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Mazda New Lightweight and Compact V6 Engines

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ABSTRACT

Mazda has developed new-generation V6 engines. The new V6 series comprises 2.5-litre, 2.0-litre and 1.8-litre engines. The development objective was to ensure high output performance for excellent "acceleration and top-end feel", while satisfying "Clean & Economy" requirements. The engines also had to have a pleasant sound. Mazda selected for these engines a short stroke, 60° V-shaped 24 valve DOHC with an aluminum cylinder block. Various techniques are adopted as follows:

- Combustion improvement and optimization of control to achieve high fuel economy and low emissions
- Improvement of volumetric efficiency, inertia reduction of rotating parts and optimization of control to achieve excellent "acceleration and top-end feel"
- Adoption of a high-rigidity, two-piece cylinder block and crankshaft and weight reduction of reciprocating parts to achieve a pleasant engine sound
- Material changes and elimination of dead space to achieve a compact, lightweight engine

INTRODUCTION

These days, people are not as concerned with material wealth as they are with spiritual wealth. As for automobiles, there is a growing demand for a vehicle which can be deeply satisfying to drive and is environmentally safe (low emission and high fuel economy). V6 engines are becoming popular for their smooth and quiet characteristics. However, in the "family-use" and "compact-speciality" car classes, conventional V6 engines can not meet the lightweight, compact and pleasant drive requirements. Newly developed K-series engines are small, matching stylish and compact vehicles and appeals to the customer's sensitivity and is pleasant to drive. The K-series comprise 2.5-litre V6DOHC(KL), 2.0-litre V6DOHC(KF) and 1.8-litre V6DOHC(K8) engines.

DEVELOPMENT OBJECTIVES

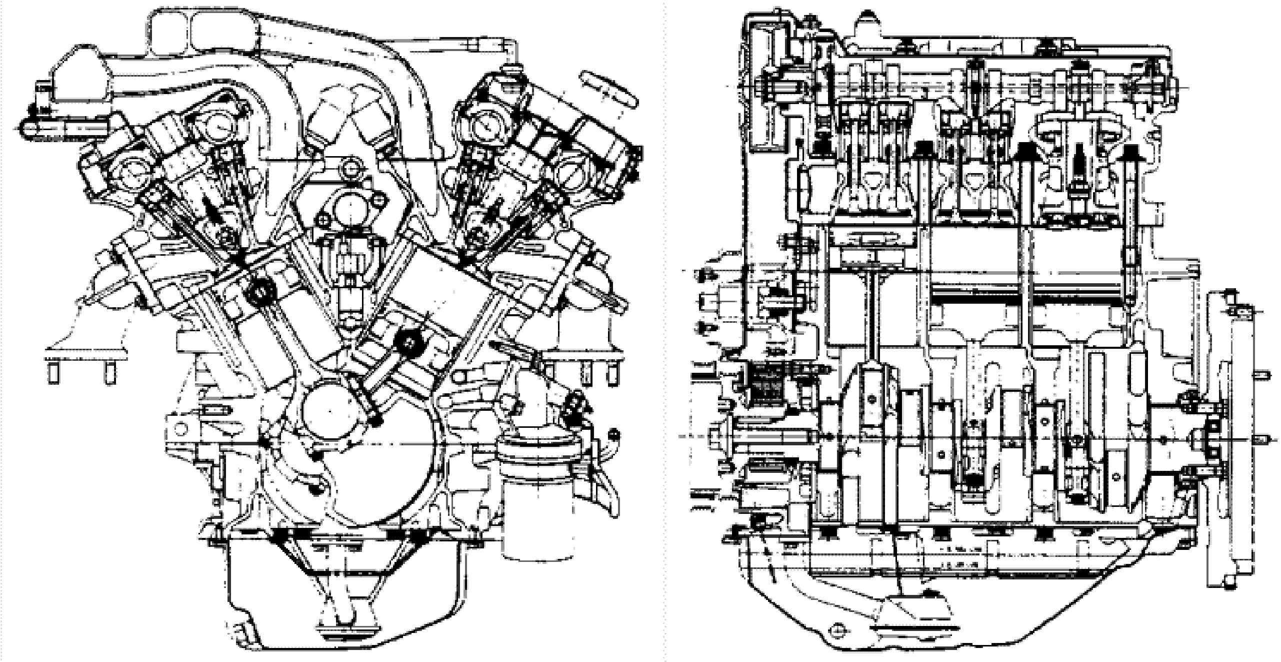
To achieve drive feeling which appeals to total human sensitivity and as a contribution to the unique "low hood & short nose" styling, the following four major objectives were set in developing the K-series engines:

1. Low fuel consumption, low emissions
2. Excellent "acceleration and top-end feel" and pleasant engine sound
3. Most compact and lightweight engine of all mass produced V6 engines
4. Long-life durability with high performance

MAIN SPECIFICATIONS AND PERFORMANCE

To achieve high combustion efficiency, excellent acceleration and top-end feel, the K-series engines were designed with bore and stroke of 84.5x74.2 mm for KL, 78x69.6 mm for KF and 75x69.6 mm for K8. To contribute to the "low hood & short nose" vehicle style, 60-degree bank angles, which are superior in reducing vibration, noise, and packaging size, were selected. Fig. 1 shows a sectional view of the KL engine and Table 1 shows the main engine specifications.

Fig 1 Sectional view of the KL engine



To achieve excellent top-end feel in the high speed range while ensuring driving performance in normal operating range, high torque was realized in all engine speed ranges. The engine performance curves are shown in Fig. 2.

The following represents the techniques employed in the K-series engines, focusing on the "KL" engine.

Fig 2 Performance curve of K-series engines

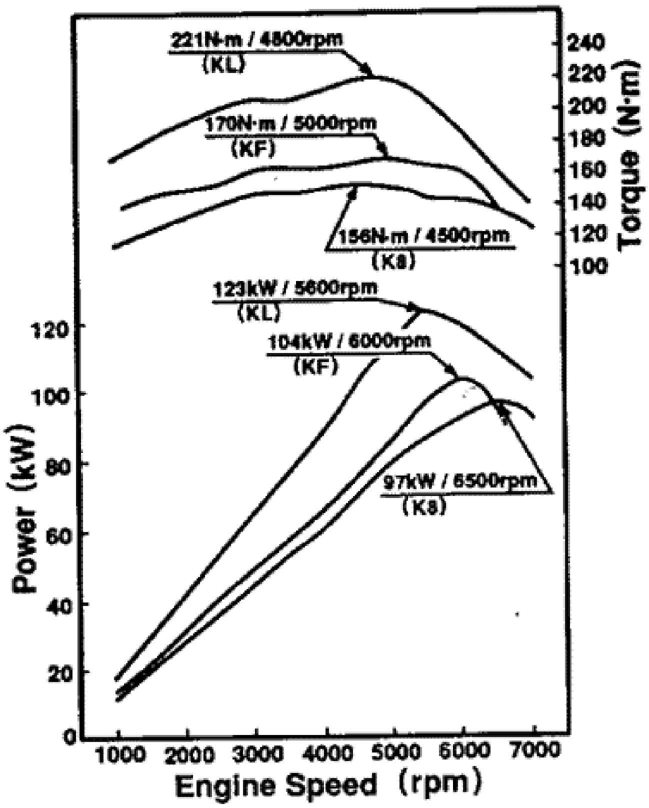


Table 1 Engine specifications

	KL	KF	K8
Type	Gasoline, 4-cycle	< --	< --

No. of Cyl. & Arrangement	6 cylinders, 60° V type	< --	< --
Displacement (cc)	2497	1995	1845
Bore x Stroke (mm)	84.5x74.2	78x69.6	75x69.6
Valve Mechanism	DOHC Belt-driven	< --	< --
Valves/Cyl.	4	< --	< --
Combustion Chamber	Pentroof	< --	< --
Compression Ratio	9.2	9.5	9.2
Max. Output (kW/rpm)	123/5600	104/6000	97/6500
Max. Torque (N · m/rpm)	221/4800	170/5000	156/4500
Fuel System	EGI	< --	< --
Dimensions (L x W x H) (mm)	620x675x640	650x685x660	650x685x655

TECHNIQUES

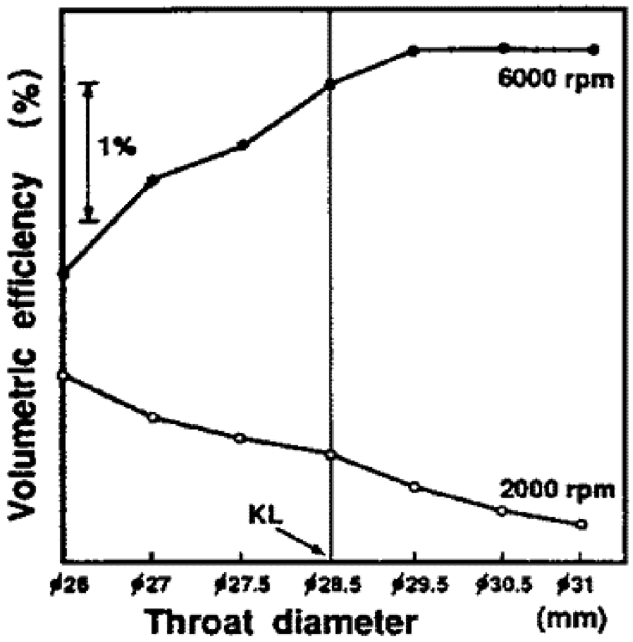
LOW FUEL CONSUMPTION AND LOW EMISSIONS - Regarding "clean and economy" as basic requirements, work was done to improve combustion and optimize control.

