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TRANSIENT PERFORMANCE OF AN SI ENGINE BY TRANSIENT RESPONSE SPECIFICATIONS

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ABSTRACT−The analysis and evaluation of the transient performance by the transient response specifications under various acceleration speeds and types based on driver's typical acceleration habit are implemented by the experimental study to provide the appropriate direction for the transient control in a gasoline engine. The concept of the transient response specifications which consist of delay time, rising time, maximum overshoot and settling time, and the analysis method using them are introduced to evaluate the characteristics of the transient performance quantitatively. Furthermore four acceleration speeds and four acceleration types are set respectively to realize the various transient states which are similar to the real drive. Several performance parameters in terms of engine speed, manifold absolute pressure, fuel injection duration and air excess ratio are measured simultaneously during the various acceleration using a throttle actuator controlled by a PC. The transient response specifications characterized well the transient performance for the various acceleration speed and types quantitatively. Delay and rising time with increment of the acceleration speed became shorter, but settling time did longer. Intensified acceleration type appeared to be the most economical in view of fuel consumption, and linear acceleration type was found to have the least harmful emission concentration.

KEY WORDS : Transient performance, Transient response specifications, Valve opening speed, Acceleration type

1. INTRODUCTION

Concerning the vehicle engines, studies have been proceeding with the power performance in the technical view point, the fuel consumption rate in the economical view point, and the emission or noise reduction in the environmental view point. These, however, are intended to affect each other exclusively, that is, if we put the value on the power performance more, economical efficiency is likely to be worse (Hilliard and Sprinter, 1998). It's very difficult to improve both simultaneously.

Drive consists of several modes, namely ignition mode, worming mode, steady mode, accelerating or decelerating mode and idling mode. Generally inside the city, the transient state like acceleration or deceleration takes place mostly in the drive. At the steady mode, as the volume of intake air is constant, ECU is able to measure air-fuel ratio accurately using O_2 sensor, to inject fuel for stoichiometric combustion, and to reduce harmful emissions effectively using a 3-way catalyst. Thus, good power, emission control and specific fuel consumption are all guaranteed.

At the transient state, however, because of the rapid variation of the intake airflow, undesirable phenomena which the fuel injection cannot follow it appropriately, power decreases, and emission increases appear (Benninger and Plapp, 1991). So there is a strong need for the more stable control in this transient period. Especially intelligent control like neural network (Lenz, 1997) is also being studied, and the simulations and experiments are being implemented by lots of engineers too. Nevertheless it would be impossible to design an appropriate algorithm for the transient control without accurate and quantified analysis and evaluation of the transient drive prior to the transient control. So the concept and method of a new analysis way by the transient response specifications will be introduced for the quantified reference in this work. Furthermore several transient states according to driver's accelerating habit or type will be set. In particular, we measure manifold absolute pressure, mass air flow, fuel injection duration, engine speed, air excess ratio, and emissions concentration in varying the acceleration speed and types, and evaluate the transient characteristics, finally suggesting the direction for the better transient control.

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2. CONCEPT AND ANALYSIS METHOD BY THE TRANSIENT RESPONSE SPECIFICATIONS

There are several frequent phenomena during the transient drive (Yukio and Hiroshi, 1982). They are hesitation as the response delay, stumble as the power shock during the acceleration, stretch as the slow acceleration with depression, and accelerating surge as the low frequency vibration. In this study, the method using the transient response specifications in terms of delay time, rising time, maximum overshoot and settling time in the control system is adopted for the evaluation method of the transient characteristics, since the method is thought to be suitable to quantify hesitation, stumble and stretch, and to show the partial transient behavior (Cho, 1993).

Figure 1 shows the transient response specifications adopted to this study. The time delayed until the response appears after throttle valve opening is defined as delay time t_d, the time taken till it first arrives at the reference value after throttle valve opening is defined as rising time t_r, the time taken till it reaches the maximum value is defined as peak time t_p, and the time taken from the peak to the steady state is defined as settling time t_s. Also the fallen width during the transient state is defined as stumble β, and the difference between the reference and the maximum value is defined as maximum overshoot Mp. In these ways, the transient drive characteristics can be quantified with these specifications. That is, engine's hesitation can be quantified by delay time, stumble can be shown by β, the extent of stretch can be evaluated by rising time, and accelerating surge can be characterized by overshoot and settling time. Furthermore delay time rate, rising time rate, peak time rate and settling time rate which are the non-dimensional ratio of both these specifications and the accelerating time are introduced to show the response performance according to the acceleration speed. Consequently the improvement of the transient performance can be achieved by the comparison and analysis of both the transient response specifications and the non-dimensional ratios.

