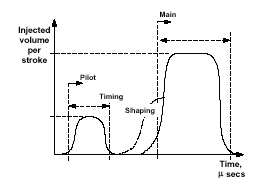
**Final Report: High-Authority Fuel Injection**

**EPA Contract Number:** 68D01031  
**Title:** High-Authority Fuel Injection  
**Investigators:** [Precurio Demo](http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.investigatorInfo/investigator/3591)  
**Small Business:** [**Mide Technology Corporation**](http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.institutionInfo/institution/3698)  
**EPA Contact:**   
**Phase:** I  
**Project Period:** April 1, 2001 through September 1, 2001   
**Project Amount:** $69,983   
**RFA:** [Small Business Innovation Research (SBIR) - Phase I (2001)](http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.rfa/rfa_id/204)   
**Research Category:** [Air Quality and Air Toxics](http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.researchCategory/rc_id/228) , [SBIR - Air Pollution](http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.researchCategory/rc_id/955) , [Small Business Innovation Research (SBIR)](http://cfpub.epa.gov/ncer_abstracts/index.cfm/fuseaction/display.researchCategory/rc_id/107) 

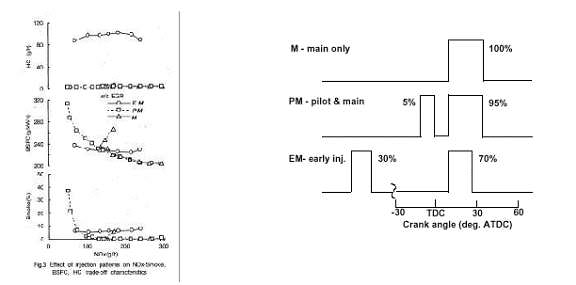
**Description:**

The goal of this Phase I project was to evaluate the feasibility of reducing emissions using a system composed of a piezoelectrically actuated fuel injection system controlled in response to measurements of exhaust constituents. The pursued control algorithm used input from exhaust sensors and a model of the injection and combustion process to identify optimum injection profiles. Generally, the overall goal was, through the use of a high-authority fuel injection (HAFI) actuator, to implement these optimum profiles.

Research has shown that fast, proportional-like control over the injection profile can significantly impact engine emissions and power density. For example, the pilot and main scheme shown in Figure 1 was introduced to lower overall NOx products in the exhaust. Typically, this performance gain comes at the cost of increased smoke and higher specific fuel consumption. Other profiles result in differing smoke, hydrocarbons, specific fuel consumption, and NOx as a function of timing, as shown in Figure 2. However, no injection profile to date has shown simultaneous reduction of all harmful emission constituents. One of the main goals of this work was to identify, analytically and empirically, such an optimum injection profile.



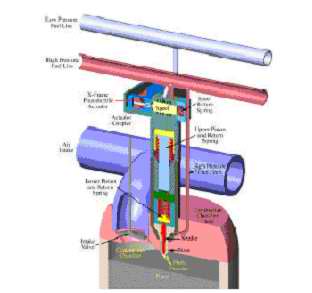
**Figure 1.** Typical diesel injection profile showing pilot and, potentially shaped, main metered quantities.



**Figure 2.**Published results for emissions and fuel consumption as a function of timing and injection profile type (Ref. Paper 981933 or SAE SP-1376).

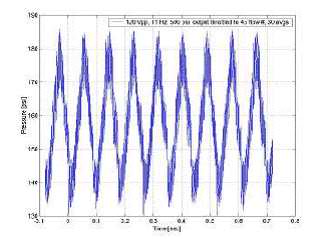
An underlying hypothesis of this work is that the optimum profile shape will not resemble the square profiles of Figures 1 or 2, but will be a trajectory that smoothly varies as a function of crank angle. A characteristic common to most, if not all, existing fuel injection systems is that they are limited in actuation bandwidth. This limitation constrains the shape with which fuel can be injected into the combustion chamber, and thus makes such a smoothly varying injection shape impossible to realize for these technologies. The HAFI system makes use of a high-efficiency, high-bandwidth gained piezoelectric actuator, the X-Frame Actuator, to provide greater authority than competing designs in injecting fuel. Through the use of this actuator, it is hoped to develop an injection system that can provide the authority to implement this ideal trajectory, or any trajectory that provides the performance required by the operator.

Mide Technology Corporation's approach was to use the X-Frame Actuator to drive a spool valve in a manner similar to that shown in Figure 3. This figure shows an X-Frame Actuator driving a fuel injector, capitalizing on the use of the high and low pressure fuel rails to inject fuel into the combustion chamber. Figure 3 gives a cross-sectional view of the entire system to highlight the operation of the injection needle.



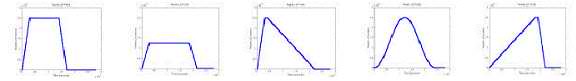
**Figure 3.** Perspective view of cross-section of fuel injection and combustion chamber system (air exhaust not shown).

