650
Durability (hours)	>3500	>5000	>5000
Emission control cost[d] ($/kW)	5	4	3
Exhaust Emission Control Device Volume (L/L)[e]	3	2	1.5
Engine Cost[d,f] ($/kW)	30	30	30
No_x Emissions[g] (g/mile)	0.2	0.07	0.03
PM Emissions[g] (g/mile)	0.02	0.01	0.01
Fuel Economy Penalty Due to Emission Control System (%)	<5	<5	<5

[a]Ratio of mechanical power out to fuel lower heating value in.
[b]Ratio of mechanical power out to fuel lower heating value in at peak power.
[c]This is the peak power output divided by the volumetric displacement of the engine.
[d]High volume production: 500,000 units per year.
[e]Volume of emission control system (in liters) per liter of engine displacement.
[f]Constant outyear cost targets reflect the objective of maintaining engine system cost while increasing engine complexity.
[g]Full useful life emissions using advanced petroleum-based fuels as measured over the FTP as used for certification in those years.

Achieving these very ambitious goals will require several simultaneous developments. The fuel-economy improvements will require optimizing the vehicle design in terms of reduced weight and improved aerodynamics, plus modification to the fuel system to optimize combustion. Reducing the emissions will also require changes to the fuel system to minimize engine-out emissions, plus catalysts and/or filters to further clean the exhaust.

Direct injection almost certainly will be needed for fuel efficiency. For passenger cars, sport utility vehicles, and light trucks, there are two options: CIDI and SIDI. CIDI engines are inherently more fuel-efficient than are SIDI engines, but CIDI engines produce larger quantities of nitrogen oxides (NO_x) and particulate matter (PM). Reducing those two pollutants to acceptable levels will require significant technical advances in fuel-system design and after-treatment technology. Since most after-treatment systems are extremely sensitive to sulfur contamination, reduced-sulfur fuels will probably also be essential. Some of the approaches being considered to meet near-term (2005) regulations in Europe are listed in Figure 1 [(2)].

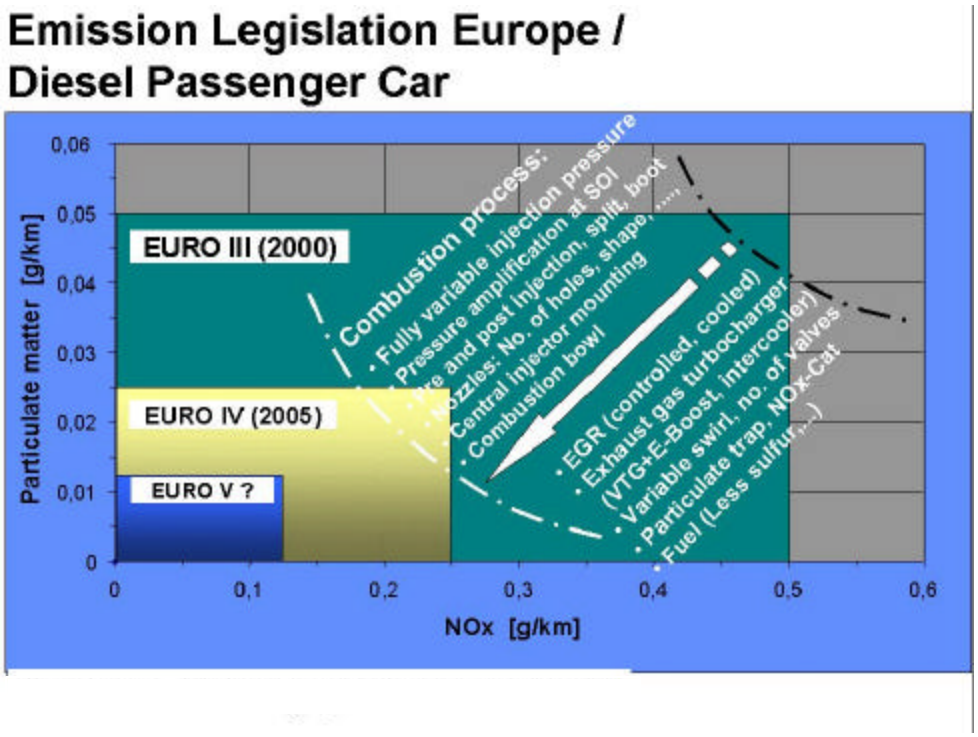


Figure 1. Approaches to Meet Near-Term Regulations in Europe

Another, although nontechnical, problem with adopting CIDI engines is the negative perception of diesel engines held by many North American customers. Although previous problems with odor, smoke, and noise have been solved, market share growth of diesel engines in North America is much slower than in most other parts of the world. Furthermore, the initial cost of a diesel engine is higher than that of a conventional gasoline engine. One also needs to realize that even if CIDI technology completely replaced SIDI, refineries would still have gasoline as a byproduct that would need an outlet in the consumer market. For this reason it is nearly impossible to have 100% CIDI market share.

Even though spark-ignited (gasoline) engines are less efficient than diesel engines and may never be able to achieve 80 mpg, marketplace demands probably will keep gasoline engines in a significant fraction of vehicles for many years. In addition to the limited gain in fuel efficiency that is possible with SIDI engines, other barriers to their use include durability and engine deposits. Also, an SIDI fuel system costs about 50% more than a port fuel-injection system.

OHVT

Specific OHVT goals for trucks in 2004 are as follows [3]:

- Heavy (Class 7-8) Trucks: Develop the enabling technologies needed to achieve a fuel efficiency of at least 10 mpg (at 65 mph) and meet emissions standards prevailing in 2004, using petroleum-based diesel fuel.

- Medium (Class 3-6) Trucks: Develop and demonstrate commercially viable vehicles that achieve, in an urban driving cycle, at least double the fuel economy of comparable 1999 vehicles and reduce criteria pollutant emissions to a level at least 30% below EPA standards prevailing in 2004.

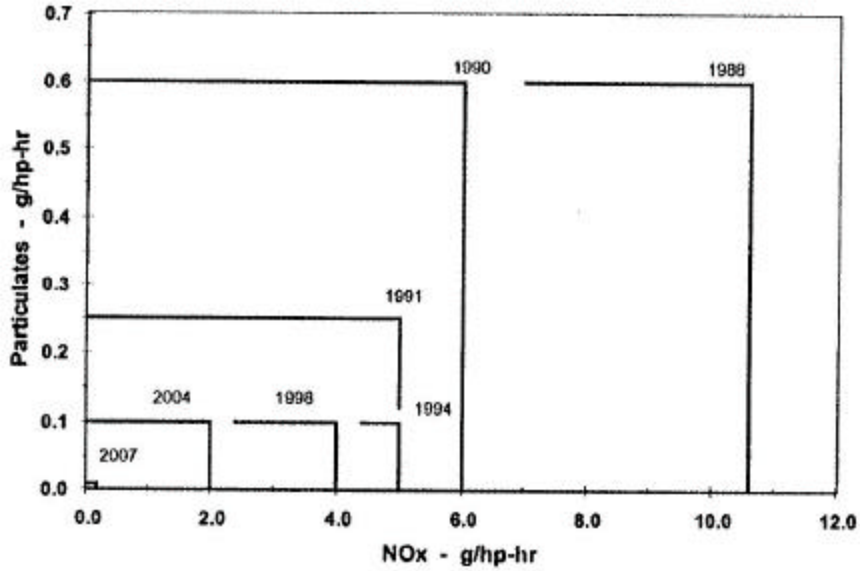
- Light (Class 1-2) Trucks: Develop the enabling technologies for clean diesel engines to be competitive with (and at least 35% more fuel efficient than) equivalent gasoline engines for light trucks, while meeting Federal and state emissions standards prevailing in 2004.

Figure 2a shows the considerable improvement that the industry has already made for heavy trucks since 1988, and the goals for 2004, which represent a 50% reduction in NO_x from current levels.[4] Despite those tremendous advances, the proposed goals in Figure 2b for 2007 (which is about the earliest that a new research project would result in a commercial application) represent an additional 90% reduction in both NO_x and PM. The proposed 2007 goals are clearly beyond the capabilities of current technology.