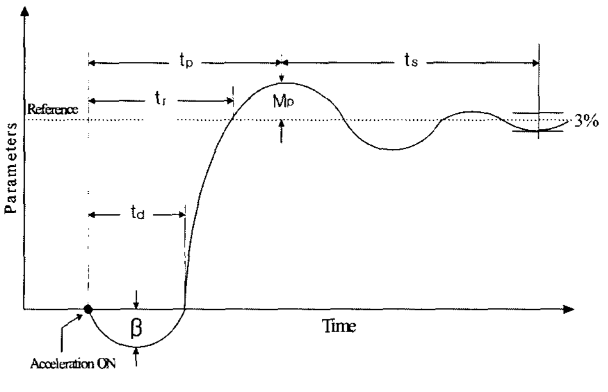
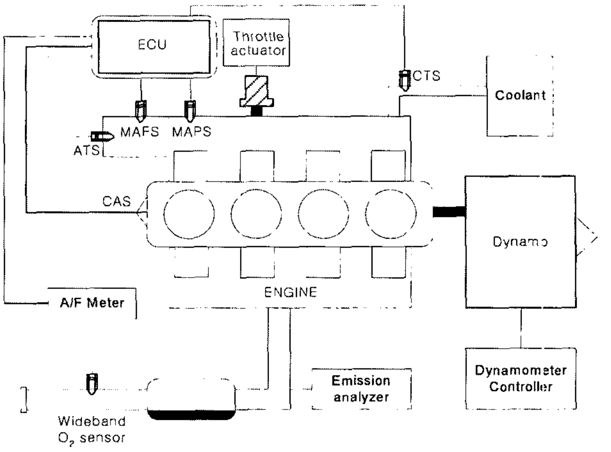


Figure 1. Definition of the transient response specifications.



ATS : Air temperature sensor
CAS : Crank angle position sensor
CTS : Coolant temperature sensor
MAFS : Mass air flow sensor
MAPS : Manifold absolute pressure sensor

Figure 2. Schemat of the experimental apparatus.

3. EXPERIMENTAL APPARATUS AND PROCEDURE

3.1. Experimental Apparatus

In Figure 2, the experimental apparatus consists of engine, dynamometer, controller, sensors, throttle valve actuator and the emission analyzer. A dynamometer is connected to the engine to give constant load and to measure torque. Mass airflow sensor (MAFS) inside the

Table 1. Specification of the experimental engine.

Type	Gasoline, 4cycle, SOHC		
Bore × Stroke	80.60 × 85.00 mm		
Displacement	1796cc		
Compression ratio	8.9		
Firing order	1-3-4-2		
Valve timing (CA)	Intake	Open	BTDC 19°
		Close	ABDC 57°
	Exhaust	Open	BBDC 57°
		Close	ATDC 19°
Idle speed	750 rpm		
Fuel injection	MPI		

Table 2. Experimental condition.

	According to the acceleration speed				According to the acceleration type
Accel. range (%)	10~17				
Accel. type	Linear				Linear Continual Intensified Decayed
Accel. speed (%/s)	3.5	10	47	93	10
Accel. time (sec)	2	0.7	0.16	0.08	0.7

intake air entrance, manifold absolute pressure sensor (MAPS) on the intake manifold, and wideband O_2 sensor on the exhaust pipe are installed to obtain information about the engine state. A step motor as a throttle actuator is also installed on the throttle valve and is controlled by computer so as to control the valve opening speed and types which are acceleration ones, and so as to realize the situations of the various transient states. Emissions concentration is measured using an emission analyzer. Table 1 shows the specification of the experimental engine.

3.2. Experimental Procedure

When it is defined that the closed position of the throttle valve is 0% and wide open position is 100%, the engine is accelerated from 10% to 17% in taking constant load by dynamometer, since the range is applicable to the most frequent transient drive range of 1500~3000 rpm. It is accelerated according to the four acceleration speed from 3.5%/s to 93%/s, and according to the four different types in terms of linear, continual, intensified and decayed acceleration. The temperatures of the coolant and intake air are maintained constantly as 80°C and 20°C respectively. The experimental condition is shown in Table 2.

Figure 3 shows the various defined acceleration speed and types considered by driver's typical habit. Linear acceleration is a general type with constant inclination, continual acceleration has twice of linear acceleration with a short break during the acceleration, intensified type is accelerated smoothly in early time but becoming faster later, and decayed type is opposite to the intensified type. Four types are all accelerated under the same condition, namely, the same accelerating time of 0.7 sec, and the same accelerating quantity of the throttle valve. We observe the variation of the performance parameters in terms of manifold absolute pressure, fuel injection duration, air excess ratio and engine speed, and analyze engine's transient performance according to the throttle valve opening speed and types. All responses are shown after being averaged with 30 times of data in each condition for repeatability. Emissions concentration is measured for one minute at 5-second intervals after each acceleration using the emission analyzer with electric chemical sensor.

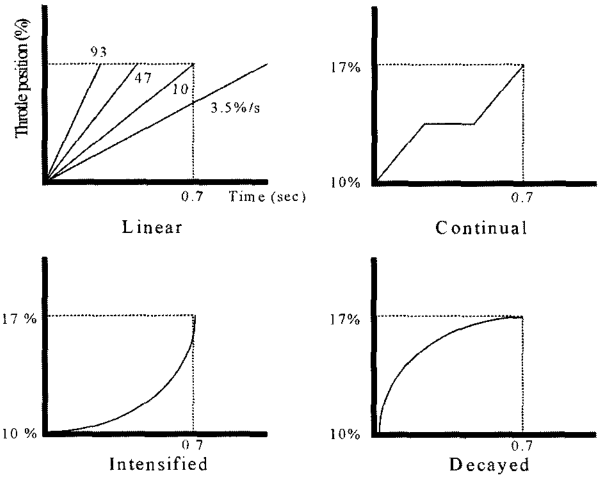


Figure 3. Acceleration speed and types.

