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DIESEL ENGINE INJECTION RATE-SHAPE OPTIMIZATION USING GENETIC ALGORITHMS AND MULTIDIMENSIONAL MODELING

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SUMMARY/OVERVIEW:

A computational optimization study was performed for a heavy-duty direct-injection diesel engine using the recently developed KIVA-GA computer code. The effects of 11 engine input parameters on emissions and performance were studied. Start of injection (SOI), amount of EGR, boost pressure and eight parameters defining the fuel injection rate-shape were included in the search. The optimized configuration results in very low soot and NOx emissions together with relatively low fuel consumption.

TECHNICAL DISCUSSION

It is well known that diesel combustion and emissions formation strongly depend on the rate of fuel injection. Diesel fuel injection systems typically employ either a square, rising or falling rate of injection. Rising rate-shapes are commonly believed to be "optimal," however this view was established when injection durations were typically long in length and injection timings were relatively advanced. It is clear that alternative rate-shapes should be investigated with the use of modern high-pressure, short duration injections. Recently, a number of experimental and computational investigations have demonstrated the capability of multiple injections to reduce both NOx and soot emissions simultaneously. For example, Montgomery and Reitz [1] showed experimentally that particulate and NOx emissions, as well as fuel consumption, can be reduced over the entire engine operating map with the use of multiple injections and EGR.

Senecal and Reitz [2] performed a computational optimization study including two split injection parameters, as well as boost pressure, EGR, injection duration and start of injection timing. In that study, a realistic split injection rate-shape was used, with the amount of mass in the first injection pulse and the dwell between injections changing in the optimization. The KIVA-GA code was introduced was used to find an optimal set of parameters that resulted in significantly lower emissions, as well as improved fuel consumption, compared to the baseline case. The present study is similar to the study of Senecal and Reitz [2], however a much more general rate-shape parameterization is included, as described below. The parameterization allows for single or double injections, different peak injection velocities for each of the two injections, and a range of opening and closing durations.

Baseline Design

A single cylinder version of the Caterpillar 3400 Series diesel engine was chosen for the present study due to the large amount of available experimental data for this engine [1]. The baseline engine specifications and operating conditions are presented in Table 1. For this study, a 57% load, 1737 rev/min operating point was investigated. It has been shown that the present multi-dimensional model predictions agree well with measured data at this operating point for a variety of boost pressures, EGR levels and injection strategies [2].

Bore × Stroke	137.2 × 165.1 mm
Compression Ratio	16.1
Displacement	2.44 L
Combustion Chamber	Quiescent
Engine Speed	1737 rev/min
% of Maximum Load	57

Table 1. Engine specifications and operating conditions for the baseline engine case.

The design factors and ranges considered in the present study are given in Table 2. The parameter ranges for boost pressure, EGR and SOI are identical to those used in the previous study of Senecal and Reitz [2], however, a much more general injection rate-shape parameterization is used in this study. As shown in Fig. 1, eight parameters are used to define the injection velocity profile. The present parameterization allows for single or double injections.

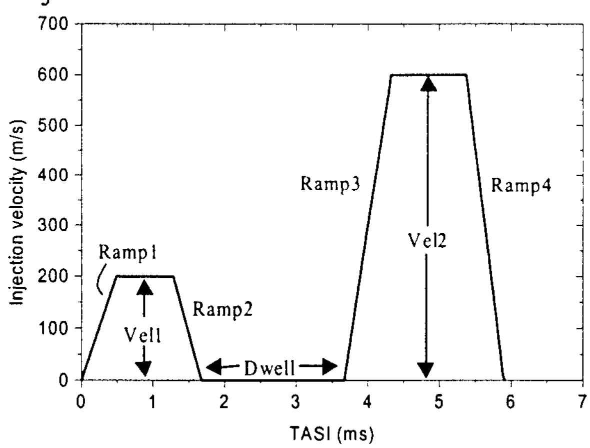


Figure 1. Example injection rate-shapes in the present parameterization. Injection velocities are presented as a function of Time After the Start of Injection (TASI) in ms.

Objective Function and its Evaluation

The objective (merit) function used previously by Montgomery and Reitz [3] and Senecal and Reitz [2] is also used in the present study. The merit function includes fuel consumption and engine-out NOx, Hydrocarbon (HC) and soot emissions levels, and is given by

$$f(\mathbf{X}) = \frac{1000}{R_1^2 + R_2^2 + R_3}$$

where

$$R_1 = \frac{\text{NOx} + \text{HC}}{W_1(\text{NOx} + \text{HC})_m} \qquad R_2 = \frac{\text{PM}}{W_2\text{PM}_m} \qquad R_3 = \frac{\text{BSFC}}{\text{BSFC}_0}$$

and the parameter vector **X** is defined in Table 2. In addition $(\text{NOx+HC})_m$ and PM_m are EPA mandated emissions levels (3.35 and 0.13 g/kW-hr, respectively) and BSFC_0 is a baseline fuel consumption (215 g/kW-hr in the present work). Furthermore, W_1 and W_2 are weighting constants (safety factors) set to 0.8 for this study.