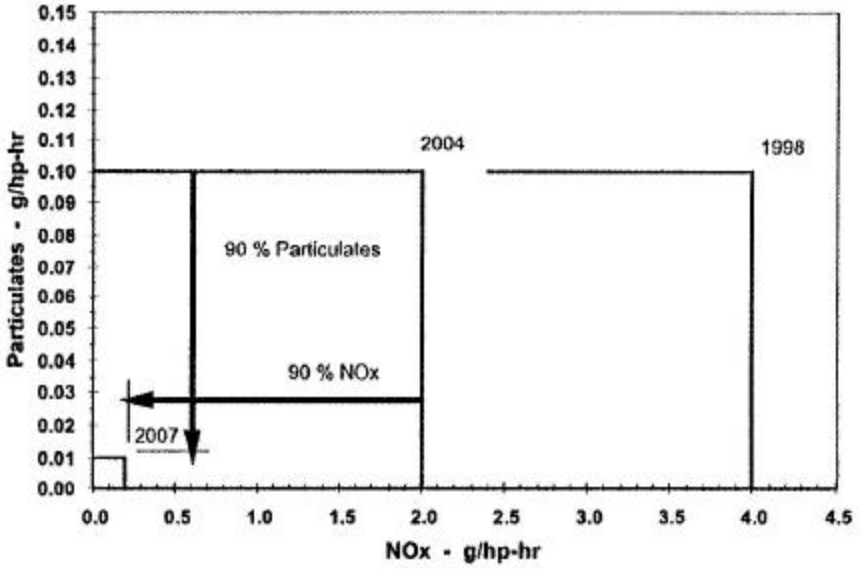
What makes those goals particularly challenging is that most techniques for reducing NO_x tend to increase PM, and vice versa. For example, retarding the timing and decreasing the combustion temperature decrease NO_x, but both increase PM.

As with the automotive goals, meeting the future heavy-truck goals will require a combination of improvements to the fuel system and after-treatment technologies. However, for heavy trucks, SI engines are not considered a practical alternative, so only CIDI engines will be considered for that application.

This report and the workshop on which it is based focused only on fuel systems. After-treatment technologies and modification to fuel are considered only as they have an effect on requirements for the fuel system. Those subjects, along with aerodynamic drag and parasitic energy losses, have been covered in other workshops.[5]



a. Historical progression of diesel emission regulations



b. Details of emission regulations in recent years

Figure 2. Emissions Targets for Heavy Trucks

DESIRED FEATURES OF FUEL INJECTION SYSTEMS

CIDI

Although the specific design details of fuel systems will be different for heavy vehicles and light vehicles, most of the desired features are generally common to all CIDI engines. Therefore, they will be treated together in this section.

[Please note the terminology 'cf', 'sf', 'cb', and 'sb' throughout the text that follows is used to correlate the various desired features/targets with their associated technical barriers and the required research to overcome those barriers. Each feature and each barrier have been assigned a two-letter designation, where the first letter denotes CIDI (c) or SIDI (s), and the second letter denotes feature (f) or barrier (b). These designations are used in Tables 2 through 26.]

Rate Shaping and Multiple Injections (cf-1). Very complex patterns of injection rate versus crank angle (CA) may be necessary to achieve the desired results in terms of fuel efficiency and low emissions. Figure 3 illustrates a number of possibilities for timing of various injections.[(6)] An early pilot injection, approximately 60° before top dead center (TDC), could be used for control of noise and emissions, as could a close pilot injection of a few degrees before TDC. It is important that the small amount of fuel (0.5 to 2 mm^3 per shot) in the pilot injection be stable and repeatable. A close post-injection, approximately 30° past TDC, can be used to control NO_x and soot. A late post-injection of 50° to 60° past TDC can be used to create a rich mixture (lambda less than 0.8) for regenerating the NO_x trap. A very late post-injection of about 120° past TDC could be used for hydrocarbon enrichment for after treatment. Post-injection also can be used to increase the exhaust temperature for soot reduction and regenerate the diesel particulate filter.

The use of multiple injections might require additional measures to prevent wear and fatigue, because moving components in the fuel system would be exposed to greater numbers of cycles.

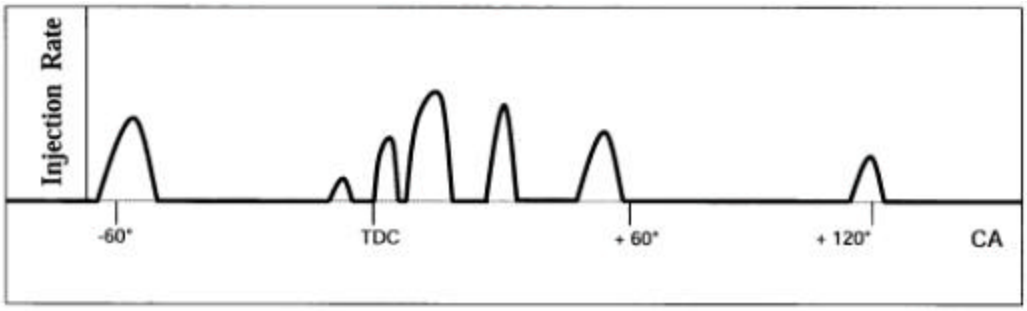


Figure 3. Schematic Diagram of Possible Injections Timings for Various Purposes

The shape of the main injection also is important (see Figure 4). A slow start of injection (SOI) minimizes the quantity of fuel injected during the ignition delay, thereby reducing noise by slowing the combustion pressure rise and reducing NO_x by lowering the peak combustion temperature. Conversely, a fast SOI shortens the injection duration, which improves full-load fuel efficiency and increases the initial injection, reducing smoke by improving atomization and mixing. Thus, flexibility in adapting the shape of the injection pulse to specific needs is important. In some cases, as illustrated in Figure 3, the main injection might even be split into two or more pulses.

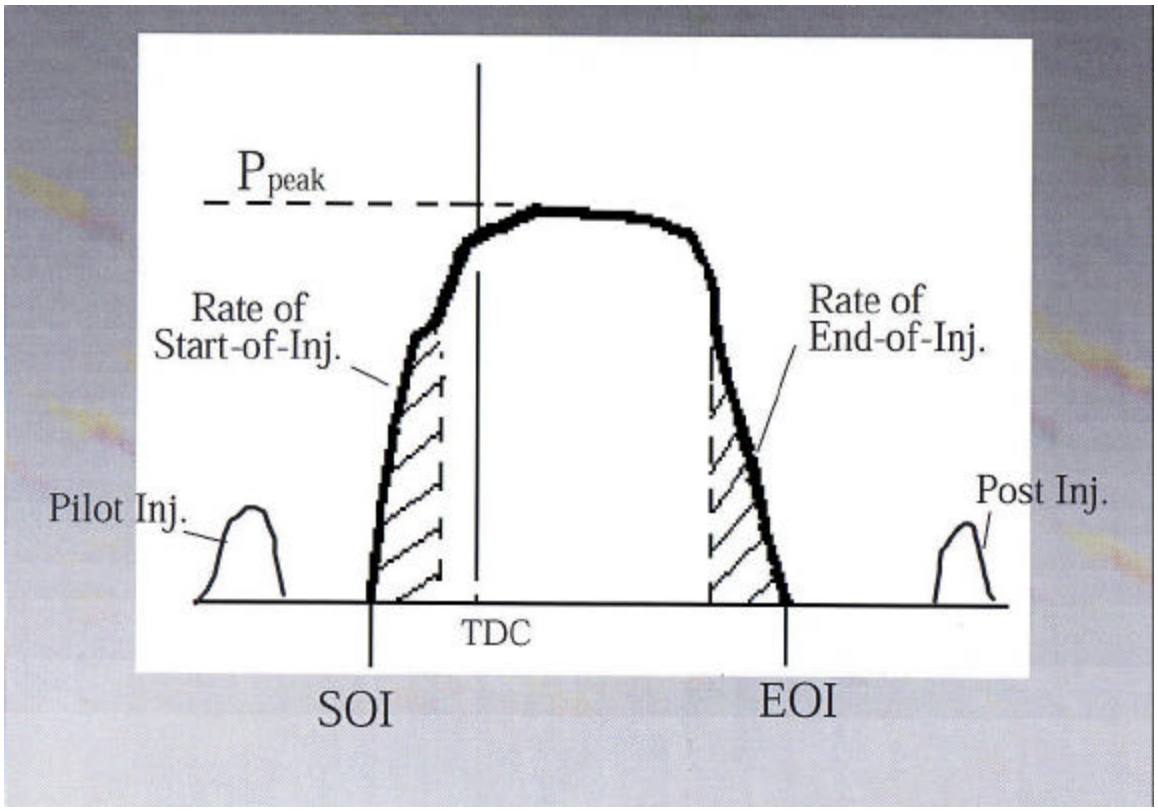


Figure 4. Shape of Split Injection Pulse[7]

A rapid end of injection (EOI) is desired to minimize the amount of poorly atomized fuel that is injected into the oxygen-depleted combustion chamber. That would reduce the particulates and unburned hydrocarbon emissions.