4. EXPERIMENTAL RESULTS AND CONSIDERATIONS

4.1. Manifold Absolute Pressure Responses

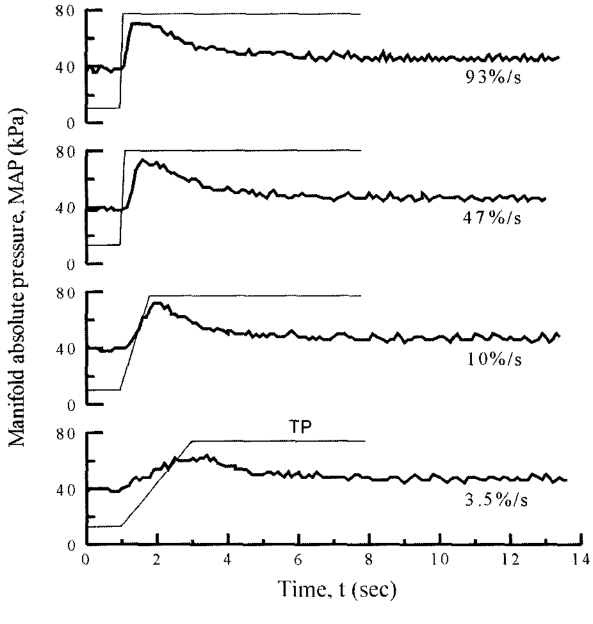
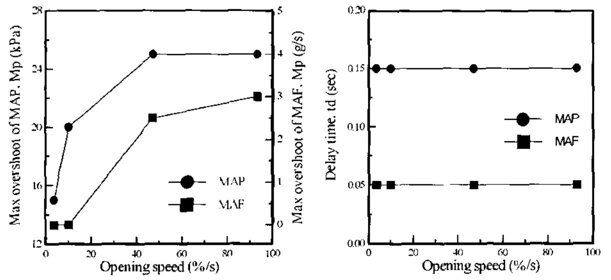
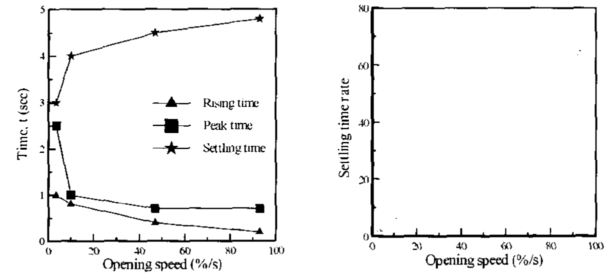


Figure 4. MAP responses according to the throttle valve opening speed.



(a) Max. overshoot

(b) Delay time



(c) Rising, peak and settling time of MAP

(d) Settling time rate of MAP

Figure 5. Transient response specifications of the air flow.

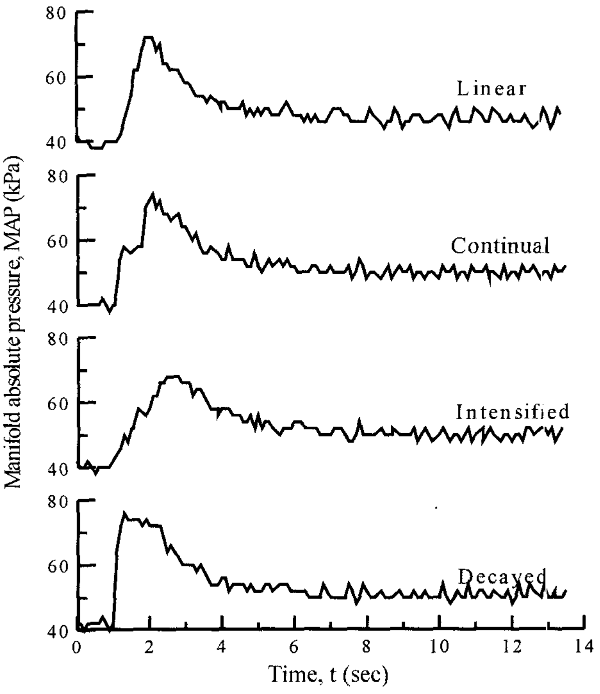


Figure 6. MAP responses according to the acceleration

Figure 4 shows the behaviors of manifold absolute pressure according to the valve opening speed in the experimental condition. Acceleration begins at $t = 1$ sec. MAP increases with increment of the intake air, especially arrives at the peak with maximum overshoot, and decreases slowly into the steady state, which is considered as that density in the intake manifold increases rapidly by the entrance of the air, and immediately becomes stable with increment of the engine speed.

