

Research for Emissions Reduction Systems for Small Motorcycles

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ABSTRACT

Emissions regulations for small motorcycles are becoming increasingly stringent every year in various countries throughout the world. Therefore, we conducted research on high-precision control of the air-fuel ratio with an emissions reduction system for small, fuel-injection motorcycles, in particular, for motorcycles equipped with a 100cm³ four-stroke engine. Fuel injection is controlled by two injection amount maps applied according to throttle opening, engine speed and intake pressure. The control index used in this control system maintains the engine intake pressure peak when the intake valve is open in order to eliminate the major impact of intake pressure fluctuation exhibited by single-cylinder engines. Moreover, O₂ feedback control and three-way catalyst systems were applied for exhaust emissions purification, and a small, power-saving fuel pump was developed to improve fuel economy.

In addition, a control system to obtain excellent starting ability with a kick starter was also developed. By adopting these systems, hydrocarbons were decreased to about 1/30 of the regulation value provided in the European motorcycle emissions regulation "Directive 97/24/EC chapter 5" (EURO-1), and the fuel economy was improved by approximately 20% compared to the base engine.

1. Introduction

Emissions regulations for small motorcycles are becoming increasingly strict every year. For example, in Thailand, a major market for 100cm³ small motorcycles, the fourth emissions regulation is currently in force, and the even more restrictive fifth emissions regulation is scheduled to be introduced in 2003. Table 1 shows emissions limits for motorcycles in major regions.

To this point, most emissions reduction systems for small motorcycles have been based on the use of a carburetor, air injection, and catalyst in combination.

When fuel is supplied by the carburetor, there is a limit to the precision with which the air-fuel ratio can be controlled, and in recent years it has become difficult to both improve emissions purification and maintain driveability.

Therefore, research has been conducted on the incorporation of fuel injection in 100cm³ four-stroke engines as an effective means of reducing emissions for small motorcycles.

This paper describes how we adapted a fuel injection system and an exhaust-gas conversion device for small motorcycle applications, and the results that we achieved.

2. Target Emissions Levels

One focus of this research was to reduce THC emissions, so we set our THC target level to the same level mandated for passenger vehicles under Japan's 2000 emissions regulations. This level is approximately 1/30 of the THC standard in Europe's "Directive 97/24/EC chapter 5" (EURO-1) motorcycle emissions regulations. We also set the same levels called for in the above regulations for CO and NOx emissions. Table 2 summarizes the target emissions levels that we set for this research.

Table 1 Current emission limits for motorcycles

	CO (g/km)	THC (g/km)	NOx (g/km)
EURO-1 (4 stroke)	13	3	0.3
Japan (4 stroke)	13	2	0.3
Thailand Level 4	4.5	3 (combined)	

Table 2 Targets emissions

	CO (g/km)	THC (g/km)	NOx (g/km)
Targets	0.67	0.08	0.08

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3. Overview of Test Engine

Our test engine was a Honda 100cm³ four-stroke engine used widely around the world. Table 3 lists the major specifications for this engine.

Table 3 Major specifications of the test engine

Items		Specifications
Bore × Stroke	(mm)	50.0 × 49.5
Displacement	(cm ³)	97.2
Compression ratio		8.8
Valve system		OHC 2 Valve
Max. power	(kW / r / min)	5.32/8000
Max. torque	(Nm / r / min)	7.23/6000

4. Issues Concerning the Utilization of Fuel Injection

Some of the technologies that are commonly used for emissions reduction are listed below.

- (1) Use of fuel injection in the fuel supply devices, with precise control of the air-fuel ratio.
- (2) O₂ feedback control that monitors the density of O₂ in the exhaust gas and adjusts the air-fuel ratio to the stoichiometric air-fuel ratio.
- (3) Installation of a three-way catalyst in the exhaust pipe, purifying the exhaust gas through oxidation and reduction.
- (4) Introduction of secondary air in the exhaust port to promote the purification of unburned gases.

In order to apply such devices in a small-displacement single-cylinder engine used in a small motorcycle, it is necessary to be able to control minute quantities of fuel, keep the weight light, prevent a decrease in engine output, and keep costs low.

The following issues needed to be addressed:

- (1) The fuel supply control would have to be suitable for single-cylinder engines, which exhibit major fluctuations in engine intake pressure.
- (2) The installed catalyst must not lower engine output.
- (3) The system must reduce the electrical load on the engine as the electrical load has a negative effect on fuel economy.
- (4) The engine must still be startable by means of a kick starter.