Higher Pressure (cf-2). There has been a continuing trend in the industry toward higher injection pressures, which enable the duration of the injection to be shortened, thus improving fuel efficiency and enabling the engine to be operated at higher speeds. High pressures also improve fuel atomization and mixture preparation, which reduce requirements for charge swirl. The improved atomization also reduces particulate formation by increasing the smoke-limited power output and increasing the tolerance to higher rates of exhaust gas recirculation (EGR) and injection-timing retardation. The disadvantages of higher pressures are that they tend to increase NO_x emissions, noise, and

vibration, along with power requirements for the fuel pump, and they impose much more severe tribological conditions for fuel system components.

Estimates for the desired maximum pressure generally are in the range of 2000 to 2500 bar, with some vendors considering pressures up to 3000 bar.

Variable Pressure (cf-3). It will also be important to vary the pressure within a single firing cycle. For early pilot injection and late post injection, pressures of 400 to 500 bar are desired for low penetration. However, high pressures are needed near TDC for efficient diesel combustion.

Smaller Spray Holes (cf-4). Production of soot can be reduced by reducing the size of the injector spray holes.

Variable-Orifice Geometry (cf-5). Different nozzle configurations are needed for low and high in-cylinder densities. Conical nozzles also would have advantages.

Closed-Loop Control (cf-6). A closed-loop control system is desired to compensate for manufacturing variability and deterioration of components. It should include a sensor built into the injector to measure cylinder pressure. Also needed are sensors for injection pressure, needle position, and fuel quality.

Ability to Inject Lube Oil (cf-7). The ability to inject used lube oil would be helpful for reducing hazardous wastes.

Durability and Reliability (cf-8). The fuel system ideally should be service-free for the overhaul life of the engine.

Low Cost (cf-9). The cost of the system should not be significantly more than that of current systems.

The desired features for future CIDI fuel systems are summarized in Table 2.

Table 2 - Summary of Desired Features for Future CIDI Fuel Injection Systems (denoted as cf-x)

Rate Shaping and Multiple Injections (cf-1)
Higher Pressure (cf-2)
Variable Pressure (cf-3)
Smaller Spray Holes (cf-4)
Variable-Orifice Geometry (cf-5)
Closed-Loop Control (cf-6)
Ability to Inject Lube Oil (cf-7)
Durability and Reliability (cf-8)
Low Cost (cf-9)

SIDI

The desired features of an SIDI fuel system are, in many ways, similar to those of a CIDI fuel system. They include the following:

Higher Pressure (sf-1). Although SIDI fuel systems operate at considerably lower pressures than do CIDI systems, pressure has a significant effect on droplet size, especially at relatively low pressures (see Figure 5). Some people believe that additional benefits would be obtained by increasing the pressure to about 200 bar. Further research is needed to understand the effects of pressure at those higher levels

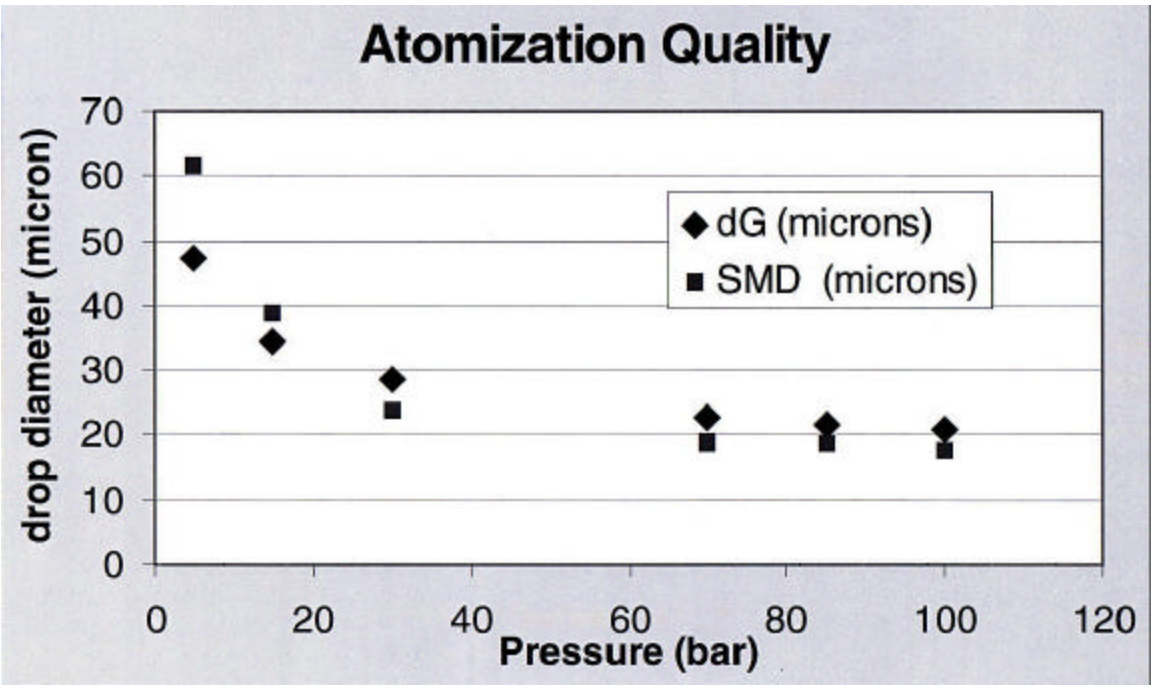


Figure 5. Effect of Pressure on Atomization Quality for SIDI Engines;[8] dG = Calculations from 1-dimensional model, SMD = Experimental measurements.

Better Atomization (sf-2). Modification to the nozzle design also may be required to achieve better atomization.

Control of Spray Penetration (sf-3). To achieve fuel economy at least 15% better than that from port injection (compared with the current level of less than 10%), it will be necessary to develop a robust spray-guided system (see Figure 6) and reduce the dependence on wall-guided systems. A spray-guided system also has the potential for about a 40% reduction in exhaust hydrocarbons compared to a wall-guided system.

There is a general consensus that spray-guided combustion systems offer the highest potential for reducing fuel consumption by extending the global lean limit and by

increasing the amount of charge stratification. In addition to developments in injection systems, ignition systems also need improvements. Since the ignition source (spark plug) is typically located directly in the spray of this type of combustion system, the spark plug is subject to an extremely adverse operating environment. The spark plug can experience extreme thermal shock, when exposed to cool, evaporating fuel. The spark plug also is subject to fouling during cold operation before the plug has a chance to warm up to its normal operating temperature. Research in ignition system materials (precious metals), energy supplies, and control systems is needed to develop ignition systems that are robust enough to take advantage of the new fuel systems for spray guided combustion concepts.

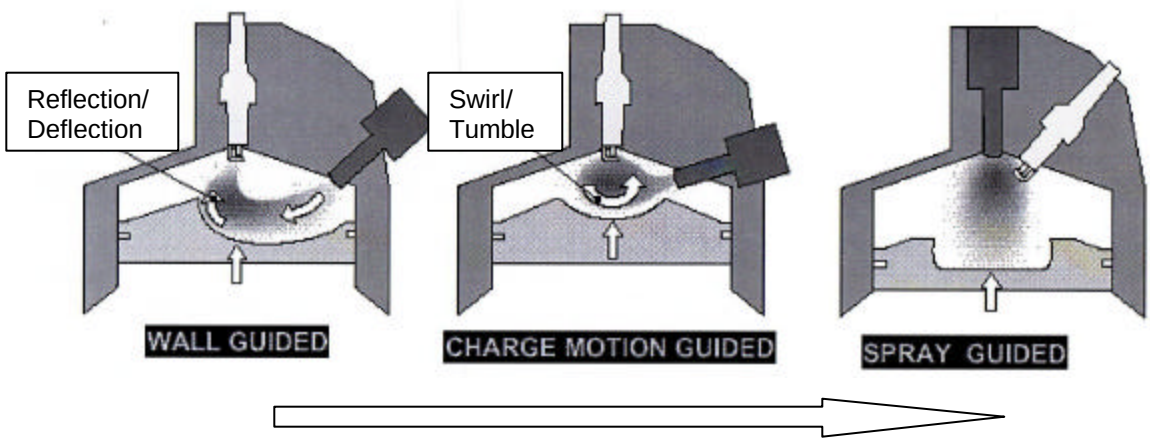


Figure 6. Future Trend in Combustion System Design for SIDI Engines [8]

Operating Flexibility (sf-4). To optimize combustion for various operating conditions, it is desirable to control the timing and shape of the injection pulse and even to have split injection.