In Figure 5(a), the faster the valve opening speed is, the larger maximum overshoot of MAP and MAF is. If fuel injection is not appropriate in this time, the instant variation of the air-fuel ratio becomes large. Figure 5(b) shows the delay time of MAP and MAF. Both have constant delay times regardless of the valve opening speed. From this fact, it can be known that the air always enters the cylinder well for the different valve opening speed. The reason why MAP's delay time is a little longer than MAF's is thought as it needs some time to increase whole pressure in the manifold after air incoming. Figure 5(c) shows rising, peak and settling time of MAP. Peak time becomes shorter as the valve opening speed becomes fast, but it has a limit and doesn't decrease any more in the case of rapid acceleration of the valve opening speed over 47%/s. Settling time is 3 sec at the slow acceleration of the valve opening speed 3.5%/s, and is 4.8 sec at the fast acceleration of 93%/s. So it can be known that settling time into the steady state is longer in the rapid acceleration. Figure 5(d) shows that settling time rate of the non-dimensional ratio becomes much larger in the rapid acceleration. The faster it is accelerated, the worse the airflow performance becomes relatively because of the flow variation.

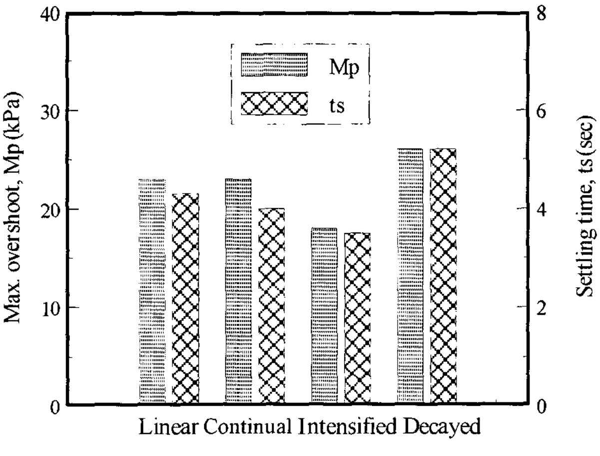


Figure 7. Transient response specifications of MAP.

Figure 6 shows the behaviors of manifold absolute pressure according to four different acceleration types. Throttle valve is opened at the position of 10% and 1500 rpm, and is accelerated to 17% of the valve position. Accelerating time is 0.7 second in all cases. In Figure 7, decayed type accelerated rapidly in early time has the most maximum overshoot, linear and continual type have

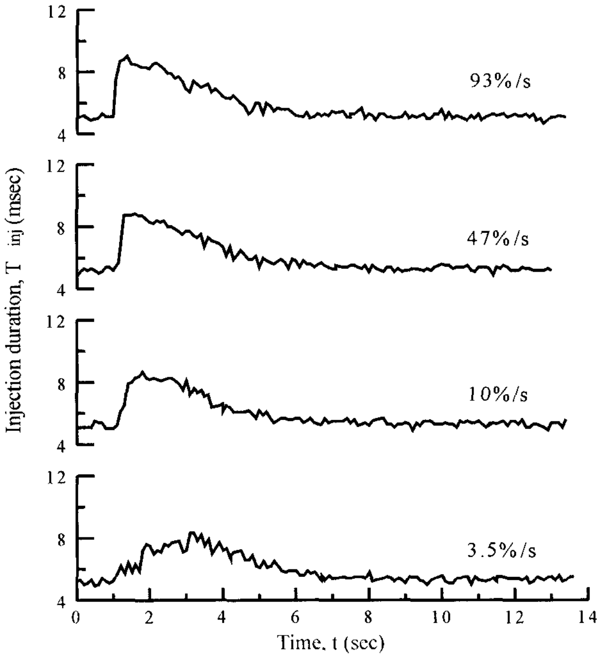


Figure 8. Fuel injection duration responses according to the valve opening speed.

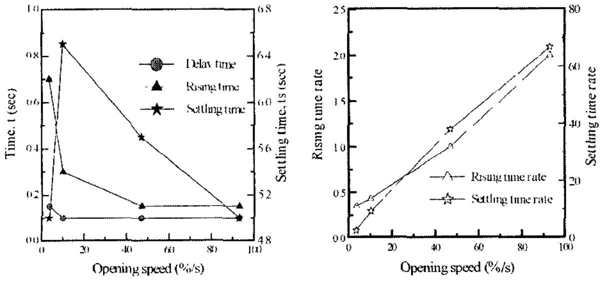
medium values and intensified type has the least maximum overshoot. Concerning settling time, the same trend as maximum overshoot is shown. Intensified acceleration type is revealed to be the most stable for the MAP response.

4.2. Fuel Injection Duration Responses

Figure 8 shows the behaviors of the fuel injection duration according to the valve opening speed in the same condition. They increase with a big overshoot and then arrive at the steady state. As the throttle valve opens fast, the fuel is injected rich, and maximum overshoot becomes larger, lasting longer. Consequently air-fuel ratio deflection in the rapid acceleration probably becomes larger, and the emission becomes worse.

