System Model of a Multi-Cylinder SI Engine in Lotus Engine Simulation

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Abstract

A complete system model of a naturally aspirated, four-cylinder spark ignition (SI) engine was built in the Lotus Engine Simulation (LES) program. The model represents the Honda K20A, a 2.0 L inline-4, with its cylinders, intake and exhaust valves, ports, manifold volumes and throttle. Combustion is described by a single Wiebe function and in-cylinder heat transfer by the Annand correlation. The engine was run from 1200 RPM to 8400 RPM, and torque, power, brake specific fuel consumption (BSFC), brake mean effective pressure (BMEP), volumetric efficiency, in-cylinder pressure and temperature, and combustion phasing were extracted. Power and torque fall off above roughly 6000 RPM, well short of the published rating, and the gas-exchange results point to the exhaust side of the model as the likely cause.

1 Introduction

A single-zone model computes only the closed-valve part of the engine cycle. It says nothing about how much air the engine actually breathes, because the valves, ports and manifolds sit outside the model. A multi-cylinder system model closes that gap: air flows through the throttle, intake plenum, ports and valves into each cylinder, is burned, and leaves through the exhaust system, so volumetric efficiency and its effect on torque and power become results of the simulation.

This project builds such a model in Lotus Engine Simulation (LES) and uses it to predict the full-load performance of a real engine over its operating speed range. This report describes the engine, the components of the model and the parameters supplied to each, and discusses the resulting performance, in-cylinder and gas-exchange behavior.

1.1 Engine Selection

The Honda K20A was chosen for this simulation. It is a 2.0 L, naturally aspirated, inline-4, four-stroke SI engine. It was used between 2000 and 2011 in a number of models, including the Accord, CR-V, Civic, Civic Si and Civic Type R. Because it is an older and very popular engine, its specifications are widely available.



Figure 1: Honda K20A engine

The K20A features Variable Valve Timing & Lift Electronic Control (VTEC). This

technology is not included in the model, so a single fixed set of valve events is used over the whole speed range.

2 Engine Specifications

The specifications used to build the model are listed in Table 1.

Table 1: Honda K20A engine parameters

Parameter	Value
Configuration	Inline-4
Displacement	1998 cm^3
Bore $\times$ stroke	86.0 mm $\times$ 85.9 mm
Connecting rod length (L)	139 mm
Compression ratio (CR)	11.5
Intake valve diameter	35.15 mm
Exhaust valve diameter	30.15 mm
Intake plenum volume	2.530 L
Exhaust manifold collector volume	0.6 L
Throttle bore	60 mm
Redline	8400 RPM

3 System Model

3.1 Model Layout

The model is assembled in LES from the components shown in Figure 2. Air enters through an ambient source and a throttle, passes into the intake plenum and is distributed to four intake ports. Each cylinder has two intake and two exhaust valves, so the model contains four cylinders, eight intake and exhaust valves in total, and four intake and exhaust ports. The exhaust ports lead into a common exhaust plenum that discharges to ambient. The cylinder firing order is 1-3-4-2.

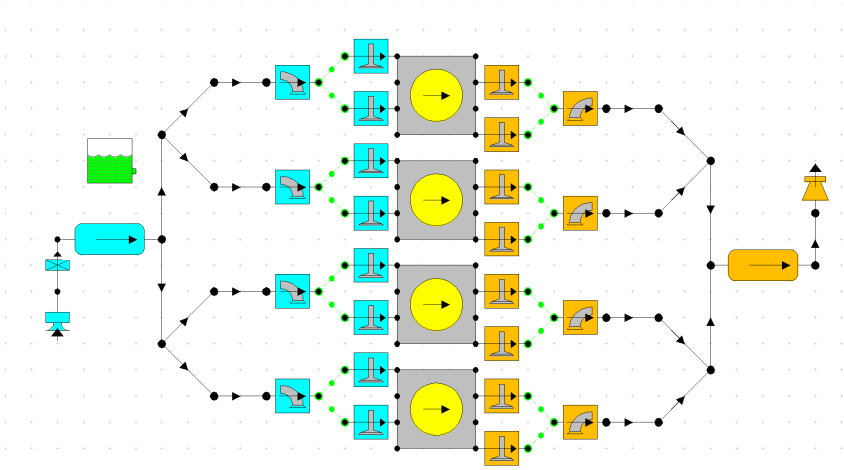


Figure 2: K20A engine model in Lotus Engine Simulation

3.2 Cylinders and Combustion

The geometry supplied to each cylinder is given in Table 2. The swept volume per cylinder computed from the bore and stroke is 0.498 98 L, which gives a total swept volume of 1.995 91 L.