5. Overview of the Emissions Reduction System

Fig. 1 shows the emissions reduction system that we adopted. A 16-bit CPU is used for the fuel injection ECU. The ECU controls the fuel injection amount, the fuel injection timing, and the ignition timing. The ECU controls the fuel injection amount in response to the O₂ density that is detected in the exhaust gas by an oxygen sensor installed between the engine and the catalyst. Fuel is delivered to the injector under pressure by a power-saving internal gear-type fuel pump located in the fuel tank. In order to reduce the electrical

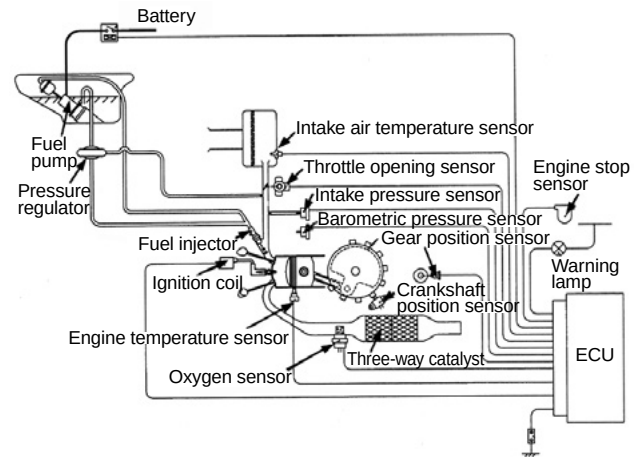


Fig.1 Emission reduction system

load of the fuel pump, the fuel supply pressure is set at 250kPa. By adjusting both the carburetor specifications and the intake pipe length, we were able to maintain the engine torque characteristics and by reducing the number of curves in the exhaust system, we were able to lower the exhaust resistance. The injectors are positioned so that the fuel injection is directed at the back of the inlet valve. Fig. 2 shows the location of the inlet system. The exhaust-gas conversion system has the metal substrate of the three-way catalyst located inside the muffler.

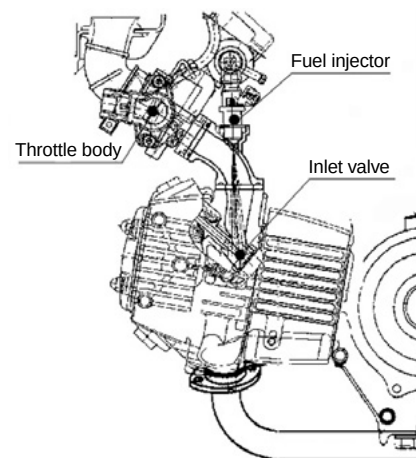


Fig.2 Air intake system

6. Fuel Supply Devices

6.1. Fuel Injection Control

We decided to use a fuel injection system with two injection amount maps. The switching between the two maps is controlled in accordance with the throttle opening and the engine speed.

- (1) At low loads, slight changes in the throttle opening are detected by the engine intake pressure, and an engine intake pressure injection amount map based on the engine intake pressure and the engine speed is used.
- (2) At high loads, a throttle injection amount map that is

based on the throttle opening and the engine speed is used, allowing continual detection of changes in the throttle opening.

Although it is necessary to know the engine intake pressure as an indicator for controlling the amount of fuel injection, the combustion interval in a single-cylinder engine is 720 degrees, so there are large fluctuations in the intake pressure on which the fuel injection amount control is based.

As shown in Fig. 3, the engine intake pressure varies during the combustion interval. Therefore, the value of the engine intake pressure sensor output varies according to when the output is checked, which means that it cannot be used for controlling the amount of fuel injection. In the system that we developed, the ECU stores the peak engine intake pressure while the inlet valve is open, and then uses that value as the indicator for controlling the amount of fuel injection.

In a conventional fuel injection system, reluctors are located every 30 degrees on the crankshaft in order to determine the rotational angle of the crankshaft. These reluctors were used in combination with the signal from the camshaft position sensor in order to determine the rotational angle and stroke of the crankshaft. In our system, we have eliminated the camshaft position sensors. Instead, we left a 120-degree interval between the reluctors in just one location. The system is then able to determine the position of the crankshaft by detecting the location of this longer interval. The stroke is determined on the basis of the difference in intake pressure between the intake stroke and the expansion stroke.