In Figure 9(a), delay time of the fuel injection duration is constant over the valve opening speed of 10%/s, rising time also becomes constant over 47%/s. This is considered as that ECU responses sensitively for the acceleration enrichment in the rapid acceleration. To make delay time shorter, a designer must control the acceleration sensitivity appropriately. If it is too high, the mixture would be rich easily for even the slow acceleration, and the emission would be worse. Reversely if it is too low, delay and rising time of the injection duration would be longer, and the acceleration performance would decrease. Settling time is 5 sec at the valve opening speed 3.5%/s, but increases to 6.5 sec at 10%/s, and decreases again with increase of the valve opening speed. Figure 9(b) shows that rising and settling time rate become higher in the fast acceleration, which means that rising and settling time cannot be reduced as much as the decrease of acceleration time in the rapid acceleration. Transient drive must be controlled in direction to reduce the difference value of the time rate between the fast and slow acceleration.

Figure 10 shows the fuel injection duration responses according to the different acceleration types in the same condition. In Figure 11, decayed type has the biggest maximum overshoot of 4 msec, and intensified type has the smallest one of 3.4 msec. Decayed acceleration results in the instant rich combustion because of the sudden



(a) Delay, rising and settling time (b) Rising and settling time rate

Figure 9. Transient response specifications of the fuel injection duration.

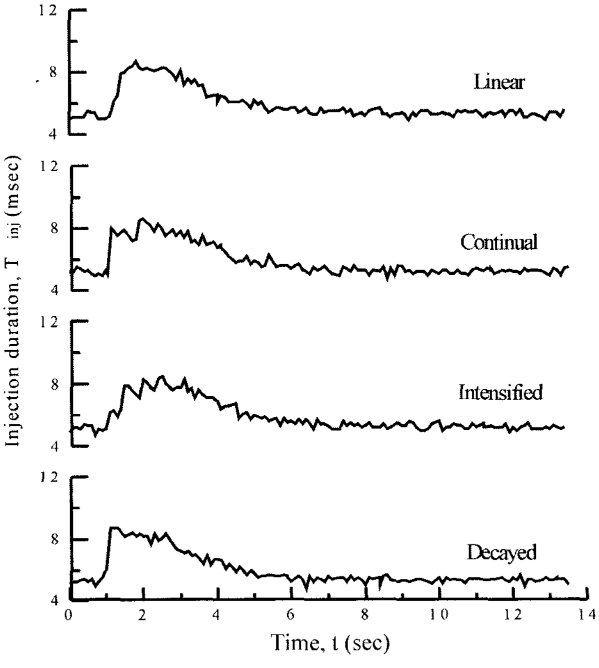


Figure 10. Fuel injection duration responses according to the acceleration type.

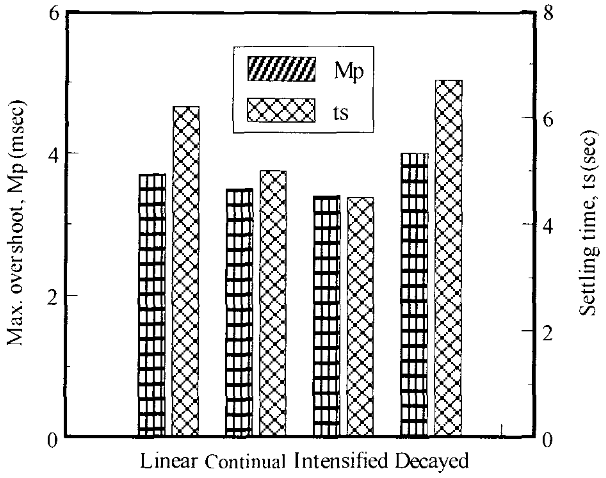


Figure 11. Transient response specifications of the fuel injection duration.

acceleration, and has the longest settling time of 6.7 msec. Concerning continual acceleration, fuel is injected twice by two times of continual accelerating, and the total injection duration becomes long, so fuel consumption increases. Intensified acceleration type has the shortest settling time of 4.5 msec. Consequently the decay rate of acceleration enrichment in the ECU program should be increased in decayed acceleration for the reduction of settling time, and the acceleration sensitivity should be decreased in continual acceleration to reduce overshoot.

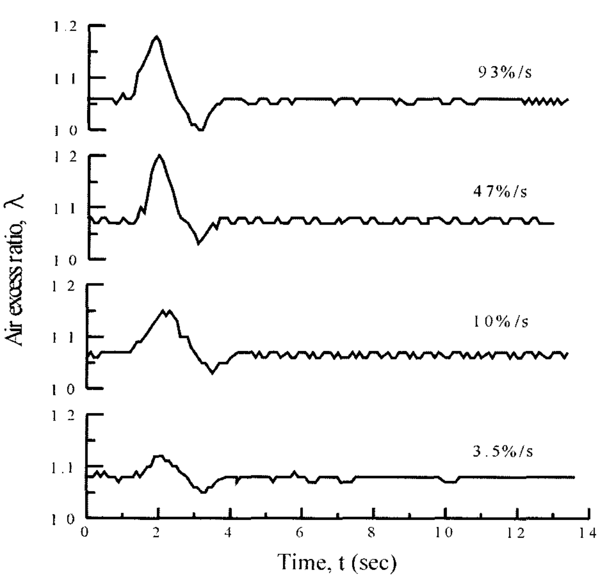
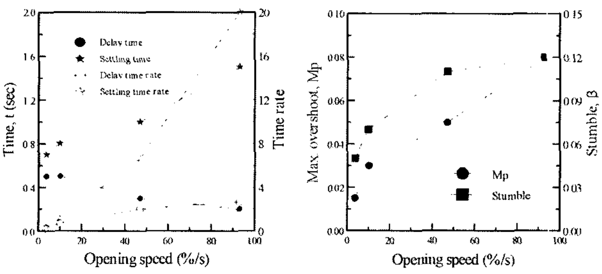


Figure 12. Air excess ratio responses according to the valve opening speed.