Combustion is modeled with the single Wiebe function, which gives the mass fraction burned x_b as a function of crank angle:

$$x_b(\theta) = 1 - \exp\left[-A\left(\frac{\theta - \theta_{start}}{\Delta\theta}\right)^{M+1}\right] \tag{1}$$

where θ_{start} is the start of combustion, $\Delta\theta$ is the burn duration, and A and M are dimensionless shape parameters. The user-defined values $A = 6.910$ and $M = 2.000$ were entered in place of the LES defaults of 10.000 and 2.000. In the form of Equation (1), $A = 6.91$ corresponds to about 99.9 % of the charge burned at the end of the burn duration, since $e^{-6.91} \approx 0.001$.

Table 2: Cylinder and combustion parameters (identical for all four cylinders)

Parameter	Value
Bore	86.0 mm
Stroke	85.9 mm
Swept volume per cylinder	0.498 98 L
Total swept volume	1.995 91 L
Connecting rod length	139.00 mm
Piston pin offset	0.00 mm
Compression ratio	11.50
Clearance volume	0.047 522 L
Wiebe parameters (A, M)	6.910, 2.000

3.3 Heat Transfer

Heat transfer between the gas and the cylinder surfaces is modeled with the Annand correlation, which combines a convective term based on a Nusselt-Reynolds relation with a radiation term:

$$\dot{q} = \frac{k}{D} A \,\mathrm{Re}^{B} \left(T - T_{wall}\right) + C \left(T^4 - T_{wall}^4\right) \tag{2}$$

where k is the gas thermal conductivity, D a characteristic length, Re the Reynolds number and T_{wall} the surface temperature. The exact reference lengths and velocity scales are those of the LES implementation. Separate coefficient sets are used for the open part of the cycle (valves open) and the closed part, and the LES default values were used for both (Table 3). The open-cycle set has no radiation term. The surface areas were user defined as ratios to the bore area.

Table 3: Heat transfer parameters

Parameter	Value
Open cycle, Annand A, B	0.200, 0.800
Closed cycle, Annand A, B	0.120, 0.800
Closed cycle, radiation C	$4.29 \times 10^{-9}\,\mathrm{W\,m^{-2}\,K^{-4}}$
Head area / bore area	1.10
Piston area / bore area	1.05
Liner segments	4

3.4 Intake and Exhaust Valves

Each valve is described by its opening and closing angles, its maximum lift and the angle of maximum opening (MOP), with a fast-lift polynomial lift curve. The

values for the first intake and exhaust valves are listed in Table 4, and the same events are applied to every valve of the engine. The resulting timing is plotted in Figure 3: intake valve opening (IVO) 10° before TDC, intake valve closing (IVC) 50° after BDC, exhaust valve opening (EVO) 50° before BDC and exhaust valve closing (EVC) 10° after TDC. Both valves therefore stay open for 240° of crank angle, with a valve overlap of 20°.

Table 4: Valve parameters

Parameter	Intake	Exhaust
Valve opens	10° BTDC	50° BBDC
Valve closes	50° ABDC	10° ATDC
Maximum lift	12.27 mm	10.77 mm
MOP	110°	−110°

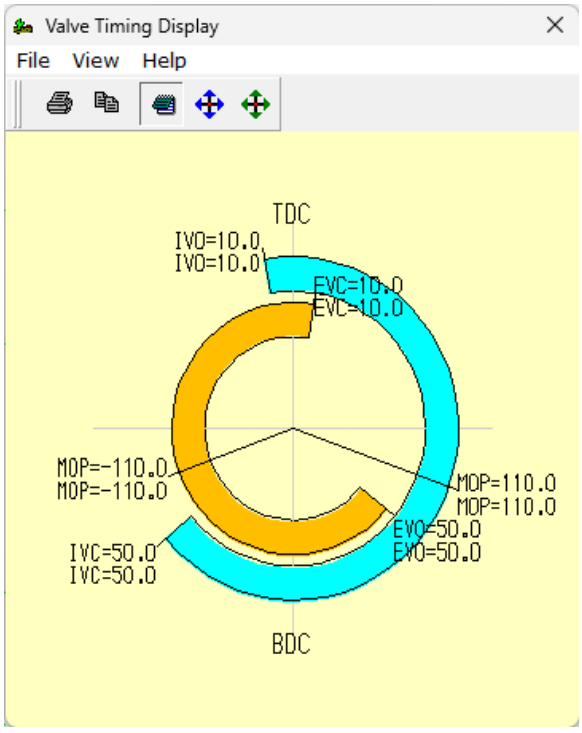


Figure 3: Valve timing diagram

Figure 4 shows the lift curves of both valves for all four cylinders over the 720° cycle. The cylinders are phased 180° apart in the firing order 1-3-4-2.