Combustion improvement - Efforts were concentrated on the development of a combustion chamber which offers high thermal efficiency over the entire operation range with lowered emissions.

First, an optimum intake air throat diameter was selected to maintain volumetric efficiency in the high-speed range and maximize intake air flow velocity in the low- and mid-speed ranges, thus enhancing volumetric efficiency in all speed ranges with the output performance in high speed range being ensured. The valve angle was then narrowed for optimization and the combustion chamber made more compact (reduction of surface/volumetric ratio) to reduce cooling loss for higher thermal efficiency, without relinquishing adequate throat diameter. (Fig. 3) Squish area, which creates turbulance of the air/fuel mixture (squish) during the compression stroke, was given around the valves to ensure high volumetric efficiency and high combustion speed. (Fig. 4) (1) As a result, the combustion chamber is a compact pentroof with intake and exhaust valve angles of 27 degrees. Squish area to bore area ratio is 17.3 percent and the squish clearance is 0.68 mm. The throat diameter is 28.5 mm on the intake side; and 25 mm on the exhaust side. (Fig. 5)

Fig. 3 Effect of throat diameter on volumetric efficiency

Fig. 4 Effect of the adoption of squish area on volumetric and thermal efficiencies



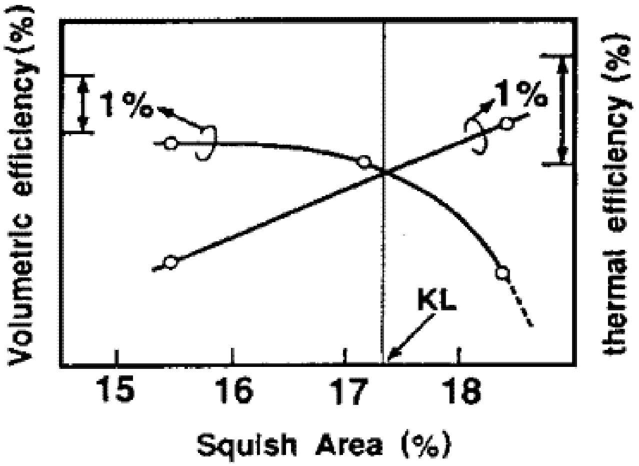
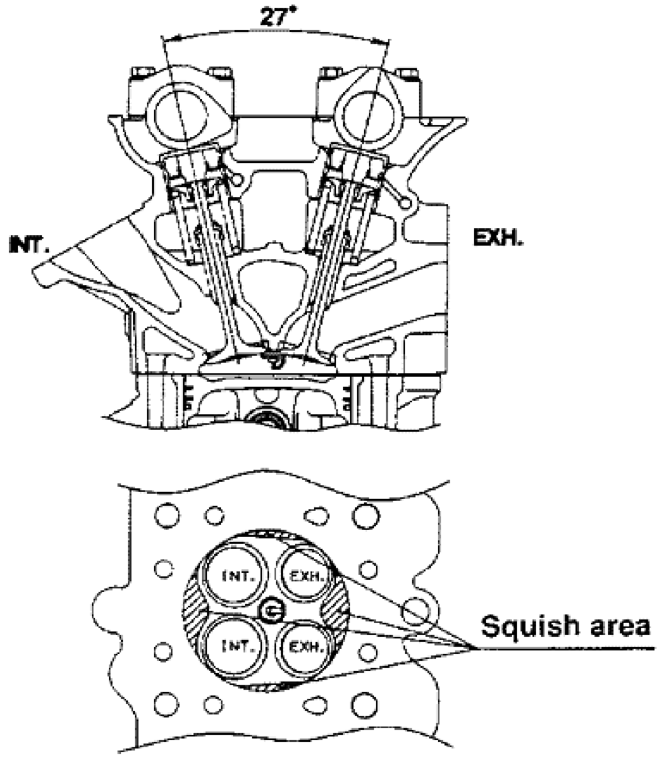


Fig. 5 Combustion chamber design



The emission of hydrocarbons has been greatly reduced by eliminating the crevice volume, the space around the piston top land, valves, and spark plug that extinguishes the flame. Fig. 6 shows the locations of these changes and the hydrocarbon reduction effect.

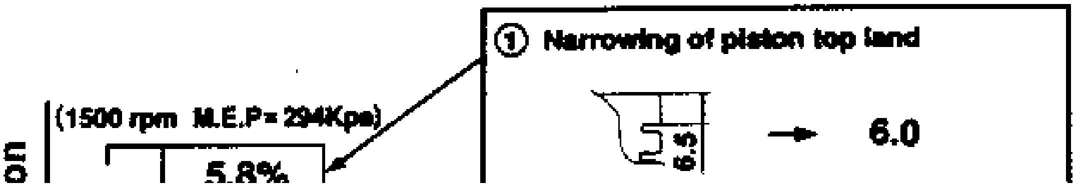
Optimization of Control **-** To attain superior running performance, low fuel consumption, low emissions, and other targets, the overall control of KL engine is handled by a microcomputer. The main controls include those for fuel injection, air/fuel ratio feed-back, idle speed, EGR, Purge.

Each injector's fuel injection volume and timing were optimized by a multi-point sequential fuel injection system. The effect of this system on reductions of fuel consumption and emission depends on how air/fuel ratio is controlled to handle sudden changes in engine speed and load in acceleration and deceleration.

Presision of each bank's A/F ratio is enhanced with air/fuel ratio feed-back control made on right bank and left bank individually to reduce emission.

Improved control system made it possible to reduce idle engine speed and extend the engine speed range where fuel is saved, thus enhancing fuel economy.