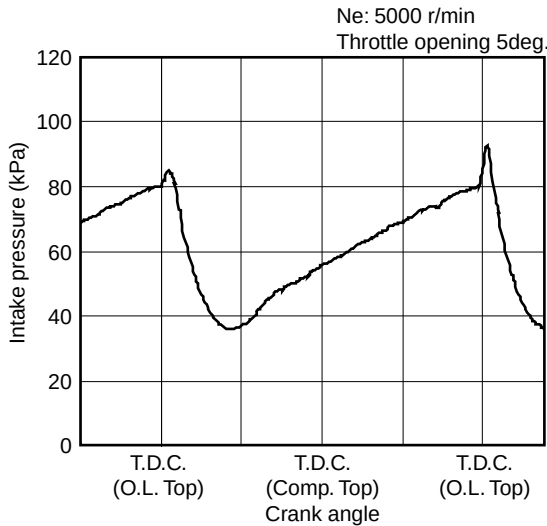


Fig.3 Change of engine intake pressure

6.2. Fuel Injector

In order to use fuel injection in a small displacement engine, it was necessary to adopt a small-flow injector that was suited to measuring out minute quantities of fuel. Table 4 lists the fuel flow specifications for two injectors.

We used three types of injectors to study the effect of fuel particle diameter on emissions: pintle nozzle injectors, four-hole plate injectors, and air assist injectors.

Fig. 4 shows the injection forms and Sauter's Mean

Table 4 Fuel flow specifications of injectors

Items	Developed Injector	HONDA VFR800FI
Dynamic Injection quantity at 2 msec ($\text{mm}^3/\text{stroke}$)	1.68	4.38
Static Injection quantity(cm^3/min)	107.5	248.5

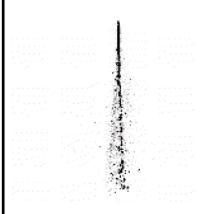
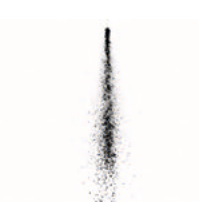
Pintle nozzle	4-hole plate	Air assist
		
S.M.D.:125 μm	S.M.D.:95 μm	S.M.D.:40 μm
Measurement conditions: Fuel pressure: 250kPa Assist air pressure: 26kPa S.M.D.: Measured by LDSA		

Fig.4 Forms of injectors and Sauter's mean diameter

Diameter (S.M.D.) for each of the injectors that we tested.

Because small motorcycle engines usually operate at high revolutions per minute, the inlet valve is usually open for only a short period of time. As a result, some of the injected fuel does not directly enter the combustion chamber; instead, it stays around the back of the inlet valve which has become heated. The fuel is vaporized by the heat and then enters the combustion chamber. Therefore, in testing of the ECE40 mode, which has a warm-up cycle, we were not able to determine whether the atomization produced by different injectors was effective in reducing emissions or not. As a result, we performed an emissions comparison test in LA-4 mode which does not have a warm-up cycle.

Our results indicated that LA-4 mode is more suitable than ECE40 mode as a means of evaluating injector particle diameters. Fig. 5 shows that in LA-4 mode, when using a pintle nozzle, greater atomization produced a decrease in CO and THC, but an increase in NOx. When these results

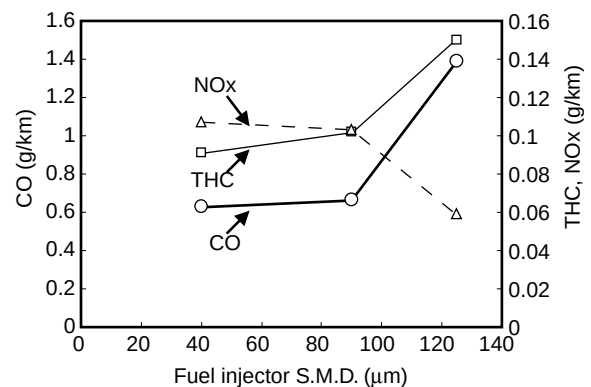


Fig.5 Emission results in LA-4 mode

were compared with results obtained using a four-hole plate injector and an air assist injector, no major differences in emissions were found. As a result of these findings, we elected to utilize the four-hole plate injector due to its simple structure and low cost.