Low Cost (sf-5). Current designs and manufacturing techniques result in a high ratio of costs to benefits of SIDI fuel systems. New, lower-cost manufacturing technologies are needed to make SIDI engines cost-effective.

The desired features for future SIDI fuel systems are summarized in Table 3.

Table 3 - Summary of Desired Features for Future SIDI Fuel Injection Systems

Higher Pressure (sf-1)
Better Atomization (sf-2)
Control of Spray Penetration (sf-3)
Operating Flexibility (sf-4)
Lower Cost (sf-5)

TECHNICAL BARRIERS TO FUEL INJECTION SYSTEM IMPROVEMENTS

CIDI

Listed below are a number of technical barriers to achieving the desired features of future CIDI fuel systems.

Inadequate Models (cb-1). Design of fuel systems relies heavily on empirical approaches. Current models do not provide enough information about the relationships between spray characteristics and combustion characteristics, including a lack of adequate spray models for inward opening injectors. Even if the desired spray characteristics are known, current models do not provide enough guidance in designing the nozzles.

Manufacturing Technology (cb-2). The move to higher pressures and the need for uniformity between cylinders will require machining tolerances of 0.5 to 5 µm. Current manufacturing technology is not adequate to produce such close tolerances repeatably.

Measurement Techniques (cb-3). The quantities of fuel in pilot, multipulse, and post-injections will be very small, with close tolerances on variability. Current measurement techniques are not accurate enough for quality control.

Speed of Actuators (cb-4). Multiple injections with rate shaping will require extremely rapid actuators. At the same time, actuator movement must be less abrupt to minimize pressure waves and reduce noise. It is clear that solenoid actuators will have to be replaced with piezoelectric actuators, but even the best piezoelectric actuators are not entirely satisfactory.

Sulfur Contamination of After-Treatment Devices (cb-5). Most after-treatment devices are extremely sensitive to contamination from sulfur in fuel. As shown in Figure 7, a NO_x adsorber will lose its effectiveness in a few hours with a low-sulfur (400 ppm) fuel and in less than 150 hr with an ultra-low-sulfur (5 ppm) fuel.[6] Therefore, it will be necessary to develop the production capabilities and delivery infrastructure for very-low-sulfur diesel fuel.

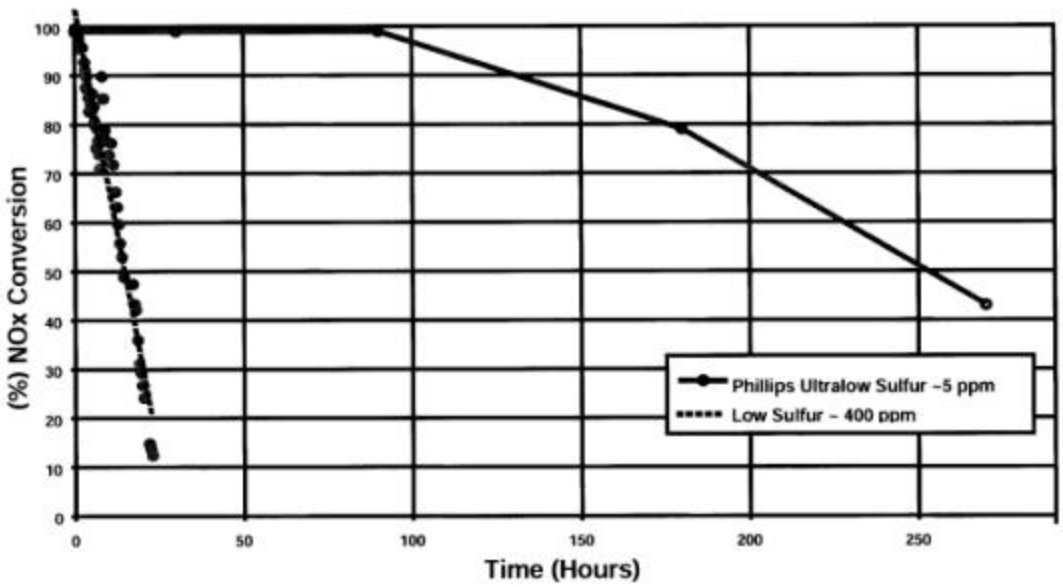


Figure 7. Effect of Fuel Sulfur on Performance of NO_x Adsorber

Seizure and Wear (cb-6). Low-sulfur fuels will have lower lubricity, and that, along with higher pressures and temperatures, will place increasing demands on moving surfaces (see Figure 8). To complicate matters, fuel lubricity can vary considerably from country to country and even from region to region within a single country. A few examples are given in Figure 9, where the wear scar from a ball-on-plate test is shown for three countries (the maximum acceptable wear-scar diameter is 460 µm). In addition, smaller and more precise actuators will require minimal wear to maintain performance and accuracy.

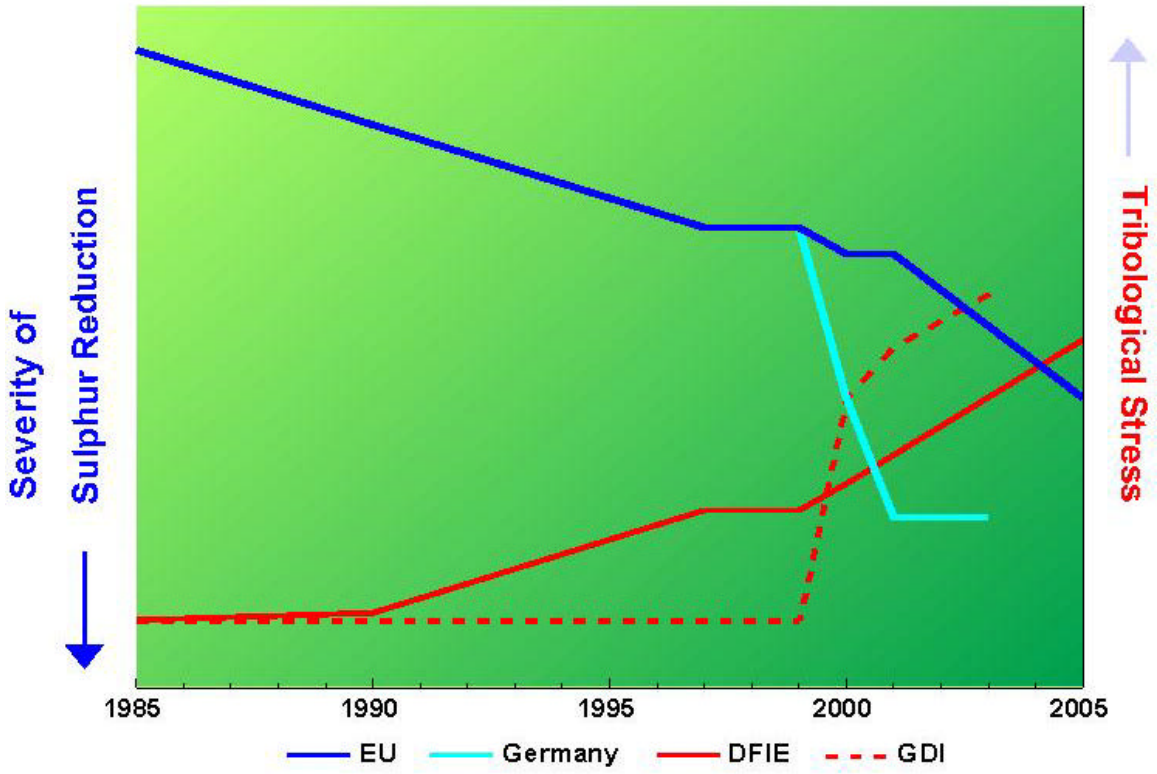


Figure 8. Effect of Low-Sulfur Fuels on Tribological Stress [9]

Structural Integrity (cb-7). Higher pressures, multiple injections, and smaller sizes will place increased demands on fatigue strength of materials. The industry trend toward strand casting and away from ingot casting results in decreased cleanliness, which is deleterious to fatigue strength. Conversely, vacuum-arc-remelted steels, which have much lower inclusion contents, have poor machineability.

In principle, fatigue resistance can be improved by generating compressive residual stresses at critical locations. However, it is currently difficult to predict the level of residual stresses that will be generated by various heat treatments and secondary operations.