Fig.6 Crevice volume reduction and the effect on HC reduction

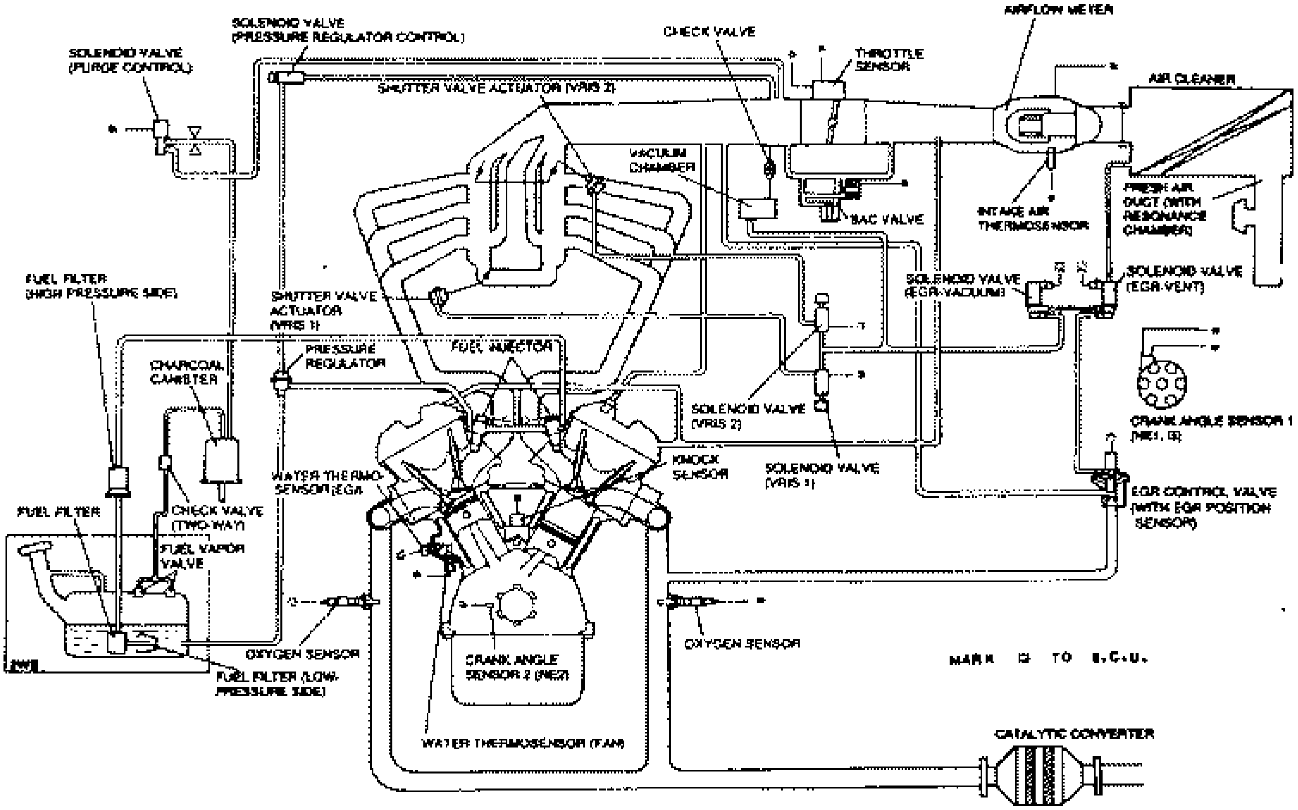


EGR flow rate is optimized by electronic control of the duty-solenoid valve as required for

engine speed and
load to achieve low emissions and low fuel consumption.

The evaporated fuel absorbed in the canister is sent to the engine via the solenoid valve to avoid gasoline volatilization. Fig. 7 shows the engine control systems.

Fig. 7 Engine control system



LIGHTWEIGHT - KL engine became the lightest in their displacement classes among V6 engines by the implementation of several measures: using aluminum alloy for the cylinder blocks and auxiliary brackets; resinating the belt cover and airflow meter; utilizing a short stroke; integrating the inlet manifold and surge tank; and decreasing the exhaust manifold size.

EXCELLENT ACCELERATION AND TOP-END FEEL - To improve drive feeling, much effort was put into achieving excellent "acceleration and top-end feel." Fig. 8 shows a quantitative method that uses vehicle acceleration characteristics in which "response" and "acceleration" make up "acceleration feel"; and the area of further extension from the top of vehicle acceleration curve, makes up "top-end feel". (2) The object was to get smooth vehicle acceleration characteristics in the "response" area, powerful and linear vehicle acceleration in the "acceleration" area, and to keep high vehicle acceleration characteristics in "top-end feel" area. These objects were attained by ensuring high continuous torque characteristics in all engine speed ranges, reducing the inertia weight of rotating parts, and optimizing ignition timing. (Table 2)

High Continuous Torque Characteristics - Efforts were concentrated on the improvement of volumetric efficiency and the optimization of setting. The technical features incorporated in each area are shown in Table 3.

Fig. 8 Vehicle acceleration and top-end feel

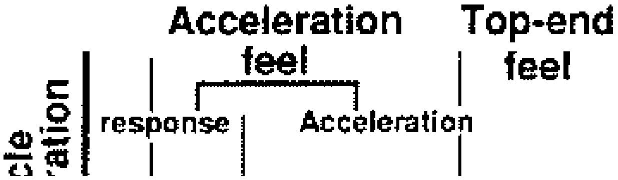


Table 2 Techniques for improvement of acceleration and top-end feel

	Acceleration feel		Top-end feel
	Response	Acceleration	

Torque improvement techniques	XX	XX	XX
DOHC 24valve	X	X	X
Short Stroke	X	X	X
Weight reduction of rotating parts	XX	X	X
Active IG timing control	XX		

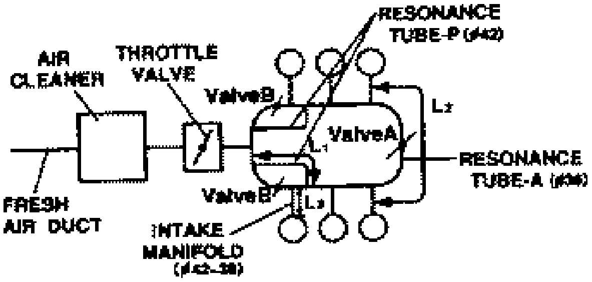
Fig.9 Volumetric efficiency calculated by intake air simulation

Table 3 Techniques for torque enhancement

	Engine speed		
	Low	**Mid**	**High**
4-stage VRIS	X	X	X
Semi-dual exhaust system		X	
Crank angle sensor			X
Trace knock control	X		

To obtain high torque in all engine speeds, a multi-stage Variable Resonance Induction System(VRIS) was adopted in the intake system. In the VRIS, surge tanks in both banks were connected to each other by resonance tubes. The resonance induction generates high torque characteristics around the resonant frequency. The resonant frequency changes by changing the tube's length.(3) Each resonance tube of multi-stage VRIS has a switching valve, which are operated according to the engine speed and load. And the system of multi-stage VRIS changes the resonant frequency to use the effect of resonance charge in all engine speed ranges. In the K-series engines, to optimize the resonance effect with small packaging size, the length of each resonance tube was optimized by simulation research.(Fig. 9)

Because the switching valves are operated according to driving conditions, it is possible to utilize the different resonance tube characteristics, thus realizing smooth and high torque in all engine speed ranges. The structure of VRIS is shown in Fig. 10. Fig. 11 shows the valve drive controls and 4-stage VRIS torque characteristics in low, mid and high speed ranges.



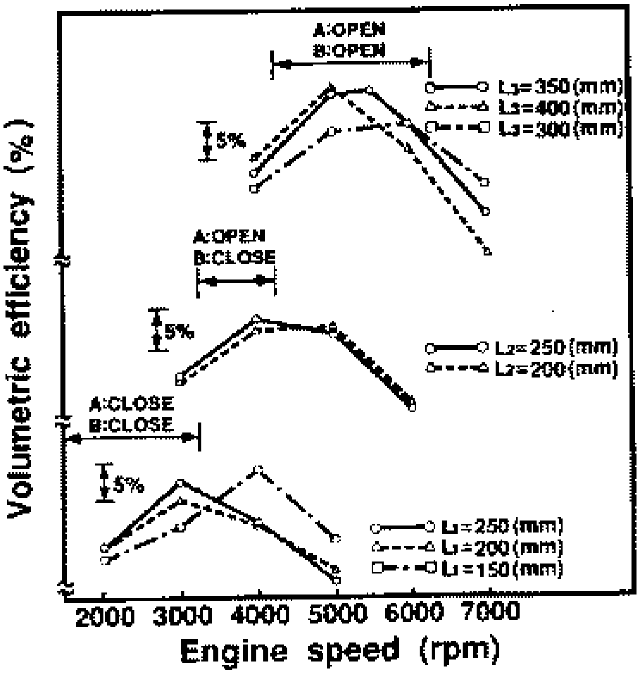
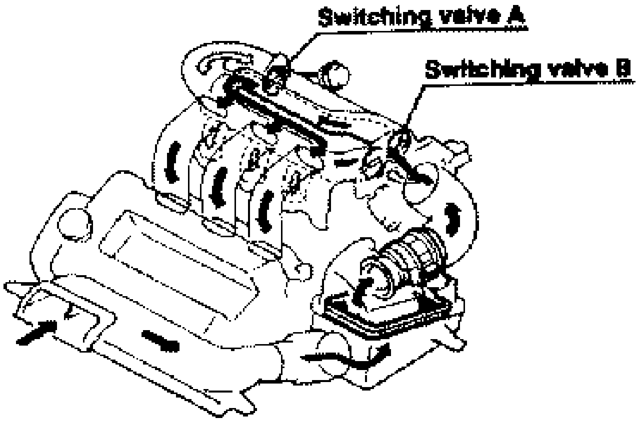
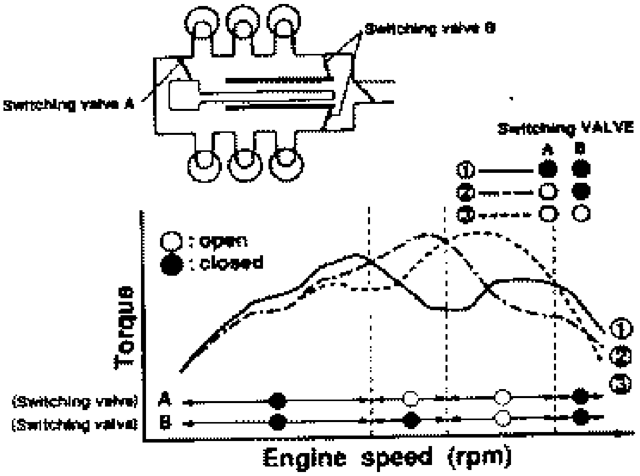