6.3. O₂ Feedback System

To keep the air-fuel mixture at the stoichiometric air-fuel ratio, we adopted a feedback system that uses an oxygen sensor in order to efficiently utilize the performance characteristics of the three-way catalyst installed in the exhaust system. In a single-cylinder engine, fuel is injected into the cylinder once for every 720 degrees of crank rotation. As a result, there was concern that the effects of slow injection control and the exhaust pulse would prevent the oxygen sensor from generating a stable output. Because the relationship between the oxygen sensor output and the air-fuel ratio is not linear, we artificially increased and decreased the fuel supply and used feedback control to control the air-fuel ratio. We were able to implement O₂ feedback control effectively by shortening the cycle as compared with a conventional four-cylinder engine.

7. Exhaust-gas Conversion Devices

7.1. Catalyst Location and Early Activation

In order to activate the three-way catalyst early and promote purification, it is necessary to locate the catalyst in a position where the exhaust gas is hot. However, the exhaust resistance at such a position is high. In order to attain the required output, it is necessary to reduce the exhaust resistance. We studied the placement of the catalyst in a location that would be able to satisfy these two opposing requirements. Fig. 6 shows the exhaust gas temperature at different points in ECE40 emissions measurement mode.

In ECE40 mode, there are two warm-up cycles prior to the measurement cycle; it is essential that the catalyst become fully activated during these two cycles. Therefore, we set the target catalyst activation temperature at the third peak of the first cycle in ECE40 mode to at least 350°C. In our test engine, we were able to achieve the target temperature by locating the catalyst at a position within 480mm of the exhaust valve. After performing computer simulations with the purification rate required by the exhaust gas volume, we settled on a catalyst substrate cell number of 300, and a

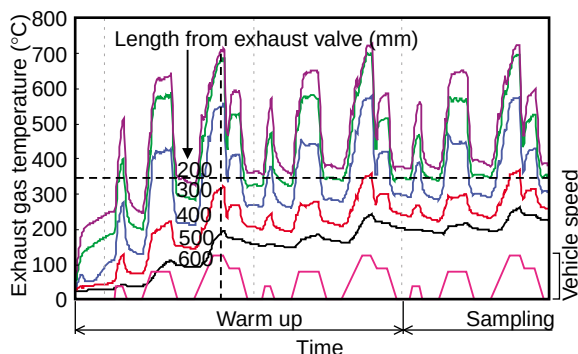


Fig.6 Exhaust gas temperature (ECE40 mode)

volume of 250cm³. Regarding catalyst placement, we studied two cases with catalysts of different diameters, as shown in Table 5.

Figs. 7 and 8 show the results of THC emissions and output measurement in ECE40 mode.

Greater output is obtained when using the catalyst with the larger diameter because that catalyst permits utilization of the exhaust pulse in the pre-catalyst chamber, and because it has lower output resistance. However, because it permits little flexibility in setting the installation position, the catalyst ends up being positioned towards the rear of the exhaust system. This results in a lower catalyst temperature, which in turn results in a lower purification rate than with the smaller-diameter catalyst. In our system, we adopted a large-diameter (60mm) catalyst located 460mm behind the exhaust port, minimizing the decrease in output while still maintaining the catalyst activation temperature.

Table 5 Specification of Test catalyst

Items	Spec. A	Spec. B
Substrate material	20 Cr 5 Al	
Diameter (mm)	60	40
Length (mm)	90	90
Number of catalyst	1	2
Volume of catalyst (cm ³)	254	226
Substrate cell number (cpsi)	300	
Wall thickness (μm)	50	
Precious metal	Pt/Rh	