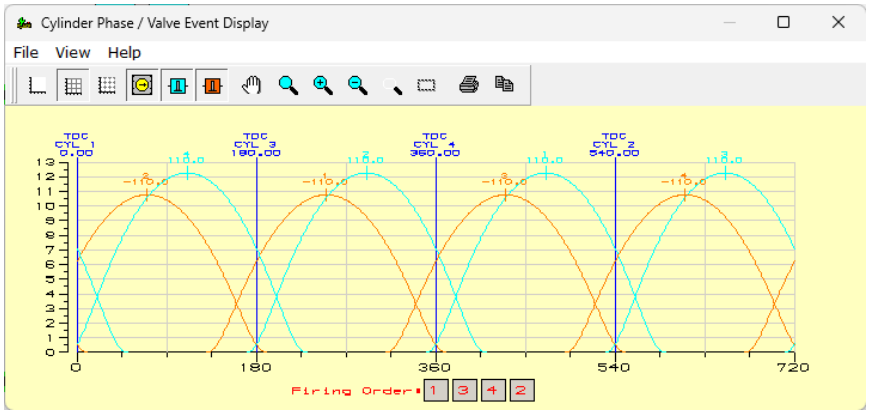


Figure 4: Valve lift and firing order

3.5 Ports, Manifolds and Throttle

Each cylinder is fed by one intake port and drained by one exhaust port, each serving two valves and using the default "good port" flow characteristic. The intake plenum and exhaust plenum are modeled as volumes with a surface area and a wall temperature, and the throttle is modeled as a simple area with a fixed discharge coefficient. These parameters are listed in Table 5.

Table 5: Port, manifold and throttle parameters

Parameter	Intake	Exhaust
Valves per port	2	2
Valve throat diameter	30.9 mm	26.5 mm
Plenum volume	2.53 L	2.53 L
Plenum surface area	1.3×10^4 mm^2	1.3×10^4 mm^2
Plenum wall temperature	20 °C	100 °C
Throttle discharge coefficient	0.6	
Throttle minimum flow area	2827 mm^2 (60 mm equivalent diameter)	

The exhaust plenum was left at its default values, which are the same as the intake plenum. In particular, its volume of 2.53 L is considerably larger than the 0.6 L exhaust collector volume listed in Table 1. This mismatch is returned to in the discussion.

4 Results and Discussion

The engine was simulated from 1200 RPM to 8400 RPM, since 8400 RPM is the redline of the K20A. The brake mean effective pressure and brake specific fuel

consumption reported by LES follow from the usual definitions,

$$P_b = T_b\,\omega, \qquad \mathrm{BMEP} = \frac{4\pi\,T_b}{V_d}, \qquad \mathrm{BSFC} = \frac{\dot{m}_f}{P_b} \tag{3}$$

where T_b is the brake torque, ω the angular velocity, V_d the engine displacement and $\dot{m}_f$ the fuel mass flow rate.

4.1 Performance Summary

Figure 5 shows the predicted torque, power, BSFC and BMEP over the speed range. Power would be expected to rise with speed all the way to the redline. In the simulation it rises up to about 6000 RPM, after which power and torque both decrease, and BMEP falls with them. BSFC stays fairly flat until the same region and rises steeply at the top of the speed range.

The published rating of the K20A in its high-output variants is roughly 160 kW to 165 kW at 8000 RPM, so the model falls well short of it at high speed.