Fig. 10 Construction of 4-stage VRIS

Fig. 11 Valve drive controls and 4-stage VRIS torque characteristics

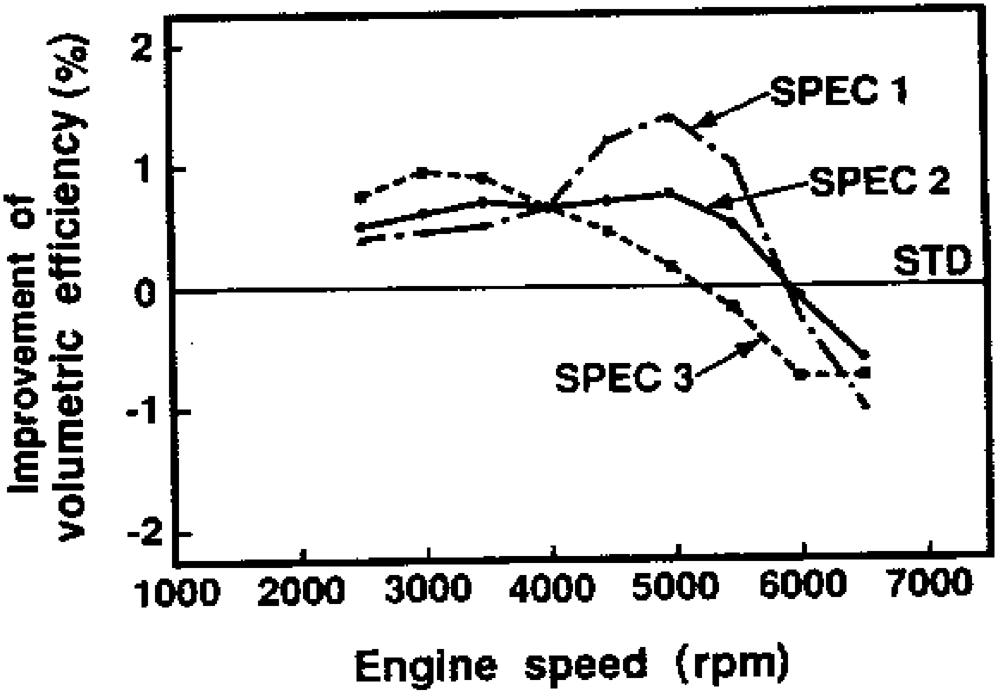


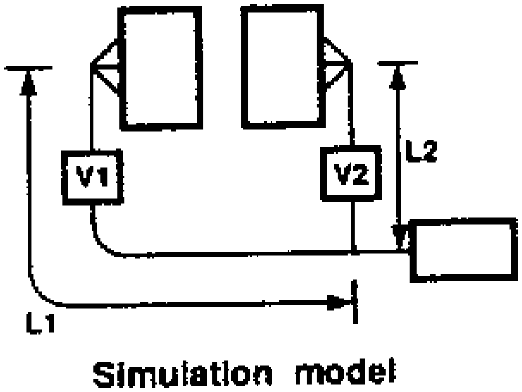


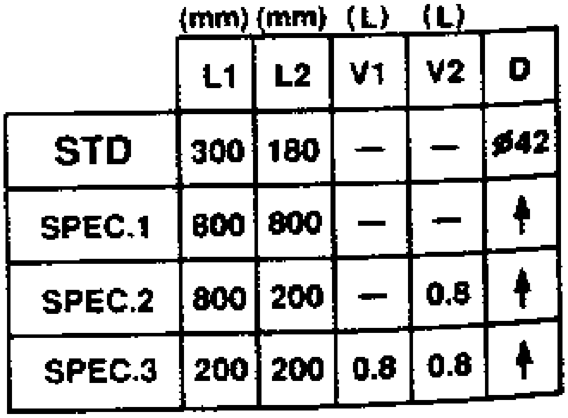
Simulation was also utilized to optimize the exhaust system specifications, obtaining exhaust-pulse scavenging in the desired engine speed ranges as shown in Fig. 12.

By adopting the semi-dual exhaust system in which two exhaust pipes have almost the same length, torque was raised in the desired, mid speed range. (Fig. 13)

Fig. 12 Volumetric efficiency calculated



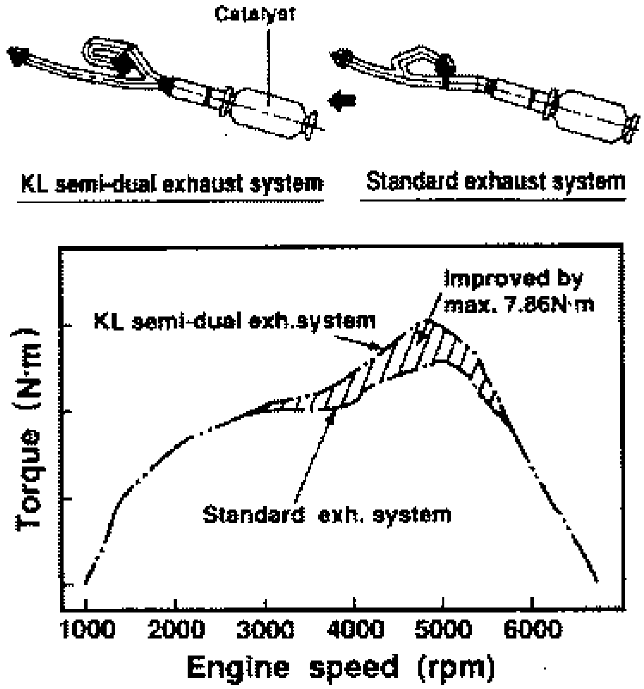




	L1 (mm)	L2 (mm)	V1 (L)	V2 (L)	D
STD	300	180	—	—	ø42
SPEC.1	800	800	—	—	↑
SPEC.2	800	200	—	0.8	↑
SPEC.3	200	200	0.8	0.8	↑

Fig. 13 Effect of KL engine semi dual exhaust system

Fig. 14 Crank angle sensor



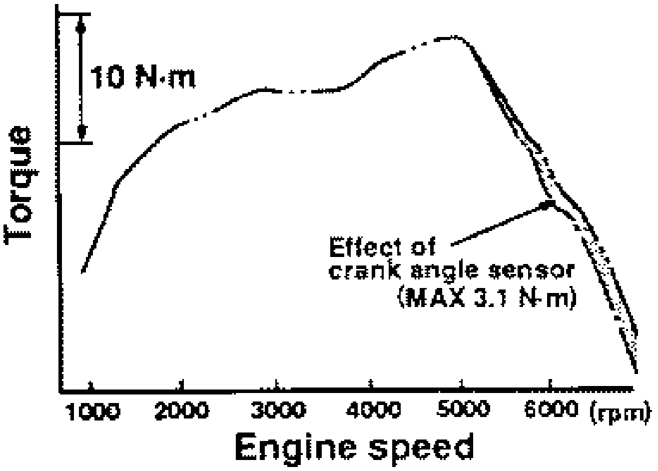


Fig. 15 Effect of crank angle sensor

Ignition control was optimized to raise torque in low and high engine speed ranges. First, to improve the control of ignition timing in the high speed range, a new direct crank-angle- detection method (crank-angle-sensor) was chosen over the conventional method, in which the angle was detected by a distributor attached to the camshaft. (Fig. 14) Fig. 15 shows the effect of the crank angle sensor on torque enhancement.