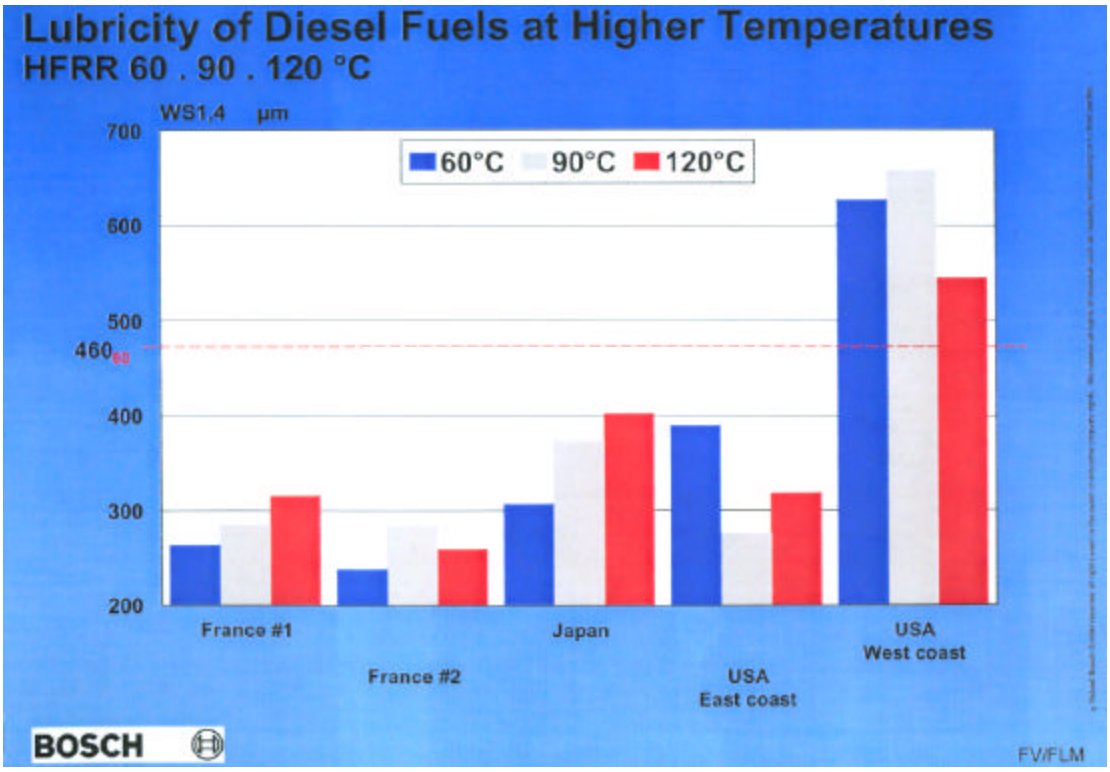


Figure 9. Variations in Rate of Wear Due to Differences in Fuel Lubricity in Various Regions [9]

Lack of Sensors to Measure Critical Parameters (cb-8). Any real-time feedback control system will require the development of low-cost and reliable sensors to measure critical fuel system parameters related to quality of combustion.

Unknown Future Requirements (cb-9). In addition to limitations of combustion and spray models to predict design requirements for fuel systems, other uncertainties about future regulation, after-treatment technologies, and fuels create large uncertainties about specific fuel-system requirements.

Deposit Formation (cb-10). Deposit formation in diesel injection systems were at one time a major concern that was resolved by proper formulation of the fuels, and injector design. It now appears that deposit formation is again becoming an issue with new injector designs where the deposit formation plugs high-taper orifices resulting in decreased flow.

These technical barriers are related to the desired improvements for future CIDI fuel systems in Table 4.

Table 4 - Technical Barriers to Improvements for CIDI Fuel Injection Systems

Barrier	Desired Improvement (from Table 2)
Inadequate Models (cb-1)	cf-1, 2, 3, 4, 5, 6, 7, 9
Manufacturing Technology (cb-2)	cf-1, 2, 3, 4, 5, 8, 9
Measurement Techniques (cb-3)	cf-1, 4, 5, 6
Speed of Actuators (cb-4)	cf-1, 3, 6, 8, 9
Sulfur Contamination of After-Treatment Devices (cb-5)	cf-2, 7, 8, 9
Seizure and Wear (cb-6)	cf-1, 2, 4, 5, 6, 7, 8, 9
Structural Integrity (cb-7)	cf-1, 2, 4, 6, 8, 9
Lack of Sensors to Measure Critical Parameters (cb-8)	cf-1, 2, 3, 5, 9
Unknown Future Requirements (cb-9)	cf-1, 2, 3, 4, 5, 6, 8, 9
Deposit Formation (cb-10)	cf-1, 2, 3, 4, 5, 6, 8

SIDI

The following are technical barriers to achieving the desired features in future SIDI fuel systems.

Inadequate Models (sb-1). The elements of a complete model for an SIDI fuel system are illustrated in Figure 10. The primary gaps in the current models concern cavitation and atomization near the tip of the injector and the nature of the flow in the dense region immediately below the injector. Modeling of cavitation will require an equation of state for the fuel, a very small mesh size, and short time intervals.

Fuel Injector Deposits (sb-2). Problems with deposits in the fuel systems of SIDI engines have been more serious than originally anticipated. The seriousness of the problem varies from one engine type to another and depends upon a variety of factors, the most important of which is surface temperature. Other factors include the chemistry of the fuel and lubricant and the nature of the metal surface. Increasing use of EGR exacerbates the problem.

Deposits can interfere with the flow and atomization of the fuel and thus can reduce fuel efficiency and increase emissions.

Potential methods for controlling deposits include fuel additives, which must be specially formulated for SIDI engines, material/design changes to move the surface temperatures out of critical ranges for deposit formation, or coatings to prevent adherence of the deposits to surfaces.

Another barrier for SIDI engines is intake system deposits. These deposits can form anywhere in the intake manifold or intake ports and are probably related to EGR (Exhaust Gas Recirculation) or crankcase ventilation gases. These deposits first became an issue when engines converted from carburetors to multipoint fuel injection systems and gasoline vapors were no longer available to act as deposit cleaning solvents. Deposits formed on the intake valve adversely affected engine air flow and performance. This phenomenon led to the standard "BMW" deposit tests and a new generation of fuel detergent additives. With fuel completely removed from the intake system in SIDI engines and with much higher EGR rates becoming typical, these deposits are now becoming an issue again. Since the fuel can no longer serve as a detergent carrier, new methods for maintaining intake system cleanliness must be developed. For example, coatings for intake components or EGR filters might be the subject of research projects.

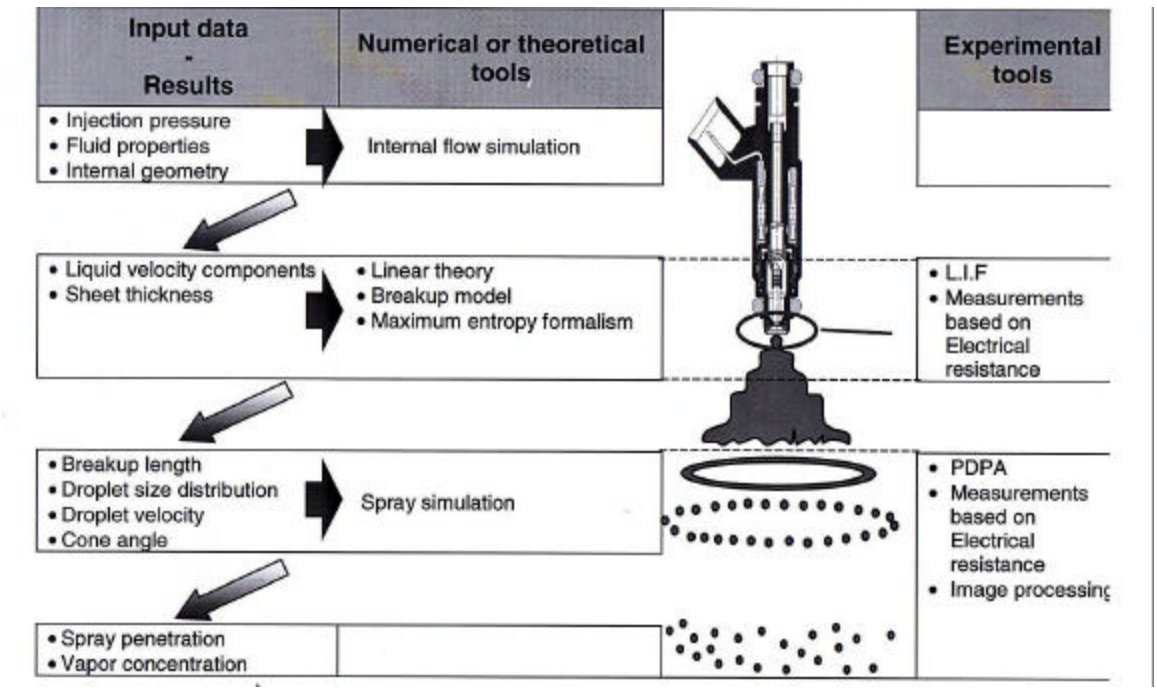


Figure 10. Elements of Model for SIDI Fuel System [8]

Unburned Hydrocarbon and Soot Emissions (sb-3). Current levels are too high to meet future requirements.