Parameter	Range	Resolution
Boost Pressure (kPa)	165 → 284	64
EGR (%)	0 → 50	32
SOI (deg. atdc)	-10 → 10	32
Vel1 (m/s)	100 → 700	32
Vel2 (m/s)	100 → 700	32
P1 (%)	10 → 90	32
Ramp1 (%)	0 → 100	16
Ramp2 (%)	0 → 100	16
Ramp3 (%)	0 → 100	16
Ramp4 (%)	0 → 100	16
Dwell (deg.)	0.0 → 15.0	32

Table 2. Design parameters, ranges and resolutions.

Results

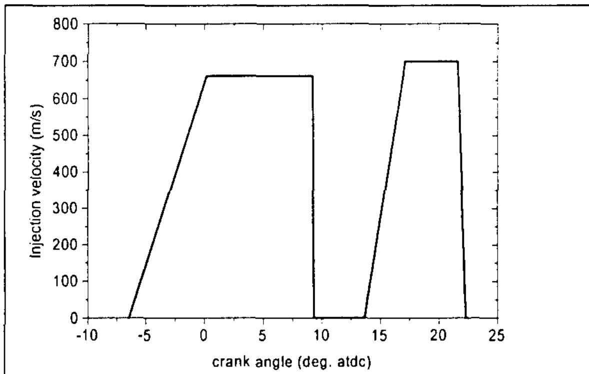
900 function evaluations (i.e., 75 × 12 KIVA runs) were performed, requiring approximately three weeks of CPU time for convergence. The parameters for this optimal case are summarized in Table 3. In addition, the optimum's injection profile is presented in Fig. 2. This rate-shape features two injection pulses, with a 4.4 deg. dwell between them. The first pulse has a relatively long opening ramp, followed by a near-maximum injection velocity of 660 m/s and a minimum closing ramp parameter of zero. The second pulse is similar to the first, but with a smaller duration and a higher peak injection velocity of 700 m/s.

Figure 3 presents soot vs. NOx points for a majority of the cases considered in the KIVA-GA optimization simulation. It is clear that the optimum design results in emissions levels well within the 2002/2004 mandates, and a relatively low BSFC value of 197 g/kW-hr was also achieved at the optimum point.

The 2002/2004 emissions mandates were also met with the less flexible injection profile considered by Senecal and Reitz [3]. However, the present optimum case reached lower NOx levels (i.e., 0.7 vs. about 1.0 g/kW-hr), similar soot levels (0.04 g/kW-hr) and lower BSFC (i.e., 197 vs. about 212 g/kW-hr) than that of the the previous study. This points out the advantage of using a more flexible injection system.

Parameter	Optimized value
Boost Pressure (kPa)	216
EGR (%)	44
SOI (deg. atdc)	-6.5
Vel1 (m/s)	660
Vel2 (m/s)	700
P1 (%)	64
Ramp1 (%)	27
Ramp2 (%)	0.0
Ramp3 (%)	27
Ramp4 (%)	6.7
Dwell (deg.)	4.4

Table 3. Optimized values of the eleven design variables.



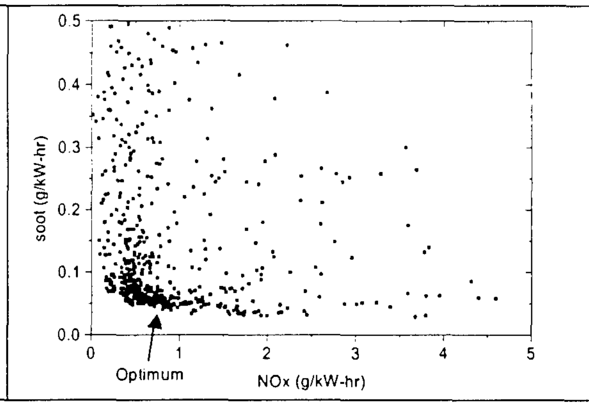


Fig. 2. Predicted optimum injection rate-shape. **Fig. 3.** Predicted Soot-NOx tradeoff

Conclusions

The KIVA-GA computational design methodology was applied to study the effects of injection rate-shape on emissions and performance in a heavy-duty diesel engine. The μGA efficiently determined a set of engine input parameters resulting in soot and NOx emissions well within the 2002/2004 mandates at the considered operating condition. The optimum case also had a relatively low fuel consumption value. The present methodology provides a useful tool for engine designers investigating the effects of a large number of input parameters on emissions and performance.

Acknowledgements

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