With trace knock control, a single sensor between the engine V-banks detects small knocking, and the ignition timing is then set at a point just prior to the generation of the knocking in low speed ranges. In the conventional method, ignition timing was set in consideration of engine compression ratio and fuel octane number. (Fig. 16) The trace knock control optimizes ignition timing. And this optimizes engine potential, which in turn raises torque. (Fig. 17)

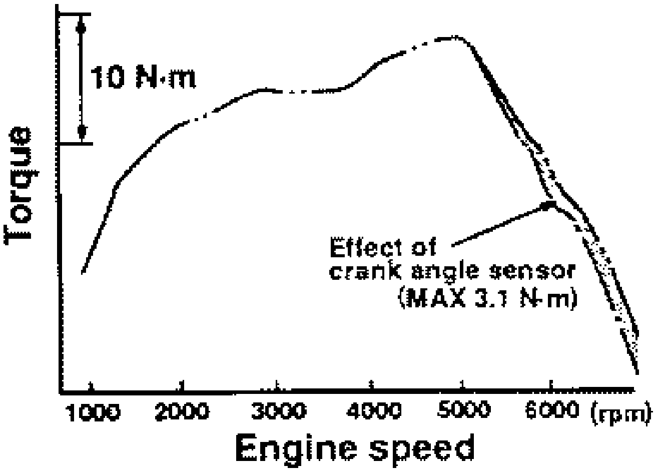


Fig. 16 IG timing with/without trace knock control(T.K.C)

Fig. 17 Effect of trace knock control(T.K.C)

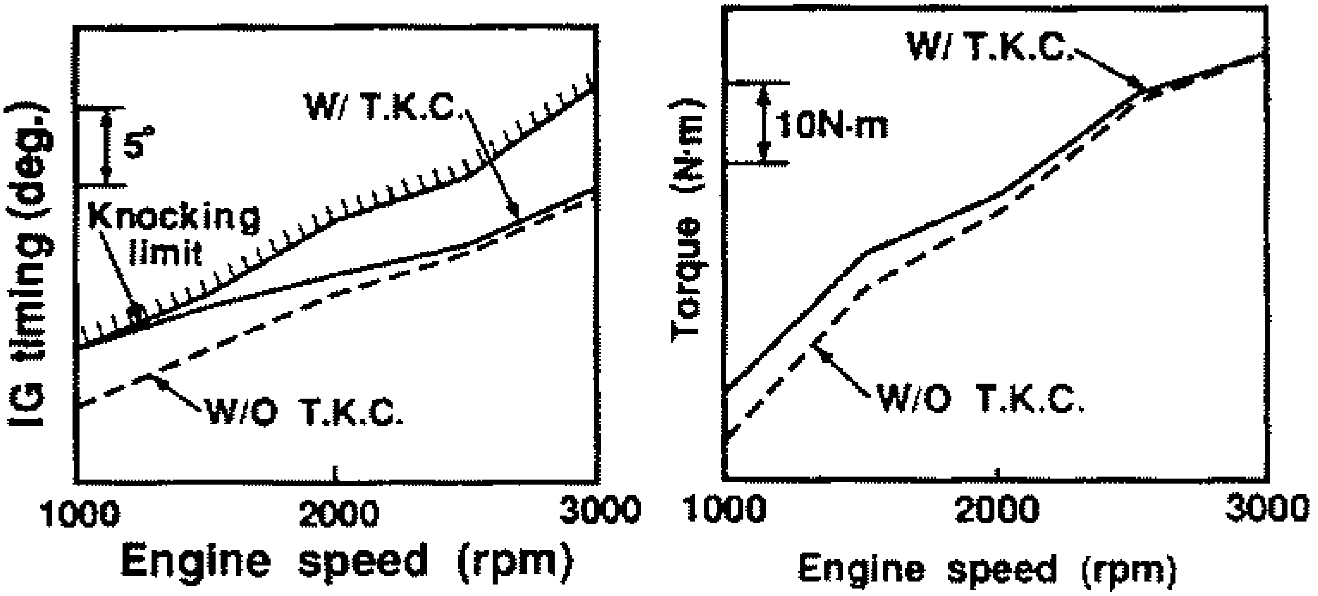
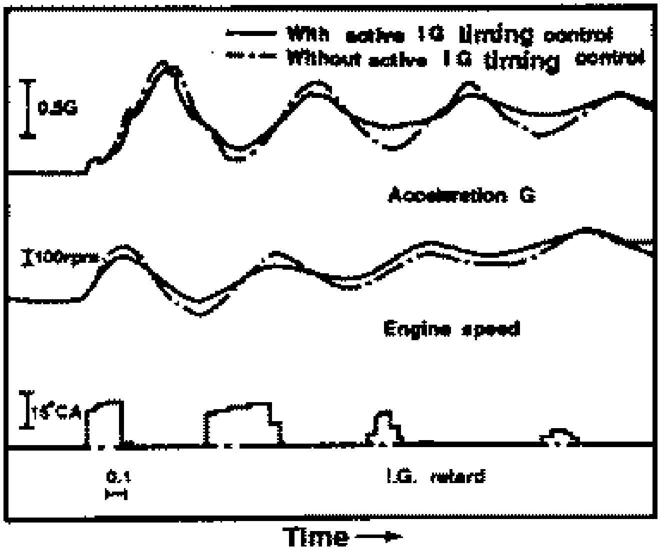


Fig. 18 Active IG timing control and its effect



Reduction of Inertia Weight of Rotating Parts - 24-valve DOHC short stroke was adopted as the basic specifications. Furthermore, the rotating inertia weight of the flywheel, crankshaft, and connecting rod was drastically lowered by making full use of Finite Element Method (FEM) analysis and acceleration response was greatly improved.

Optimization of Control - Ignition timing is actively controlled with crank angle sensor which detects changes in angular velocity of engine during acceleration; if vehicle vibration is generated, the timing is retarded, thus quickly converging vehicle acceleration value fluctuations which diminish acceleration feel, and improving acceleration in response area. (Fig. 18)

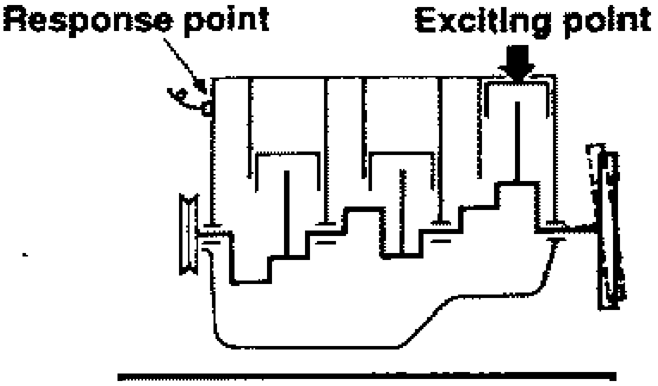
Because of the above new technologies and structure, KL engine can deliver the demanded torque characteristics and acceleration performance, while maintaining high and smooth acceleration characteristics.

PLEASANT ENGINE SOUND - Great efforts have been made not only to reduce engine vibration and noise levels but also to produce a more pleasant engine sound. To realize these objectives, engine development efforts were concentrated on the following two areas: 1) elimination of unpleasant rumbling sounds and 2) reduction of low-frequency sounds. Table 4 shows the incorporated techniques and the objectives.

Table 4 Techniques for sound quality improvement

Technical menu	decrease of rumbling noise	decrease of low frequency noise
Lower block	X	
No.4 journal widened up	X	
Forged steel crankshaft	X	
Lightweight piston & conn-rod	X	X

Fig. 19 Vibration characteristic of cylinder block



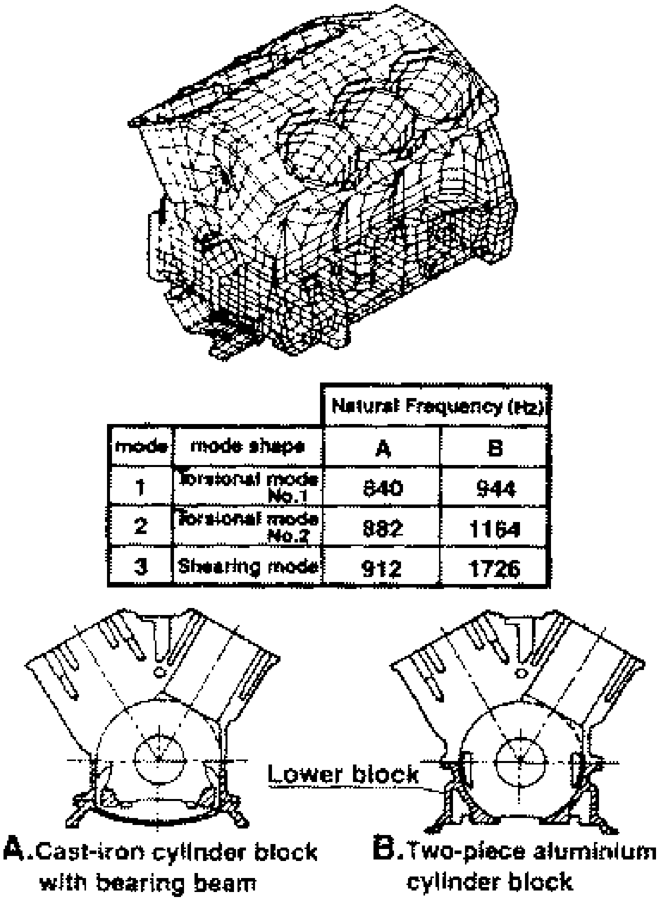
Increased transmission coupling rigidity		X

Elimination of Rumbling Noise - Unpleasant rumbling noises are often caused by crankshaft bending vibration due to flywheel face runout. This vibration is propagated through the cylinder block main bearing, block body, engine mount and vehicle body and results in an unpleasant rumbling interior noise. To reduce the noise, the engine mount's vibration level (inertance level), which responds to excitation in the cylinder, should be lowered.