Parasitic Losses (sb-4). Energy requirements for the high-pressure pump can consume half or more of the theoretical (19%) fuel-economy gain.

Durability of After-Treatment Devices (sb-5). After-treatment devices for removal of NO_x lose their effectiveness very quickly if they are exposed to sulfur. Therefore, it will probably be necessary to develop an infrastructure for providing a very-low-sulfur fuel in the future.

Friction, Wear, and Corrosion (sb-6). Low-sulfur fuels or alternative fuels, which will probably be necessary to protect the after-treatment systems, will have lower lubricity than do current fuels and therefore may cause problems with increased friction and wear of engine components. In addition, the higher injection pressures proposed for SIDI fuel systems, coupled with the low lubricity of gasoline (compared to that of diesel fuel), will seriously degrade the tribological environment for critical fuel-system components. If additives are used to restore lubricity, their effects on corrosivity of the fuel will have to be determined.

Lack of Real-Time Feedback Control System (sb-7). Ability to optimize performance for varying speed and power requirements will require new sensors to detect critical aspects of engine performance, such as misfire, and rapid actuators to properly shape and adjust the fuel-injection pulses.

Limited Measurement Capabilities (sb-8). The ability to make further improvements to the fuel system is limited by a lack of adequate techniques for measuring the behavior of the fuel in the combustion chamber. Important characteristics include mass flow versus time in the pulse, precise measurement of air-core and sheet thickness, simultaneous measurement of liquid and vapor velocities, and droplet temperature.

The technical barriers are related to the desired improvements for future SIDI fuel systems in Table 5.

Table 5 - Technical Barriers to Improvements for SIDI Fuel Injection Systems

Barriers	Desired Improvement (from Table 3)
Inadequate Models (sb-1)	sf-1,2,3,4,5
Fuel Injector Deposits (sb-2)	sf-2, 3, 4, 5
Unburned Hydrocarbon and Soot Emissions (sb-3)	sf-2, 3
Parasitic Losses (sb-4)	sf-1, 2, 5
Durability of After-Treatment Devices (sb-5)	sf-1, 2
Friction, Wear, and Corrosion (sb-6)	sf-1, 2
Lack of Real-Time Feedback Control System (sb-7)	sf-4, 2, 1
Limited Measurement Capabilities (sb-8)	sf-2,3

RESEARCH NEEDS

This section summarizes the research needs related to direct-injection fuel systems, as they were defined in the breakout sessions at the workshop.

Light-Duty CIDI

The research needs related to light-duty CIDI fuel systems were grouped within the following eight areas, which are listed in order of priority:

1. Spray and Combustion Fundamentals
2. Control Strategies
3. Alternative Fuel-Injection Methods
4. Advanced Design Concepts
5. Fuels and Tribology
6. Modeling/Simulation
7. Advanced Diagnostics and Instrumentation
8. Manufacturing and Materials

Specific research topics were grouped within those eight areas, but several topics fell within more than one area. There was considerable overlap among Areas 1, 2, and 4. The specific recommended research topics for light-duty CIDI fuel systems are listed in Table 6-13, along with references to other areas in which they fit and barriers and desired features to which they apply.

Table 6 - Recommended Research Topics for Light-Duty CIDI Fuel Injection Systems in Area 1, Spray & Combustion Fundamentals

Research Topics	Other Areas of Relevance	Related Barriers (from Table 4)	Related Desired Features (from Table 2)
Injection rate control	2, 4	cb-4,1	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Higher injection pressure	2, 4	cb-1, 7, 6	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Investigate combustion systems to take advantage of the increased flexibility in fuel injection systems		cb-1, 4	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Determine which factors control combustion: droplets or kinetic energy/entrainment	6	cb-1	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Determine conditions leading to injector plugging in high-taper orifices	5	cb-1, 2	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Compare design sensitivities and cost-benefit of components for engine-out vs. aftertreatment-out measurement	2, 4	cb-1, 8	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Develop hybrid-combustion systems combining the benefits of the conventional cycle with the emission benefits of HCCI		cb-1	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Establish database of the relationships between the configuration of the injector (orifice geometry, k-factor) and the resulting spray and combustion parameters and deposit formation	5	cb-1	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Develop a proportional-control, flexible, fuel-delivery system and use the flexibility of this system to bring combustion close to ideal P-V engine cycle	2, 3, 4	cb-1, 3, 4, 7	cf-1, 2, 3, 4, 5, 6, 7, 8, 9

Table 7 - Recommended Research Topics for Light-Duty CIDI Fuel Injection Systems in Area 2, Control Strategies

Research Topics	Other Areas of Relevance	Related Barriers (from Table 4)	Related Desired Features (from Table 2)
Injection rate control	1, 4	cb-4, 1, 8	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Increased injection pressure	1, 4	cb-1, 7, 6, 8	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Closed-loop control of injection, to compensate for injector differences; combine better sensors and intelligent algorithms to characterize combustion for feedback for closed-loop control		cb-1, 3, 8	cf-1, 2, 3, 4, 5, 6, 7, 9
Compare design sensitivities and cost-benefit of components for engine-out vs. aftertreatment-out measurement	1, 4	cb-1, 9	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Develop a proportional-control, flexible, fuel-delivery system and use the flexibility of this system to bring combustion close to ideal P-V engine cycle	1, 4	cb-1, 3, 4, 7	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Examine role of EGR used in conjunction with multiple injections		cb-1	cf-1, 2, 3, 4, 5, 6, 7, 9

Table 8 - Recommended Research Topics for Light-Duty CIDI Fuel Injection Systems in Area 3, Alternative Injection Methods

Research Topics	Other Areas of Relevance	Related Barriers (from Table 4)	Related Desired Features (from Table 2)
Explore alternative ways to achieve better atomization (low-pressure injection systems)		cb-1, 7, 2	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Investigate alternative fuel injection methods, e.g., "electrothermal injection"		cb-1, 7, 2	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Develop a proportional-control, flexible, fuel-delivery system, and use the flexibility of this system to bring combustion close to ideal P-V engine cycle	1, 2, 3, 4	cb-1, 3, 4, 7	cf-1, 2, 3, 4, 5, 6, 7, 8, 9

Table 9 - Recommended Research Topics for Light-Duty CIDI Fuel Injection Systems in Area 4, Advanced Design Concepts

Research Topics	Other Areas of Relevance	Related Barriers (from Table 4)	Related Desired Features (from Table 2)
Injection rate control	1, 2	cb-4, 1	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Increased injection pressure	1, 2	cb-1, 7, 6	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Evaluate variable orifice technology; gather available ideas, select one, build prototype, evaluate prototype, develop computer simulations		cb-2, 1	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Compare design sensitivities and cost-benefit of components for engine-out vs. after-treatment-out measurement	1, 2	cb-1, 8	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Develop a proportional-control, flexible, fuel-delivery system, and use the flexibility of this system to bring combustion close to ideal P-V engine cycle	1, 2, 3	cb-1, 3, 4, 7	cf-1, 2, 3, 4, 5, 6, 7, 8, 9

Table 10 - Recommended Research Topics for Light-Duty CIDI Fuel Injection Systems in Area 5, Fuels & Tribology

Research Topics	Other Areas of Relevance	Related Barriers (from Table 4)	Related Desired Features (from Table 2)
Determine conditions leading to injector plugging in high-taper orifices	1	cb-1, 2	cf-1, 2, 3, 4, 5, 6, 7, 9
Study the effects of fuel properties on durability of injection systems		cb-6, 7	cf-1, 2, 4, 5, 6, 7, 8, 9
Establish database of the relationships between the configuration of the injector tip (orifice geometry, k-factor) and the resulting spray and combustion parameters and deposit formation	1	cb-1	cf-1, 2, 3, 4, 5, 6, 7, 9

Table 11 - Recommended Research Topics for Light-Duty CIDI Fuel Injection Systems in Area 6, Modeling/Simulation