4.3. Air Excess Ratio Responses

Figure 12 shows the behavior of the air excess ratio according to the valve opening speed in the same condition. They seem nearly similar in the fast acceleration of the valve opening speed over 47%/s. Injection system seems to have a limit at the unique valve opening speed. After the valve opening, the air flows rapidly, air–fuel ratio becomes lean instantly, going rich back by the acceleration enrichment, and arrives at the steady state. It can be seen that the size of stumble or overshoot becomes small, as long as the valve opening speed decreases. In Figure 13 (a), though delay time becomes shorter at the faster valve opening speed, delay time rate becomes higher. Thus the response performance in the fast acceleration becomes bad. As settling time becomes longer, and the air-fuel



(a) Delay and settling time, delay and settling time rate

(b) Mp and stumble

Figure 13. Transient response specifications of the air excess ratio.

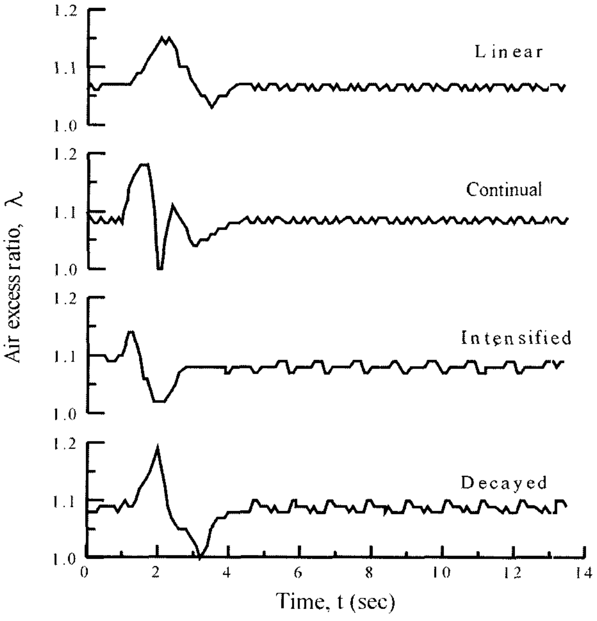


Figure 14. Air excess ratio responses according to the acceleration type.

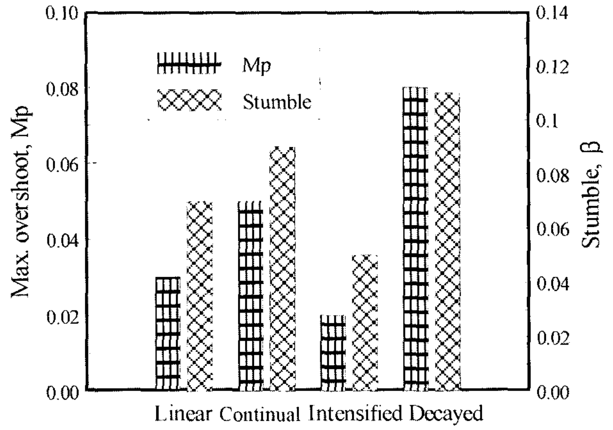
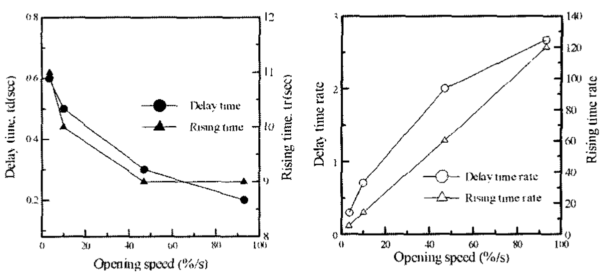


Figure 15. Transient response specifications of the air excess ratio.

ratio becomes worse, so the emission performance probably becomes worse. In Figure 13(b), stumble phenomenon is notable by the rapid air incoming at the fast acceleration, and air-fuel ratio is bad. It results in high fuel consumption rate and bad emission performance.

Figure 14 shows the air excess ratio responses according to the different acceleration types in the same condition. Twice of acceleration induces repeated rich responses in the case of continual type. In Figure 15, stumble by the sudden air entrance for decayed type is highest as 0.11, delayed and linear type follow it, and intensified type has the lowest stumble as 0.05. Maximum overshoot for the acceleration enrichment is also highest in decayed type, and is lowest in intensified type.



(a) Delay and rising time (b) Delay and rising time rate

Figure 17. Transient response specifications of RPM.

4.4. Engine Speed Responses

Figure 16 shows the behaviors of the engine speed according to the valve opening speed in the same condition. The response of engine speed becomes faster at the rapid acceleration. But, as seen in Figure 17, though the valve opening speed becomes over 47%/s, rising time will not become shorter. So it can be said that the acceleration performance has a limit, and excessively rapid acceleration only results in economical and emission problems.