Fig. 19 shows the engine mount vibration level when each cylinder is excited, the resonance mode increases the vibration level of the nonfundamental order components at which the unpleasant sound is often noticed. (4) To improve the flywheel resonance mode, that is, to reduce the inertance level and increase frequencies, cylinder block rigidity and crankshaft support rigidity of the main journal were increased.

The vibration characteristics depends on dimensions and configurations, and the optimal configurations were studied through FEM analysis. As a result of the study, a two-piece cylinder block was employed to increase rigidity of both the cylinder block itself and its crankshaft supporting area. The cylinder block was divided into upper and lower sections at the crank center face and the lower block was given a ladder frame construction integrating the main-bearing cap and bearing beam. Fig. 20 shows a comparison of rigidity between the cast-iron cylinder block and the two-piece cylinder block employed in KL engine. The conventional cast-iron cylinder block was fitted with a bearing beam and a plate connecting the cylinder block skirts to increase the rigidity of the cylinder block itself. Generally, open-decked aluminum cylinder blocks give a lower rigidity than cast-iron blocks. Nevertheless, by adopting the new cylinder block construction, the natural frequency of the block itself was increased.

Fig. 20 Comparison of cylinder block rigidity



		Natural Frequency (Hz)	
mode	mode shape	A	B
1	Torsional mode No.1	840	944
2	Torsional mode No.2	882	1164
3	Shearing mode	912	1726

For further reduction of flywheel face runout, the lower deck's No.4 journal near the flywheel was made wider than the other journals. In addition, a forged steel crankshaft was used to increase crankshaft bending rigidity. Fig. 21 shows the reduced inertance level and the increased frequency of flywheel resonance mode. By improving the vibration transmission structure, nonfundamental order components decreased from those of cast-iron block with the conventional construction. (Fig. 22)

Fig. 21 Improvement of crankshaft supporting rigidity

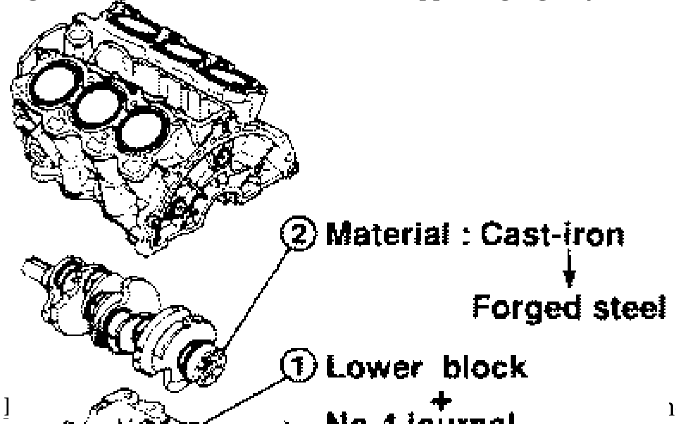
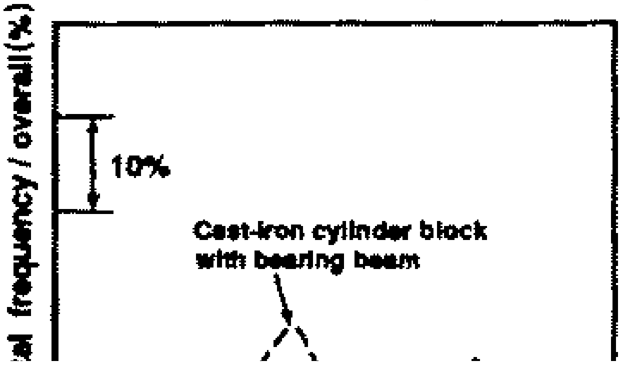


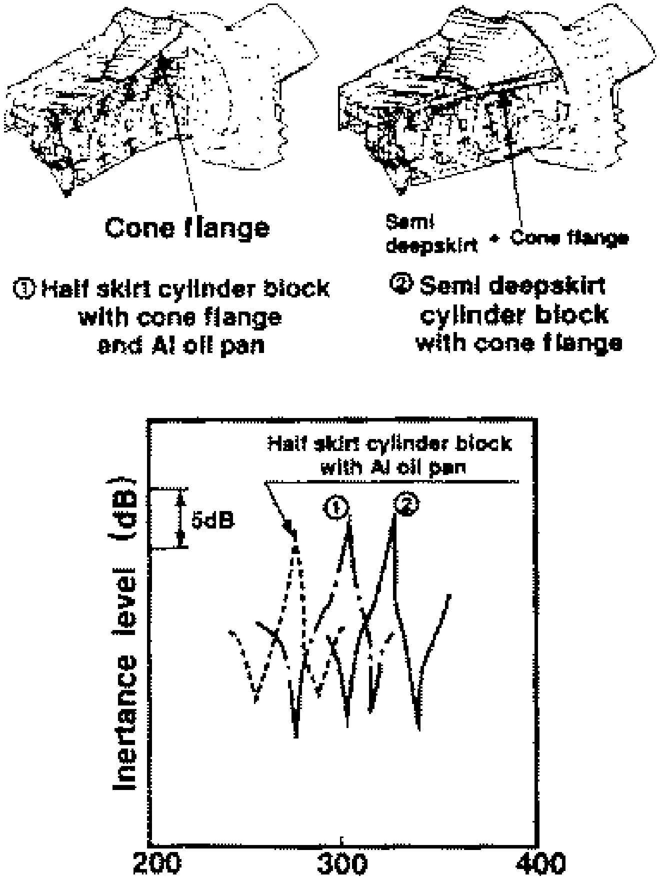
Fig. 22 Reduction of nonfundamental frequency level of KL engine



components. To do this, powerplant bending (PPB) vibration and second-order inertia couple were reduced.

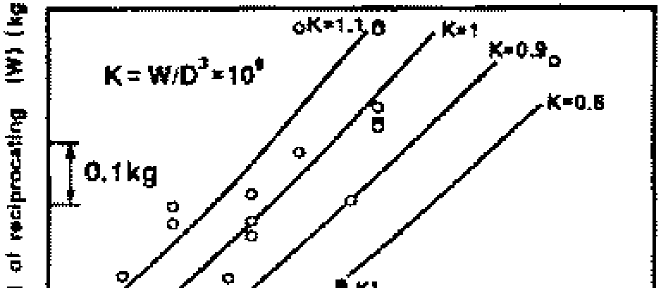
To reduce PPB vibration, coupling areas between the cylinder block and transmission should be made highly rigid. Transmission coupling rigidity was understood to be increased effectively by lengthening the cylinder block skirt and widening the coupling flange (cone flange). Fig. 23 shows the improvement effect of the above changes on in-line 4-cylinder engines' PPB vibration level calculated with FEM.

Fig. 23 MAZDA's basic concept for improvement power-plant bending (PPB) vibration



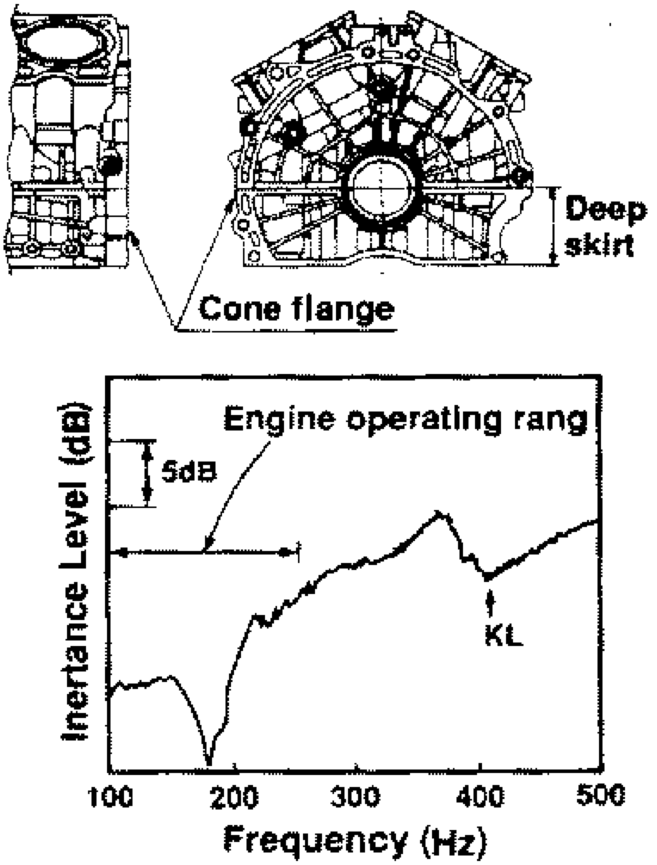
To decrease second-order inertia couple, piston and connecting rod weight, which cause excitation, were reduced by making full use of FEM analysis. As shown in Fig. 25, the reciprocating inertial weight of the piston and connecting rod is lower than all the other reciprocating inertia weight with equal diameter. Because of the reduction of PPB vibration and second-order inertia couple, the KL engine reduces the second-order vibration level which causes most low-frequency noise.