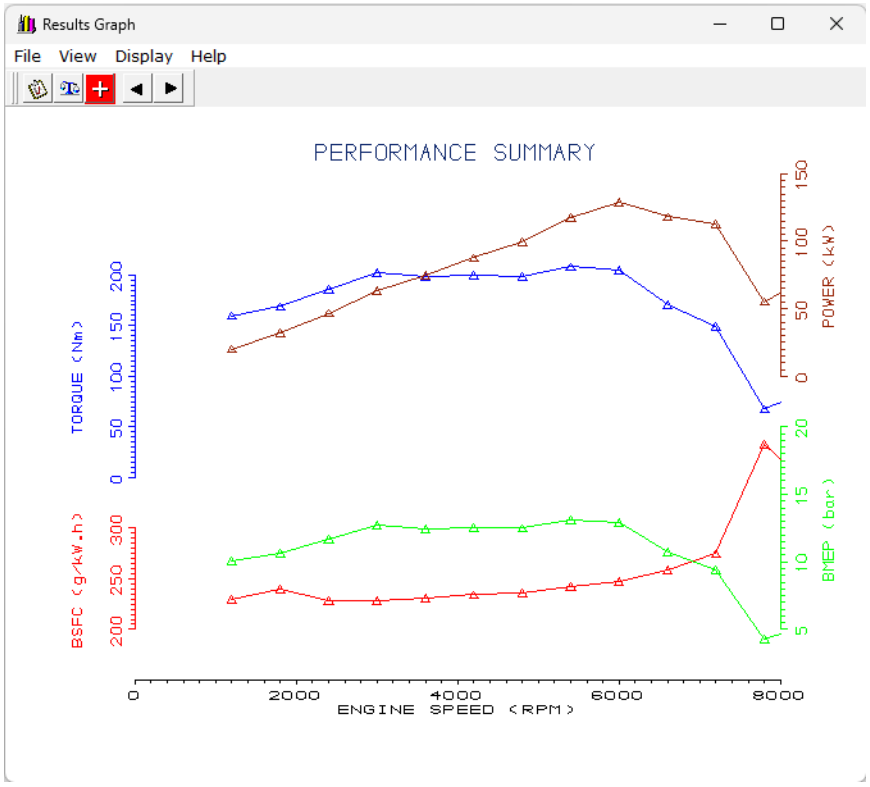


Figure 5: Performance summary of the K20A simulation

4.2 In-Cylinder Pressure and Temperature

Figure 6 and Figure 7 overlay the cylinder pressure and temperature over the crank angle for the simulated engine speeds. The curves have the expected shape: pressure and temperature rise during compression, climb sharply through combustion to a peak shortly after TDC, and decay during expansion. The peak gas temperature is close to 3000 K. The spread between the traces shows the effect of engine speed, with the lowest peak pressures belonging to the highest speeds. The temperature traces also show the exhaust blowdown and the valve overlap period, where the cylinder gas is influenced by the exhaust and intake systems.