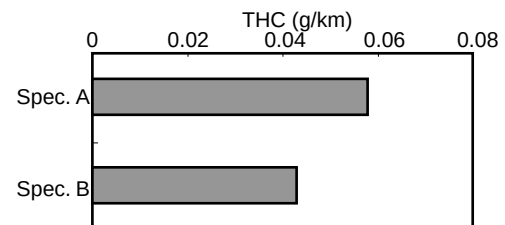


Fig.7 Result of THC emissions with different catalysts

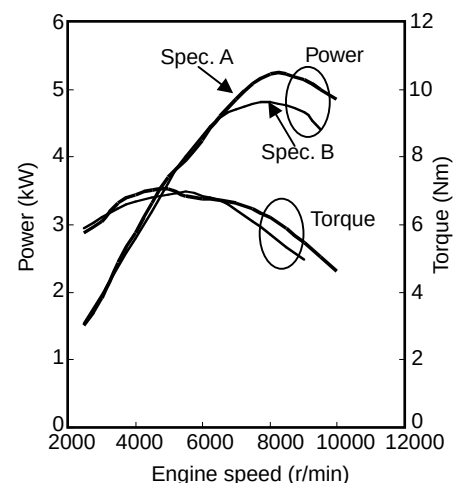


Fig.8 Engine performance with different catalysts

7.2. Secondary Air Induction System (Air Injection System)

We studied the effectiveness of reducing emissions by means of secondary air induction in the exhaust port. The ECU controls air injection by means of a solenoid valve so that air injection occurs when O_2 feedback is not functioning while the engine is cold and while the engine is idling. As Fig. 9 shows, one effect of early activation of the catalyst is an increase in temperature at the first peak in the initial stage of ECE40 mode, reducing the time until catalyst activation by 19 seconds. However, there was no difference in catalyst temperature from when emissions were measured.

Note that because the emissions reduction system that we developed met the emissions targets without air injection, we did not adopt air injection in our system.

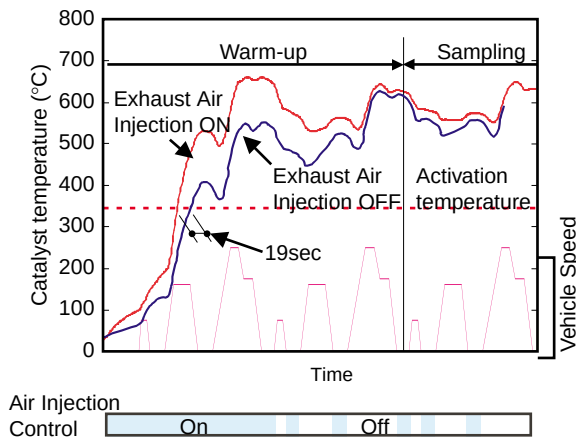


Fig.9 Catalyst temperature in ECE40 mode

8. Technologies for Improving Fuel Economy

8.1. Optimization of Ignition Timing

Because the ignition timing has a large effect on emissions, fuel economy, and driveability, we maintained the optimum ignition timing by using a three-dimensional map based on the throttle opening and the engine speed. Fig. 10 shows the ignition timing 3D map. In the partial area, we advanced the ignition timing by a maximum of 10 degrees versus the base engine in accordance with the throttle opening. The effect of this advance was a 5% improvement in fuel economy in ECE40 mode.

8.2. Low-current Fuel Pump

Because of the constraints on power generating capacity, a power-saving fuel pump is needed in small motorcycles. Therefore, we selected a high-efficiency capacity internal gear pump. Although we initially studied the use of automobile-application internal gear pumps, it was difficult to reduce the current because the large sliding surface area resulted in large friction loss. Therefore, in order to reduce the driving torque, we developed an internal gear with a smaller outer diameter and thickness. We also adopted a high-performance motor with rotors wrapped with a large

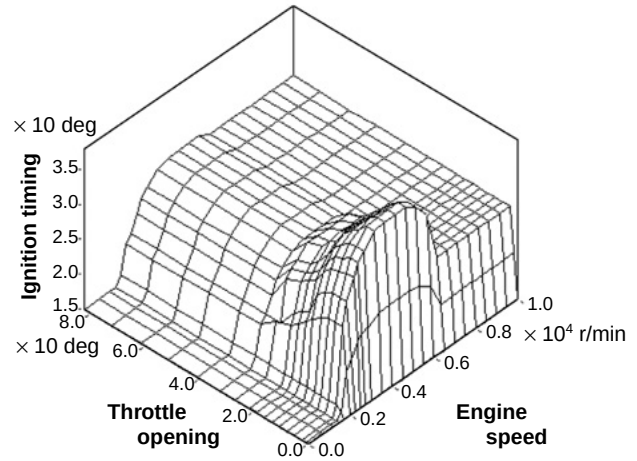


Fig.10 Ignition timing 3-D map

number of thin copper wires and magnets that generated a large magnetic flux density. We were able to reduce the current as a result and produce a power-saving fuel pump. Fig. 11 shows the characteristics of the automobile pump and the developed pump for motorcycles.

As shown in Fig. 12, by utilizing optimum control of the air-fuel ratio through fuel injection and by cutting down the fuel supply during deceleration, we were able to improve fuel economy in ECE40 mode by 20% versus the base vehicle.