Fig. 25 Comparison of reciprocating inertia weight



Based on these results, PPB vibration in the KL engine was reduced by adopting a cone flange with high rigidity as well as a longer skirt. Fig. 24 shows the PPB natural frequency characteristics of the KL engine. PPB resonant frequency was increased to the point where no resonance was produced in the engine operating speed range (less than 7,500 rpm) - even with second-order excitation.

Fig. 24 PPB frequency characteristic of KL engine



COMPACTNESS - To match the low hood & short nose vehicle style, the engine height, width and length were reduced. With a unique direct valve drive, combined with the adoption of a compact intake manifold and a compact cylinder block, the low hood could be realized. The valve drive system, as shown in Fig. 26, employs gears which directly engage each bank's intake and exhaust camshafts, and a timing belt attached to the rear bank's inner camshaft and the front bank's outer camshaft. This layout made it possible to reduce the height of the engine front as shown in Fig. 27. Also, this system, along with the adoption of a compact exhaust manifold, has reduced engine width. The combination of these design features gives KL engine the most compact packaging sizes in their displacement classes.

Fig. 26 Valve train system

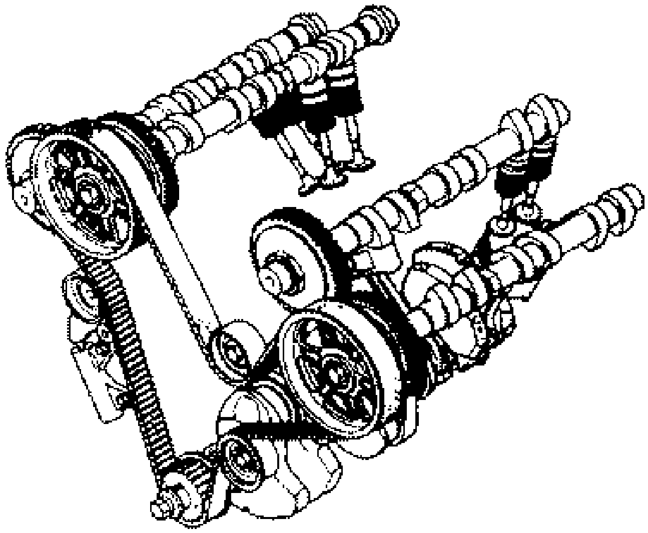
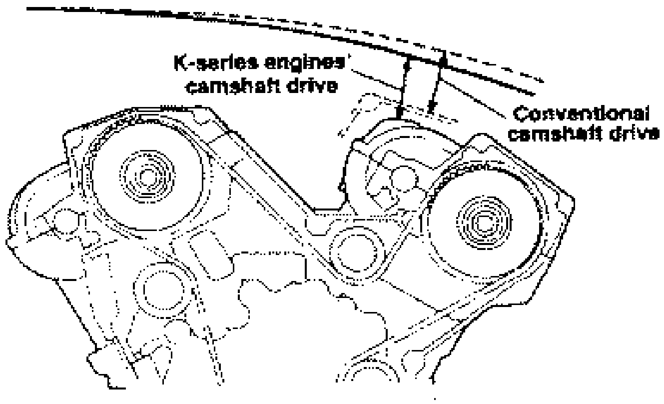


Fig. 27 Comparison of hood line



LONG LIFE AND MAINTENANCE-FREE - Efforts were made to extend the life of these engines and make them as maintenance-free as possible so that customers can be pleased with the vehicle's quality long after the initial driving period.

Long Life - The following achievements were made to ensure extended low engine oil consumption: Piston land volume and piston ring configuration were optimized through simulation analyses for stable ring behavior; and wear resistance of the cylinder liner was improved by the use of alloyed cast-iron.

The oil seal material (camshaft and crankshaft oil seals) was changed to fluorine to improve thermal resistance.

Maintenance-Free - Mazda's unique ventilation system comprises a PCV valve in the left bank and a forked ventilation hose connecting the air hose and both banks, providing the right bank a higher rate of air flow than the left bank (7:3). With this mechanism, fresh air flows in the crankcase and cylinder head cover effectively, thus ensuring stable oil characteristics.

A timing belt having STS-teeth and a hydraulic auto tensioner were designed as follows to have long-life quietness:

- Optimization was made on timing belt pitch, ejector force and leak-down time of the auto tensioner.
- H-NBR having high heat resistance and glass fiber having high bending resistance were used for the timing belt, realizing the reduction of belt width to 30mm while ensuring a satisfactorily long life.

The Hydraulic Lash Adjuster (HLA) has oil recirculation passages in its plunger to recycle the less-air-contaminated oil in the high-pressure chamber. This construction minimizes the influence of air-contaminated oil -- even in the engine-startup condition with high-air-contaminated oil -- resulting in improved quietness and the elimination of the need for valve clearance adjustment.

MAIN STRUCTURAL COMPONENTS

In this section, techniques other than those discussed above are summarized on the basis of components and systems:

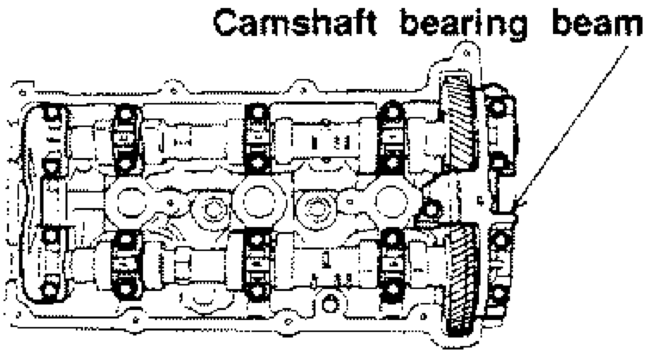
BASIC ENGINE - Cylinder Block - Die casting was utilized in the production of the aluminum cylinder block. Making use of this method's high precision and ability to produce thin-walled components, a lightweight cylinder block was realized.

In the upper block, a 3mm-thick cast-iron cylinder liner is cast-in to add durability, and plateau honing with a GC grindstone is performed for the liner to stabilize initial oil consumption. A siamese open deck with optimized liner thickness and bolt pattern ensures cooling between bores and suppression of liner deformation. In the lower block, a cast-iron main bearing cap is cast-in to control main bearing clearance fluctuations resulting from temperature changes. This new Mazda technology has been implemented to achieve quietness and improve reliability.

Cylinder Head - Low-pressure casting was utilized to refine the aluminum micro-structure, improving strength and thus reliability. Further, AC4D, with its superior thermal conductivity, is used to improve antiknock performance.

The gear housing is mounted on the front of the cylinder head and is supported on both sides of the gears by camshaft caps. In addition, a camshaft cap beam which attenuates gear engagement vibration is used on the right bank to improve supportability (Fig. 28)

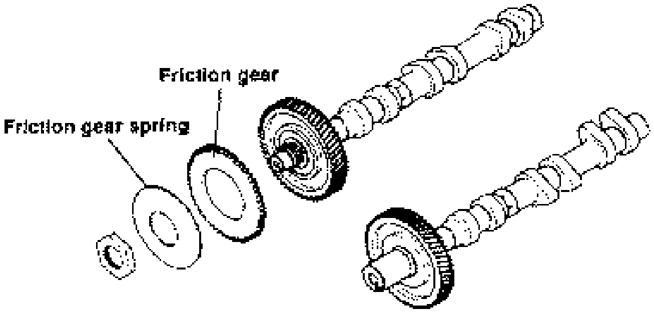
Fig. 28 Camshaft bearing beam



The engine's asbestos-free laminated cylinder head gaskets are composed of two sheets of stainless steel and have the ability to resist the high explosive pressures of the combustion chamber. They form an effective seal against oil and water leaks, and pose no threat to the environment. The cylinder head bolts, which join the cylinder head and cylinder block, are tightened in the plastic region to stabilize axial forces.