Research Topics	Other Areas of Relevance	Related Barriers (from Table 4)	Related Desired Features (from Table 2)
Determine which factor controls combustion; droplets or kinetic energy/entrainment	1	cb-1	cf-1, 2, 3, 4, 5, 6, 7, 9
Develop improved spray models		cb-1	cf-1, 2, 3, 4, 5, 6, 7, 9
Develop models of multiphase spray, e.g., to study the effect of small orifices on the combustion system		cb-1	cf-1, 2, 3, 4, 5, 6, 7, 9
Model spray formation in noncircular orifices (with subtasks to verify model)		cb-1, 3	cf-1, 2, 3, 4, 5, 6, 7, 9

Table 12 - Recommended Research Topic for Light-Duty CIDI Fuel Injection Systems in Area 7, Advanced Diagnostics & Instrumentation

Research Topic	Other Areas of Relevance	Related Barriers (from Table 4)	Related Desired Features (from Table 2)
Develop new or improved devices to measure performance of injector system (instrumentation development supports manufacturing, development, modeling)		cb-3, 1, 2	cf-1, 2, 3, 4, 5, 6, 7, 8, 9

Table 13 - Recommended Research Topic for Light-Duty CIDI Fuel Injection Systems in Area 8, Manufacturing & Materials

Research Topic	Other Areas of Relevance	Related Barriers (from Table 4)	Related Desired Features (from Table 2)
Explore use of high-strength materials and advanced manufacturing techniques to miniaturize nozzles, e.g., smaller guides and nozzles, thinner walls. Related to the need for characterization devices.		cb-7, 2, 3	cf-1, 2, 3, 4, 5, 6, 8, 9

SIDI

The research needs related to SIDI fuel systems were grouped within the following eight areas, listed in order of priority:

1. Injection Design
2. Combustion
3. Deposits
4. Modeling
5. Fuels
6. Materials
7. Parasitics
8. System Integration

It also was noted that considerable research will be needed on after-treatment technologies, but that subject is outside the scope of this report.

The recommended research topics for future SIDI fuel systems are listed in Tables 14-21, each table referring to one of the above mentioned areas of interest. The tables also list the technical barriers and desired features associated with each research topic.

Table 14 - Recommended Research Topics for SIDI Fuel Injection Systems in Area 1. Injector Design

Research Topics	Related Barriers (from Table 5)	Related Desired Features (from Table 3)
Investigate various techniques for atomizing the fuel, including air assist, direct mixture injection, and electrostatics	sb-1, 3	sf-1, 2, 3, 4, 5
Develop cost-effective actuators based upon piezoelectric or magnetostrictive materials	sb-7	sf-4, 2, 1
Develop a cost-effective variable-orifice injector	sb-7	sf-4, 2, 9, 1
Investigate the feasibility of using rate shaping and other diesel-like injection strategies. Consider how to implement, possible benefits, and potential problems such as wear or fatigue due to additional contacts per cycle.	sb-1, 7	sf-1, 2, 3, 4, 5
Develop advanced spray-measurement techniques for mass flow vs. time in the pulse, air-core and sheet thickness, liquid and vapor velocity, and droplet temperature	sb-8	sf-2,3

Table 15 - Recommended Research Topics for SIDI Fuel Injection Systems in Area 2. Combustion

Research Topics	Related Barriers (from Table 5)	Related Desired Features (from Table 3)
Develop a better understanding of the factors that control production of unburned hydrocarbons, NO_x, and particulates	sb-3, 1	sf-1, 2, 3, 4, 5
Develop a system to detect misfire, to be used in real-time (in-cycle) feedback for control	sb-7	sf-4, 2, 1
Develop fast actuators to allow for rate shaping	sb-7	sf-4, 2, 1
Determine how to optimize the system for U.S. cycles rather than European driving patterns	sb-1, 3, 7	sf-1, 2, 3, 4, 5
Application of SIDI to other advanced combustion technologies such as HCCI	sb-1	sf-2

Table 16 - Recommended Research Topics for SIDI Fuel Injection Systems in Area 3. Deposits

Research Topics	Related Barriers (from Table 5)	Related Desired Features (from Table 3)
Develop a standardized test for qualifying resistance of a system to damage from deposits	sb-2	sf-2, 3, 4, 5
Develop a fundamental understanding of the factors that affect the formation of deposits and the composition and structure of the deposits	sb-2	sf-2, 3, 4, 5
Develop fuel additive/coatings to prevent deposits	sb-2, 5, 6	sf-1, 2, 3, 4, 5

Table 17 - Recommended Research Topic for SIDI Fuel Injection Systems in Area 4. Modeling

Research Topic	Related Barriers (from Table 5)	Related Desired Features (from Table 3)
Develop improved models for spray, wall/fuel interactions, and combustion of air/fuel mixtures including spray models for inward opening injectors	sb-1, 3	sf-1, 2, 3, 4, 5
Develop a model for electrostatic atomization based upon charged-particle physics coupled with spray modeling	sb-1	sf-1,2,3,4,5

Table 18 - Recommended Research Topics for SIDI Fuel Injection Systems in Area 5. Fuels

Research Topics	Related Barriers (from Table 5)	Related Desired Features (from Table 3)
Investigate methods for on-board removal of sulfur from fuel	sb-5	sf-1, 2,
Develop additives for control of deposits and improving lubricity	sb-2, 6, 5	sf-1, 2, 3, 4, 5
Investigate biofuels and synthetic fuels	sb-1, 2, 3, 5, 6	sf-1, 2, 3, 4, 5

Table 19 - Recommended Research Topics for SIDI Fuel Injection Systems in Area 6. Materials

Research Topics	Related Barriers (from Table 5)	Related Desired Features (from Table 3)
Determine the effect of sulfur and additives on fuel lubricity	sb-5, 6	sf-1, 2,
Develop a procedure for quality control of coatings	sb-6, 4	sf-1, 2, 5
Scale up a process for producing diamond-like carbon coatings to reduce cost	sb-6, 4	sf-1, 2, 5
Determine the role of sulfur, fuel additives, and alternative fuels (E85 and M85) on corrosion of fuel-system components	sb-5, 6	sf-1, 2
Investigate various materials in terms of inherent resistance to formation of deposits	sb-2	sf-2, 3, 4, 5

Table 20 - Recommended Research Topic for SIDI Fuel Injection Systems in Area 7. Parasitics

Research Topic	Related Barriers (from Table 5)	Related Desired Features (from Table 3)
Develop ways to reduce the parasitic energy losses in the low-pressure intake pump, high-pressure engine-drive pump, and air pump	sb-4	sf-1, 2, 5

Table 21 - Recommended Research Topics for SIDI Fuel Injection Systems in Area 8. System Integration

Research Topics	Related Barriers (from Table 5)	Related Desired Features (from Table 3)
Investigate stratified and lean-homogeneous air-guided and jet-guided systems	sb-1, 3	sf-1, 2, 3, 4, 5
Investigate stratified and lean-homogeneous wall-guided systems (lower priority)	sb-1, 3	sf-1, 2, 3, 4, 5

Heavy-Duty CIDI

The research needs related to heavy-duty CIDI fuel systems were grouped within five areas:

1. Manufacturing
2. Materials
3. Advanced Concepts
4. Fundamental Understanding
5. Sensors for Real-Time Feedback

The recommended research topics for future heavy-duty CIDI fuel systems are listed in Tables 22-26, each table referring to one of the above areas of interest. The tables also list the technical barriers and desired features that are associated with each research topic. Any models that are developed should be validated with experiments.