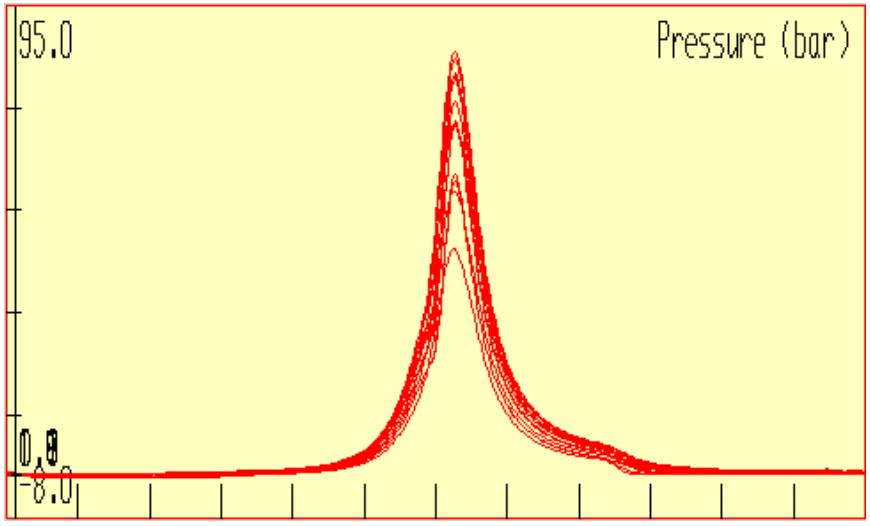


Figure 6: In-cylinder pressure against crank angle for the simulated speeds

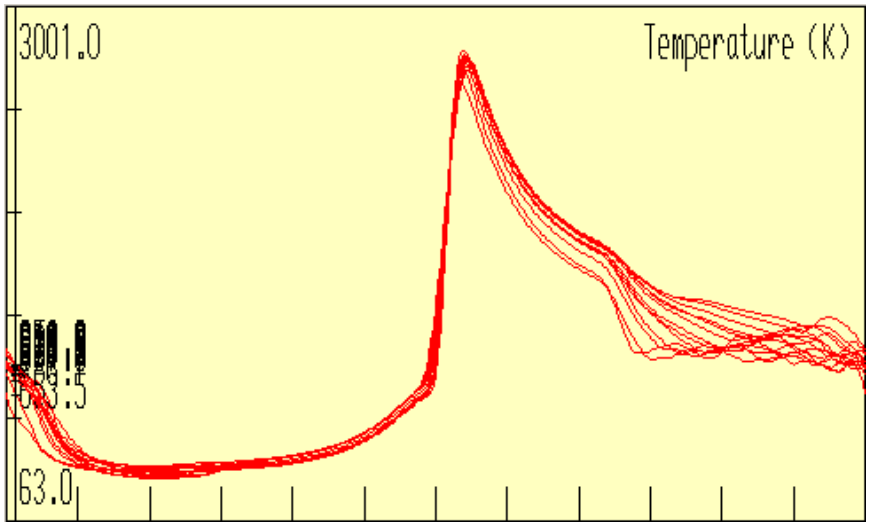


Figure 7: In-cylinder temperature against crank angle for the simulated speeds

4.3 Combustion

Figure 8 summarizes the combustion over the speed range, as peak cylinder pressure (P_{max}) and the crank angles at which 10 %, 50 % and 90 % of the charge has burned (A10, A50 and A90). The combustion phasing is nearly constant: A50 stays at about the same crank angle after TDC at every speed, A10 moves slightly earlier and A90 slightly later, so the burn lengthens a little as speed rises. P_{max} rises to a plateau and then drops sharply above about 6000 RPM.

Since the phasing hardly changes in the region where P_{max} collapses, the loss of peak pressure does not come from a change in when the charge burns.

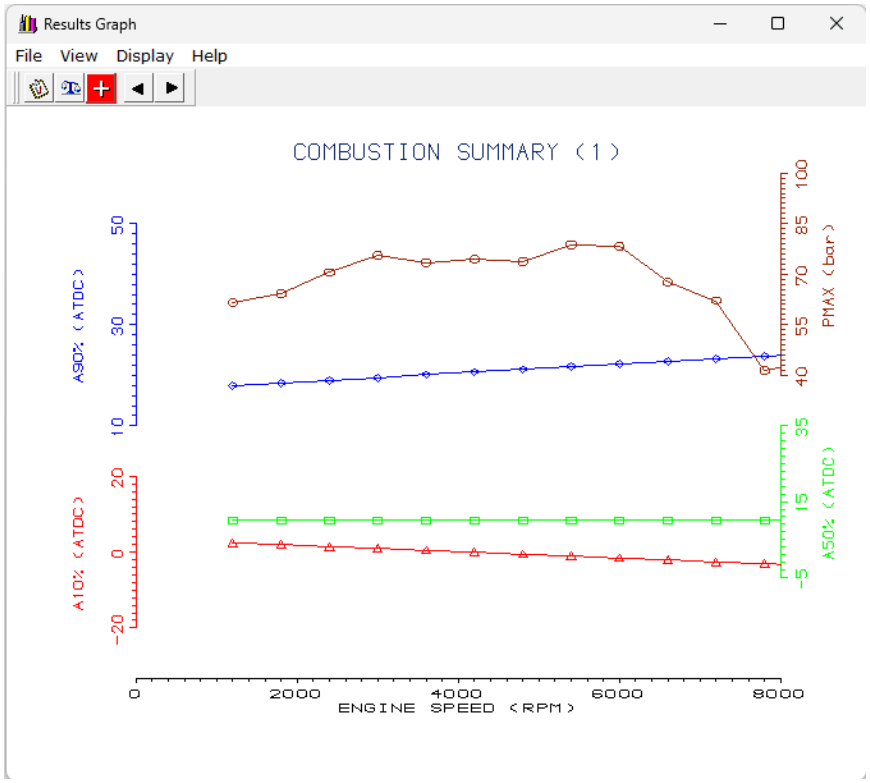


Figure 8: Combustion summary

4.4 Gas Exchange

Figure 9 shows the exhaust plenum temperature and pressure, the exit pressure and the volumetric efficiency. Volumetric efficiency increases with speed, reaches a maximum of roughly 100 % at about 5400 RPM to 6000 RPM, and then decreases. The exhaust plenum pressure rises steadily with speed and, between roughly 5400 RPM and 7200 RPM, goes beyond the 1.4 bar limit of the plot, while the exit pressure stays at ambient. The exhaust plenum temperature climbs with speed and drops at the top of the range.