**Summary/Accomplishments (Outputs/Outcomes):**  
  
System performance requirements have been identified for the actuator and injector. They focus on the eventual needle displacement and sealing forces required. These seem to be consistent between engines, as the pressurized fuel flow required for various designs is roughly equivalent for each range of load condition. However, the realized stroke and force of the actuator can be quite different depending on valve design, stroke amplification mechanism, and by how much the actuation needs to be derated for life and environmental effects. Some design and experimental work was performed to couple the X-Frame Actuator to a spool valve to demonstrate the ability to provide proportional hydraulic control. Proportional control was applied to a spool valve while driving fluid through an output nozzle at frequencies as high as 20 Hz. Figure 4 shows a typical time trace of the modulation of pressure while operating the X-Frame at 11 Hz.

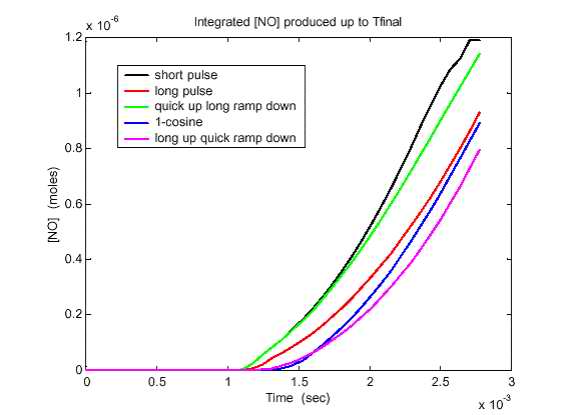


**Figure 4.** Modulation of output pressure for X-Frame driving spool valve at 11 Hz, 500 psi pump pressure.

The most critical aspect of this research in terms of proving feasibility is whether a combustion model and control algorithm can be developed that capture reality and yield an optimum injected shape of fuel to reduce emissions. In this short Phase I project, most of the effort was focused on generating a simplified combustion model that predicts the formation of one exhaust constituent, NOx, during operation of a direct injection compression ignition engine at one particular operating condition. The combustion simulation efforts were successful in providing a plausible model that captured the formation of NOx. Furthermore, Mide was able to evaluate how the different profiles, shown in Figure 5, responded in terms of injection pressures and NOx formation. The simulated history of NO production for these five profiles is shown in Figure 6.



**Figure 5.** Commanded needle trajectories for five simulated profiles.



**Figure 6.** Absolute NOx concentration levels for the five simulated needle/combustion cases.

The combustion model was combined with the adaptive algorithm to optimize the injection profile for minimized NOx. Ten iterations of this optimization were performed, and the history of NOx reduction as a function of iteration is shown in Figure 7. The optimum profile, shown in Figure 8, represents an effort by the optimization to delay the injection/combustion process towards the end of the simulation time. It is anticipated that by relaxing the maximum needle displacement and including the other unwanted emission and fuel consumption constituents, a similar modeling/simulation process will yield a profile that simultaneously combats the emissions problem.

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| Figure 7. Reduction of NOx obtained with each iteration of the optimization. | Figure 8. Optimized trajectory of needle lift for reduced NOx production. |
| **Figure 7.** Reduction of NOx obtained with each iteration of the optimization. | **Figure 8.** Optimized trajectory of needle lift for reduced NOx production. |

**Conclusions:**  
  
The results from this Phase I project confirmed the potential to realize improvement in emission characteristics using this technology. Results from the combustion modeling and implemented control algorithm indicate that varying the fuel injection profile can have a marked effect on exhaust constituents. Furthermore, the control method employed is effective in finding a minimum NOx level. Finally, preliminary actuator design and implementation have demonstrated the ability to modulate flow on a spool-type valve design at low frequencies. Modeling predicts the ability to increase the modulation and injection profile speed to the level required as predicted by the combustion control studies presented. Given this, Mide strongly recommends continuing the development of this technology in Phase II. Phase II of this effort will focus initially on implementing the results simulated in this Phase I project on an actual engine. Successfully building a HAFI system will be a significant accomplishment. Furthermore, the process of implementing this system will identify the performance possible with existing designs and highlight those aspects of the system that, through redesign, could significantly improve overall response. In parallel, additional combustion control efforts will be implemented to include hydrocarbon, particulate matter, and fuel consumption. Optimizations similar to those used in Phase I will be performed to find the optimum profile for low emissions operation. If time permits, the engine control system will be (re)designed to implement this updated injection profile, and experiments will be performed to verify this conclusion. As performance in the laboratory environment continues to be proven, Mide will be able to make a strong case to both compression and spark ignition engine manufacturers that this technology has true commercial potential.

**Supplemental Keywords:**  
  
*fuel injection, emissions, actuator, automobile engine, combustion, engineering, chemistry, mobile sources, EPA, air pollution, NOx, hydrocarbons, particulate matter.*, Toxics, Air, Waste, Scientific Discipline, RFA, Engineering, Chemistry, & Physics, Incineration/Combustion, air toxics, Chemistry, Environmental Engineering, particulate matter, VOCs, mobile sources, motor vehicle exhaust, ambient air quality, hydrocarbons, emission control strategies, hydrocarbon, particulate emissions, automobiles, combustion, Nox, fuel injection system, air pollutants, engines, Nitrogen Oxides, emission control technologies, gas turbines, atmospheric chemistry, vehicle emissions, piezoelectric actuator, combustion emissions, automotive combustion