Camshaft Friction Gear - Between the two camshafts are drive and driven gears with 55 teeth each and a friction gear with 56 teeth. The friction gear, superimposed on the driven-gear by spring force, was designed to be free from backlash with its extra tooth. The friction resulting from this structure absorbs fluctuations in drive-gear rotation, effectively suppressing gear rattle noise. In addition, tooth flank precision is optimized through simulation techniques to eliminate gear engagement noise. (Fig. 29)

Fig. 29 Friction gear mechanism



Piston - The die-cast aluminum short-skirt pistons developed are light and yet reliable for continuous high-speed operation. The piston rings comprise two compression rings and one oil ring. By applying Molybdenum disulfide coating on the sliding face of the piston skirt, a decrease in piston clearance was achieved with no increase in sliding resistance, thus preventing piston "slapping." This results in improved quietness in the high-speed range.

Connecting Rod - To reduce both weight and weight variation, a weight adjustment cut-off boss is mounted to the large end, with the actual adjustment taking into account the weight variation of the small end. A connecting cap is joined to the rod by means of plastic-region tightening bolts (without nuts). This tightening method reduced weight in the large end and ensures highly stable axial forces.

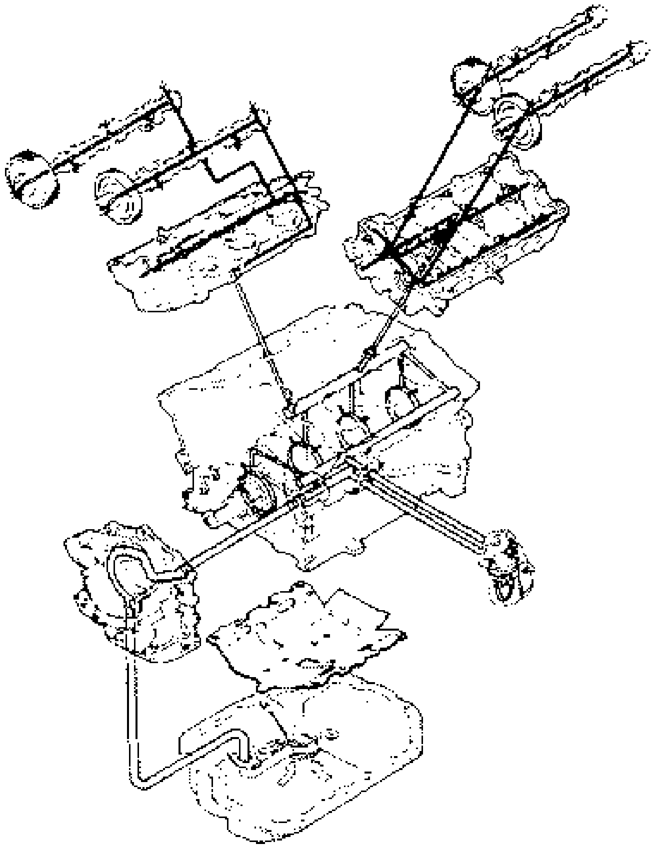
Crankshaft - To ensure reliability, the crankshaft is composed of forged steel; five counterweights are adopted to achieve light-weight; the bearing fillets are heavy-duty rolled to increase fatigue resistance; the journals are high-frequency hardened, then mirror finished; and heavy-duty three-layer copper-lead bearings are used to ensure adequate durability.

LUBRICATION SYSTEM - Mounted to the front of the engine is a highly efficient trochoid oil pump, which is directly driven by the crankshaft and has nine internal and ten external teeth. To reduce vibration and noise caused by oil pressure fluctuations on the delivery side, the clearance with the inner rotor on the crankshaft was adjusted and the configuration of the partition between the suction and delivery sides was optimized.

To control output loss caused by crankshaft oil diffusion and to reduce the amount of air in the oil, superior oil baffle plate configuration has been adopted. Combined with the revision to the oil strainer configuration, it ensures stable pressure even when the oil level varies during high-speed cornering.

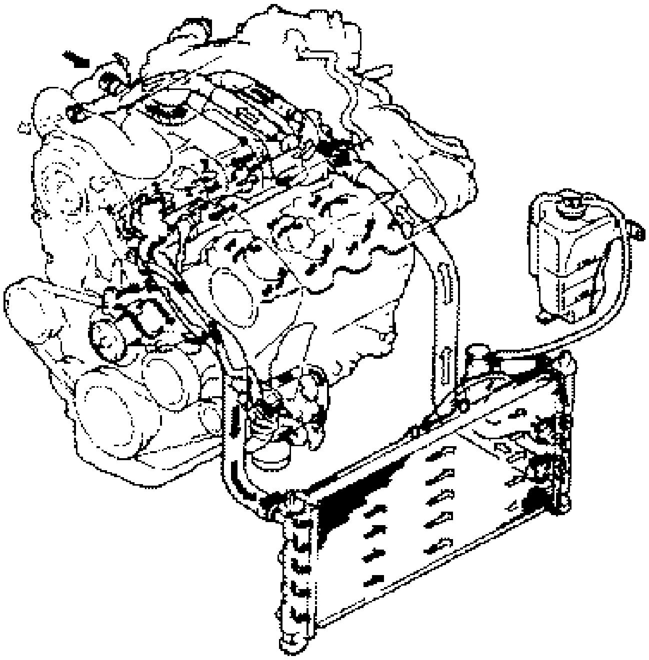
A water-cooled oil cooler and piston-cooling oil jet are employed to increase durability against high-temperature loads. (Fig. 30)

Fig. 30 Lubricating system



COOLING SYSTEM - A belt-driven centrifugal pump supplies coolant evenly to the left and right banks. To prevent the temperature of the coolant in the cooling circuit from rising too rapidly, such as during a cold start, an inlet thermostat mechanism is utilized. Adoption of a two-stage electric cooling fan brought about noise reduction. (Fig. 31)

Fig. 31 Cooling system



FUEL SYSTEM - A microcomputer-controlled sequential electronic fuel injection system containing several unique characteristics has been adopted.

First side-feed method, where fuel is supplied from the side of the injectors, is used to reduce the discharge of vapor produced from rising fuel temperatures. This results in improved engine restartability after high-speed and/or high-load driving. Second, the weight of the injector's mobile parts has been reduced to improve response and lessen operating noise. Third, an internal fuel control mechanism is utilized to ensure that injected fuel quantities will not change with vehicle age. Finally, a harness attached to fuel distribution pipe improves the exterior view of the engine and adds to its compactness.

MANUFACTURING INPUT - To guarantee top-quality engines, several manufacturing technologies had to be developed.

Casting Techniques - To obtain consistently high quality, automatic casting of the cylinder head and cylinder block was introduced. All important technical casting data such as mold temperatures and pressures, are fed back to the control unit.

Machining Techniques - The following highly precise machining techniques were adopted to ensure high reliability under high-load/speed driving conditions: Precise mirror-like surfaces of the crankshaft pins and journals with oil passages are obtained from triple-lapping and a precise surface of the cylinder block main bearing is achieved through triple-honing. Simulating the conditions when head bolts are tightened, machining of the holes in the cylinder head cam journals is done to prevent changes in precision caused by tightening head bolts.

Assembling Techniques - To obtain consistent product quality in the production line in which various types of engine are produced, 60% of the assembly line for K-series engines are controlled automatically by computer.

CONCLUSION

The K-series engines contain all the design techniques Mazda has developed, including combustion chamber, intake/exhaust systems, electrical controls, noise reduction and reliability, for high performance engines.

The K-series engines described in this paper are mounted in the new Mazda 626, MX-6 and MX-3 vehicles. The authors are quite confident that the various development objectives required to these vehicles have been achieved at a high level, making use of the above techniques. The following four points summarize the accomplishments made in developing the K-series engines.

1. K-series engines have achieved low fuel consumption and low emissions by adopting a compact, high-squish combustion chamber and optimizing all controls by microcomputer.
2. High smooth vehicle acceleration characteristics that give excellent "acceleration and top-end feel" have been gained because of two improvements: a compact design that makes full use of intake and exhaust dynamic effect; and an engine control system that optimizes ignition timing.
3. With a more rigid cylinder block and a more rigid crankshaft support structure, low-frequency noise was reduced and rumbling noise suppressed, resulting in a pleasant engine sound.
4. A design that aimed for reduced weight and compactness, realized by such modifications as an aluminum cylinder block and an integrated surge tank/inlet manifold, has made the K-series engines the lightest and most compact in the same displacement class of V6 engines, thus contributing to improve fuel consumption and realize a lower hood styling.

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