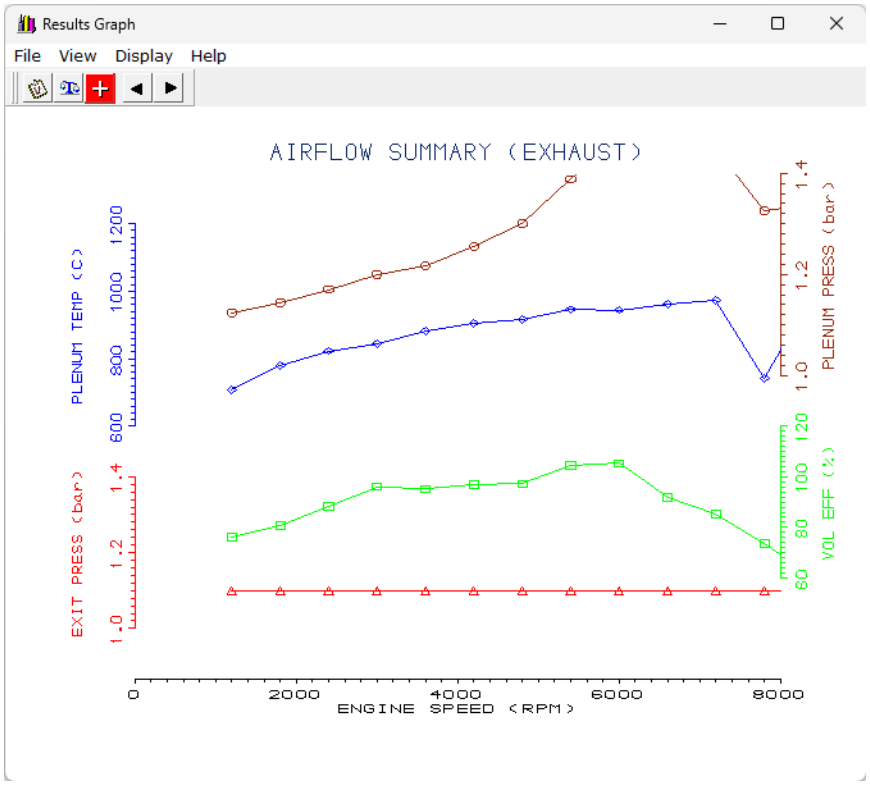


Figure 9: Exhaust airflow summary

4.5 Discussion

Taken together, the results suggest that the fall in output above about 6000 RPM is a gas-exchange effect. Volumetric efficiency drops in the same speed range, so less charge is trapped in the cylinder, and P_{max} drops with it, while combustion phasing does not change. The high exhaust plenum pressure points to the exhaust side as the most likely place for the problem, consistent with the first suspicion.

Several features of the model could contribute, and none of them was separated in this study:

- The exhaust plenum kept the default 2.53 L volume and a 100 °C wall temperature, whereas the engine has a collector of about 0.6 L.
- The intake and exhaust ports use the default “good port” flow characteristic and no measured flow data.
- VTEC is not modeled, so a single set of valve events has to serve over the whole speed range.
- Heat transfer and combustion parameters are generic, and the model has not been calibrated against measured data.

5 Conclusion

A system model of the Honda K20A was built in Lotus Engine Simulation from its cylinders, valves, ports, manifolds and throttle, and run from 1200 RPM to 8400 RPM. It produced the expected in-cylinder pressure and temperature histories, and gave torque, power, BSFC, BMEP and volumetric efficiency over the speed range.

The predicted power and torque, however, decrease above about 6000 RPM, while the engine is rated for its maximum power at 8000 RPM. Constant combustion phasing, falling volumetric efficiency and a high exhaust plenum pressure in the same region indicate a gas-exchange limitation, most likely on the exhaust side.

The next steps are to correct the exhaust plenum so that its volume and wall temperature match the real collector, to model the exhaust manifold with runners and a collector, to represent the two VTEC cam profiles, and to compare the results with measured power and torque data.

References

[1] Honda Motor Co., “K20A Engine Specifications,” Service Manual.

[2] Lotus Engineering, “Getting Started with Lotus Engine Simulation,” Lotus Engine Simulation documentation.

[3] Annand, W. J. D., “Heat Transfer in the Cylinders of Reciprocating Internal Combustion Engines,” *Proceedings of the Institution of Mechanical Engineers*, vol. 177, no. 36, pp. 973–996, 1963.

[4] Heywood, John B., *Internal Combustion Engine Fundamentals*, McGraw-Hill, 1988.