Table 22 - Recommended Research Topics for Heavy-Duty CIDI Fuel Injection Systems in Area 1. Manufacturing

Research Topics	Related Barriers (from Table 4)	Related Desired Features (from Table 2)
Develop low-cost, ultra-precision manufacturing processes (grinding, machining, coating) to produce tighter tolerances required by higher pressures	cb-2	cf-1, 2, 3, 4, 5, 8, 9
Develop low-cost methods for producing ultra-small holes down to 40 to 50 µm in diameter to reduce particulate matter through better atomization. Include method to measure and control variability.	cb-2, 3	cf-1, 2, 3, 4, 5, 6, 8, 9

Table 23 - Recommended Research Topics for Heavy-Duty CIDI Fuel Injection Systems in Area 1. Materials

Research Topics	Related Barriers (from Table 4)	Related Desired Features (from Table 2)
Investigate materials with higher fatigue strength, higher moduli, and lower density than current steels	cb-7	cf-1, 2, 4, 6, 8, 9
Develop materials and/or coatings with improved resistance to corrosion, particulate erosion, and cavitation	cb-6, 7	cf-1, 2, 4, 5, 6, 7, 8, 9
Develop improved piezoelectric materials for actuators	cb-4	cf-1, 3, 6, 8, 9
Determine the roles of sulfur and aromatics in fuel lubricity	cb-6	cf-2, 4, 5, 6, 7, 8, 9
Develop improved filters and filter materials	cb-7, 2	cf-1, 2, 3, 4, 5, 6, 8, 9

Table 24 - Recommended Research Topics for Heavy-Duty CIDI Fuel Injection Systems in Area 3. Advanced Concepts

Research Topics	Related Barriers (from Table 4)	Related Desired Features (from Table 2)
Investigate alternatives to higher pressure for improved atomization	cb-7, 6, 1	cf-1, 2, 3, 4, 5,6, 7, 8, 9
Develop a way to produce variable-orifice geometry	cb-2, 7	cf-1, 2, 3, 4, 5, 6, 8, 9
Determine the requirements for fuel systems for novel combustion systems such as homogeneous-change combustion ignition (HCCI)	cb-1	cf-1, 3, 4, 5, 6, 7, 9
Develop an injector for full rate-shape control, including faster injection actuation	cb-2, 1, 4	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Investigate exhaust-pipe fuel injection or fuel reforming for supplying a reductant	cb-5	cf-2, 7, 8, 9
Develop improved solenoids	cb-4, 2	cf-1, 2, 3, 4, 5, 6, 8, 9

Table 25 - Recommended Research Topics for Heavy-Duty CIDI Fuel Injection Systems in Area 4. Fundamental Understanding

Research Topics	Related Barriers (from Table 4)	Related Desired Features (from Table 2)
Develop improved models for atomization and techniques for spray characterization	cb-1	cf-1, 2, 3, 4, 5, 6, 7, 9
Develop a computational fluid dynamics (CFD) model internal to the injector, including structural effects such as wear, cavitation, and fatigue	cb-1, 6, 7	cf-1, 2, 3, 4, 5, 6, 7, 9
Develop a more complete combustion model, including the effects of multiple injection events	cb-1, 4	cf-1, 2, 3, 4, 5, 6, 7, 8, 9
Develop a technique to measure injection rates and quantities from 0.5 mm^3 per stroke up to 500 mm^3 per stroke	cb-1	cf-1, 2, 3, 4, 5, 6, 7, 9
Determine the optimal amount of post-injection as a percentage of full load and the advantages and disadvantages of post-injection for smoke control	cb-1	cf-1, 2, 3, 4, 5, 6, 7, 9

Table 26 - Recommended Research Topics for Heavy-Duty CIDI Fuel Injection Systems in Area 5. Sensors for Real-Time Feedback

Research Topics	Related Barriers (from Table 4)	Related Desired Features (from Table 2)
Develop a low-cost, reliable sensor as part of the injector to measure cylinder pressure for controlling combustion quality	cb-8	cf-6, 1, 2, 3, 5, 9
Develop a needle-position sensor	cb-8	cf-6, 1, 2, 3, 5, 9
Develop a sensor in the injector to measure injection pressure	cb-8	cf-6, 1, 2, 3, 5, 9
Develop a fuel-quality sensor	cb-8, 5	cf-6, 1, 2, 3, 5, 7, 8, 9

DISCUSSION

Although specific design features, and consequently research needs, for heavy-duty CIDI, light-duty CIDI, and SIDI fuel systems are different, there are some common themes among the three types of systems. All three types of systems would benefit from research in the following areas:

- **Modeling and simulation** of spray and combustion to develop an improved fundamental understanding of those phenomena that could lead to novel concepts and designs for fuel injectors.
- **Manufacturing technologies** that would be used for cost-effectively producing ultra-small holes and controlling dimensions with ultra precision.
- **Materials and coating developments** to produce increased resistance to fatigue, wear, and corrosion, which will be needed because of the increased demands due to higher pressures, low-lubricity fuels, rate shaping, multiple injections, and EGR.
- **Sensors and controls** for real-time feedback and for diagnostics
- **Advanced, non-traditional strategies** for fuel injection need to be pursued.

REFERENCES

1. K. C. Howden, Presentation at Workshop on Research Needs Related to CIDI and SIDI Fuel Systems, Feb. 28-March 2, 2001 (see Appendix B).

2. G. Bitlinger, Robert Bosch GmbH.

3. G. Singh, "Combustion and Fuel System Research," Presented at Workshop on Research Needs Related to CIDI and SIDI Fuel Systems, Feb. 28-March 2, 2001 (see Appendix B).

4. G. Donaldson, "The Low Emission Heavy-Duty Diesel Engine," Presented at Diesel Engine TOPTEC: Emission Challenges for the Future, Indianapolis, IN, Sept. 26-27, 2000.

5. U. S. Department of Energy, Office of Transportation Technologies.

6. T. Stover, P. Pierz, and L. Peters, "Heavy Duty Truck Perspectives," Presented at Workshop on Research Needs Related to CIDI and SIDI Fuel Systems, Feb. 28-March 2, 2001 (see Appendix B).

7. S. K. Chen, "CIDI Fuel System R&D Needs---An Automotive OEM Perspective," Presented at Workshop on Research Needs Related to CIDI and SIDI Fuel Systems, Feb. 28-March 2, 2001 (see Appendix B).

8. W. Imoehl, "Research Needs Related to SIDI Fuel Systems," Presented at Workshop on Research Needs Related to CIDI and SIDI Fuel Systems, February 28-March 2, 2001 (see Appendix B).

9. Courtesy of Robert Bosch GmbH.

Appendix A

Workshop Agenda

U.S. DEPARTMENT OF ENERGY WORKSHOP
RESEARCH NEEDS RELATED TO CIDI AND SIDI FUEL SYSTEMS
February 28-March 2, 2001
Argonne National Laboratory
Guest House and APS Conference Center

Wednesday, February 28 -- Guest House

4-6 pm **Registration** -- Lobby

6:30-8:30 pm **Dinner** -- Dining Room

Thursday, March 1 -- APS Conference Center

7:30 am-5 pm **Registration** -- Lobby

7:30 am **Continental Breakfast** -- Gallery

8:30 am **Welcoming Remarks** -- Auditorium
Harvey Drucker, Argonne National Laboratory

8:40 am **Workshop Goals Related to DOE Objectives**
- 8:40 am: Ken Howden, DOE/OAAT (CIDI overview)
- 8:55 am: Rogelio Sullivan, DOE/OAAT (SIDI overview)
- 9:10 am: Gurpreet Singh, DOE/OHVT (CIDI overview)

9:30 am **Automotive OEM Perspectives**
- Kevin Chen, Ford Motor Company

10 am **Break** -- Gallery

10:30 am **Heavy Vehicle OEM Perspectives**
- Lester L. Peters, Cummins Engine Company

11 am **Fuel System Suppliers' Perspectives**
- 11 am: Robert Straub, Siemens Automotive
- 11:30 am: William Imoehl, Siemens Automotive

12 noon **Lunch** -- Gallery

1 pm	**Fuel System Designers' Perspectives** - 1 pm: Dean Tomazic, FEV Engine Technology (CIDI) - 1:30 pm: Stephen Brueckner, AVL Powertain (SIDI)
2 pm	**Fuel Suppliers' Perspective** - Frank Gerry, BP Amoco
2:30 pm	**Instructions for Breakout Sessions** - George Fenske, Argonne National Laboratory
2:40 pm	**Break** -- Gallery
3 pm	**Breakout Sessions** - CIDI light-duty -- Auditorium - CIDI heavy-duty -- E1100 Conference Room - SIDI automotive -- E1200 Conference Room
4:30 pm	**Reception** -- Gallery - Poster Session - Tour of APS
6:30 pm	**Adjourn for the Day**

Friday, March 2 -- APS Conference Center

8 am	**Continental Breakfast** -- Gallery
8:30 am	**Continue CIDI and SIDI Breakout Sessions** - CIDI light-duty -- Auditorium - CIDI heavy-duty -- E1100 Conference Room - SIDI automotive -- E1200 Conference Room
10 am	**Break** -- Gallery
10:20 am	**Continue CIDI and SIDI Breakout Sessions**
11 am	**Breakout Session Reports** -- Auditorium
11:45 am	**Concluding Remarks** - George Fenske, Argonne National Laboratory
12 noon	**Adjourn**

APPENDIX B

Workshop Presentations

APPENDIX C

Workshop Attendees

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