Figure 18 shows the engine speed responses according to the acceleration type in the same condition. In Figure

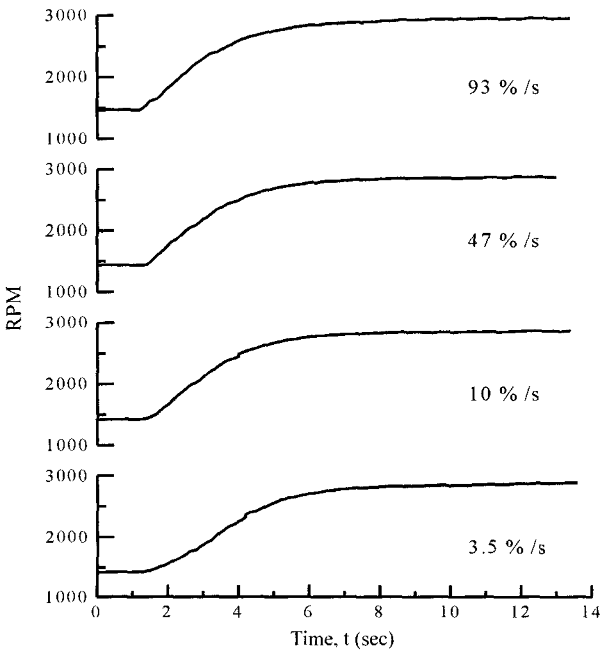


Figure 16. RPM responses of the linear acceleration according to the valve opening speed.

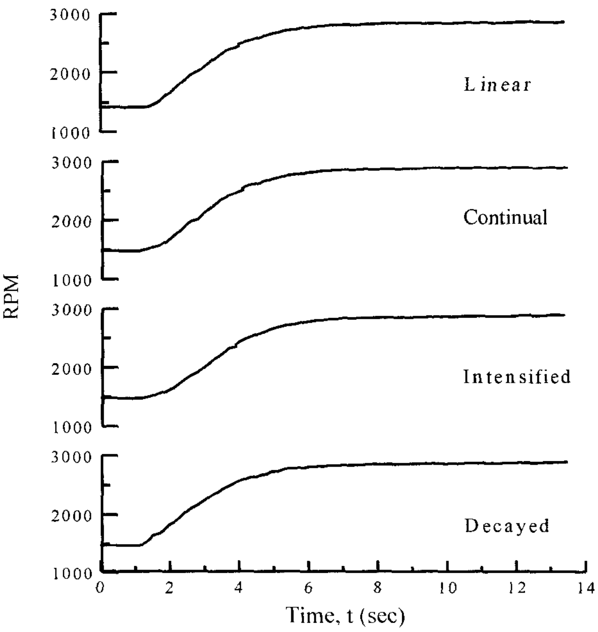


Figure 18. RPM responses according to the acceleration type.

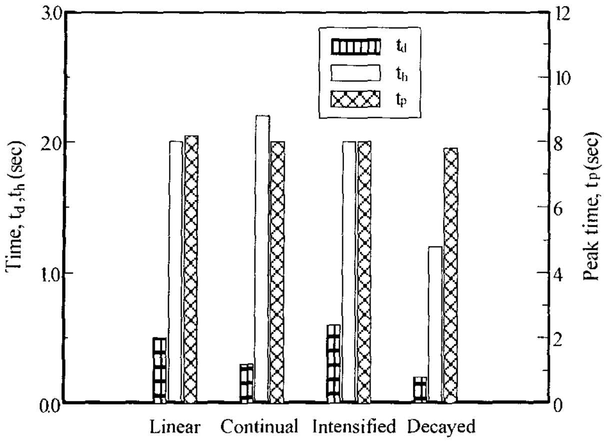
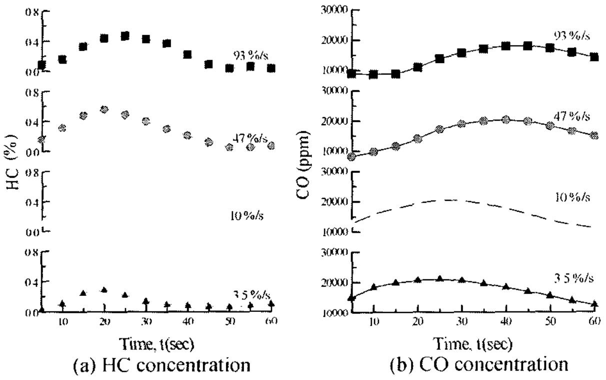


Figure 19. Transient response specifications of RPM.



(a) HC concentration (b) CO concentration

Figure 20. Emissions concentration responses according to the valve opening speed.

19, delay time which shows the quickness of responses is shortest in decayed acceleration which begins accelerating rapidly, and is longest in intensified acceleration which starts slowly. Half time which is defined as the time taking to the half of the peak value is longest in continual acceleration and is shortest in decayed acceleration. So it can be said that decayed acceleration has the best prompt accelerating performance. Peak times of four different acceleration types, however, are showed similarly, then there is not so big difference among various acceleration types in the real acceleration performance. If the economical problem is considered, intensified acceleration is thought to be most profitable.