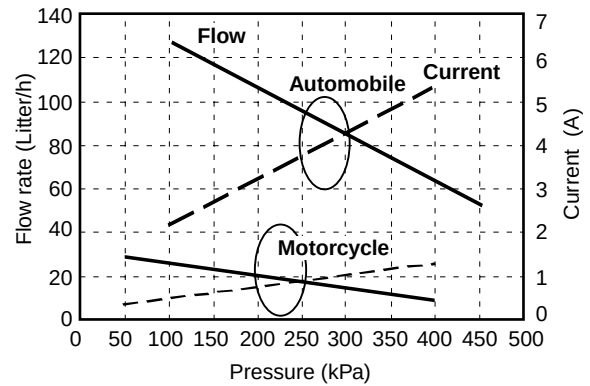


Fig.11 Features of pump developed for small motorcycles

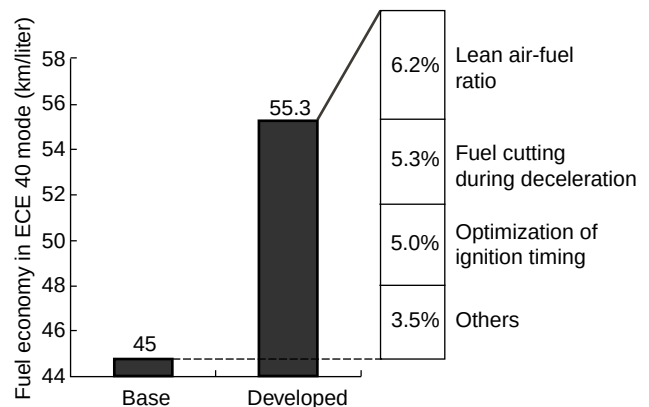


Fig.12 Fuel economy improvement

9. Control of the Kick Start

In small motorcycles, the startability of the engine with a kick starter is extremely important. Kick starting only rotates the crankshaft five or six times with one kick. Furthermore, fuel injection control requires about three rotations of the crankshaft from the start of rotation until fuel is injected in order to allow for detection of the injection interval and for operation time.

After eliminating the rotations in which there is no chance of ignition, there are only one or two rotations after a kick start during which ignition is possible. Therefore, startup can easily fail. In order to improve this situation, we introduced a special startup control system that detects the start of the rotation of the crankshaft by means of the signals from the crank position sensors; fuel injection begins when five signal pulses are detected. This control system allowed our system to start up at the same number of crankshaft rotations as the base vehicle.

10. Test Results

The results of emissions, fuel economy and output tests of our 100cm³, single-cylinder, four-stroke engine using a fuel injection system, O₂ feedback system and ignition timing control system are shown below.

- (1) Table 6 shows the ECE40 mode emissions targets and the test results.
- (2) Table 7 shows the fuel economy in ECE40 mode. Compared to the base motorcycle, fuel economy was improved by about 20%, from 45.0km/l to 55.3km/l.
- (3) Although engine output decreased from 5.32kW for the base engine to 5.22kW for our engine, Table 8 shows that our engine could still achieve a maximum speed and acceleration equivalent to the base engine.

Table 6 Test results of ECE40 mode emissions

	CO (g/km)	THC (g/km)	NOx (g/km)
Result	0.44	0.058	0.023
Targets	0.67	0.08	0.08

Table 7 Test results of fuel economy by ECE40 mode

	Fuel economy (km/l)
Result	55.3
Base	45.0

Table 8 Test results of power performance

	Maximum speed (km/h)	0-200m Acceleration time (sec)
Result	87	13.95
Base	86	13.95

11. Conclusion

In order to decrease small motorcycle emissions, we developed a fuel injection system, O₂ feedback system, three-way metal catalyst system, and ignition timing control system, all suited for a 100cm³ single-cylinder four-stroke engine. Adopting these systems made the following achievements possible:

- (1) By adopting a three-way catalyst and O₂ feedback, we were able to reduce emissions to 1/30 of the current EURO-1 regulations. The emissions in ECE40 mode are CO: 0.44g/km; THC: 0.058g/km; and NOx: 0.023g/km.
- (2) By using fuel injection to obtain a leaner air-fuel mixture, optimizing the ignition timing and adopting a low-current fuel pump, we were able to improve fuel economy by 20% compared to the base vehicle.
- (3) Our selection of the three-way catalyst installation position and size allowed us to achieve early activation of the catalyst while maintaining engine output.
- (4) By eliminating the camshaft position sensors and using engine intake pressure sensors, we were able to develop an inexpensive fuel injection system for small motorcycles.

References

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