4.5. Emissions Concentration Responses

Emissions concentration is measured for 1 minute after acceleration at 5-second intervals, not on the real time because of the measuring resolution of the emission analyzer. Figure 20 shows the concentration variation of harmful emissions according to the valve opening speed

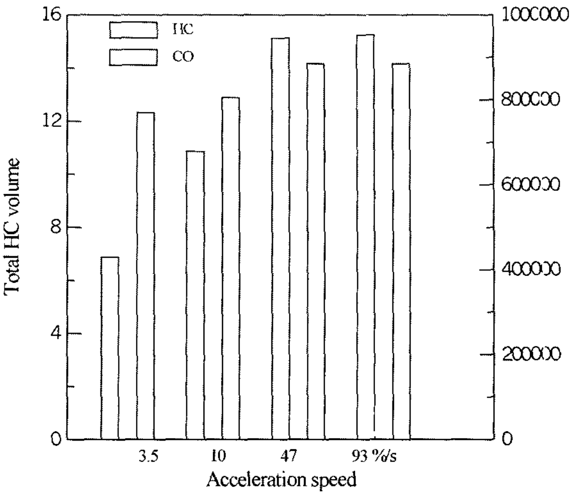
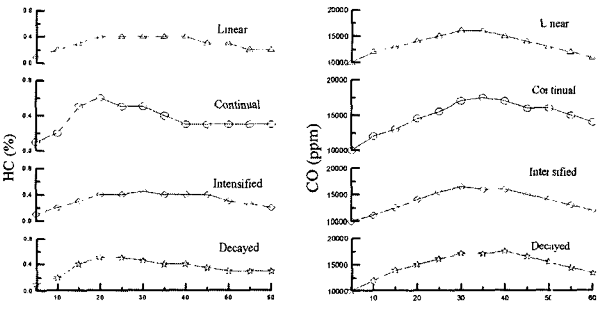


Figure 21. Total emissions volume according to the acceleration speed.



(a) HC concentration (b) CO concentration

Figure 22. Emissions concentration responses according to the acceleration type.

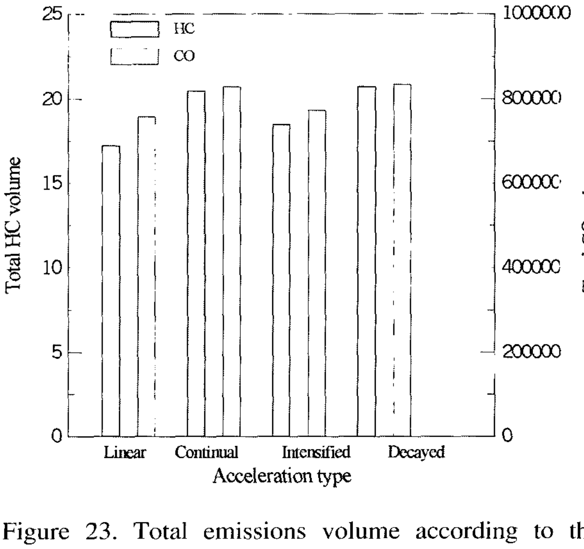


Figure 23. Total emissions volume according to the acceleration speed.

in the same condition. In Figure 21, total emissions volumes of HC and CO for 1 minute are compared, which shows HC concentration increases with increment of the valve opening speed, and CO also arises much at the faster acceleration.

Figure 22 and 23 shows the responses of the several harmful emissions concentration according to the four acceleration types in the same condition. Both HC and CO concentration are all high in continual and decayed acceleration. The total volume of HC and CO of decayed acceleration is 1.2 times and 1.1 times of those of linear acceleration which has the minimum respectively. In linear acceleration, both HC and CO concentration increase slack, and seem to be best for the emission performance. There is few difference according to the acceleration speed and types about NOx.

5. CONCLUSIONS

In this research, the transient responses of the engine performance parameters were analyzed and evaluated under various acceleration speed and types based on driver's typical acceleration habit to evaluate the transient performance and to provide the appropriate direction for the transient control, and then conclusions were obtained as follows:

(1) Transient performance according to the acceleration speed and types can be analyzed and evaluated by the transient response specifications in terms of delay, rising and settling time of the performance parameters.

(2) As the acceleration speed becomes faster, the maximum overshoot of the injection duration and the intake air becomes larger, and air-fuel ratio deflection becomes larger in the experiment according to the acceleration speed.

(3) Rising times of engine speed according to the acceleration types are nearly alike in the same experimental condition, so there are not big differences in the acceleration performance. But maximum overshoot and settling time of the injection duration are largest in decayed acceleration, and are higher than those of intensified acceleration for 0.6 msec and 2.2 msec respectively. The economical performance of intensified acceleration is the best.

(4) The concentration differences between the fastest and slowest acceleration for HC and CO in the linear acceleration experiment are about 2.2 times and 1.15 times respectively. Concerning the acceleration type, decayed acceleration has the highest emissions concentration, and linear acceleration has the lowest one in both emissions.

(5) A designer can find the appropriate direction for the transient control from the quantified transient response specifications of the performance parameters.

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