ARPN Journal of Engineering and Applied Sciences

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# AN UNCERTAINTY ANALYSIS OF A CUMULATIVE INJECTED FUEL MASS MEASURED WITH A VEHICLE DRIVING CONDITION

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**ABSTRACT**

A system that can measure the amount of fuel injected by fuel injectors on a level identical to that of an actual vehicle driving condition was constructed on a laboratory scale without driving a vehicle on a road. In order to inject fuel under conditions identical to those when driving a vehicle, various vehicles' sensor signals on an identical level to the driving condition were input to the ECU of the device. When the various vehicles' sensor signals are supplied to the ECU, the ECU drives the injector in a manner equivalent to the vehicle running condition. The vehicle performance parameters under the vehicle driving conditions were computer simulated using GT-Suite®. Vehicle specifications including the engine part load data, a vehicle automatic transmission shift map, the K-factor and torque ratio data of the torque converter, and the transmission gear ratio were used as input data for the GT-Power® simulation. In this study, FTP-75 served as the vehicle driving mode. The vehicle performance parameters simulated by GT-Suite® were the throttle opening angle, intake air flow rate, and the engine speed. Various sensor signals based on the vehicle performance parameters were generated by the FPGA board and real-time OS. When these various sensor signals generated by the FPGA board are supplied to the ECU, the injectors driven by the ECU inject fuel into each collecting chamber. A load cell and a dynamic strain amplifier were used to measure the cumulative amount of fuel injected at 0.05 second intervals after the driving of the injectors started. The cumulative amount of fuel injected while driving the ECU in the Phase I section (0-512 seconds) of the FTP-75 mode was measured and the experiment was repeated 20 times. The average and standard deviation of the cumulative amount of injected fuel were determined at each of the measurement time steps during Phase I. Moreover, an uncertainty analysis of the experimental data was conducted using the t-distribution error function. The cumulative injected fuel quantities measured at 0.05 second intervals were distributed within 2% of the mean value at a 95% confidence level.

**Keywords:** cumulative injected fuel mass, transient fuel injection rate, gasoline injector, vehicle driving mode, FTP-75, uncertainty analysis.

## INTRODUCTION

Traditionally, injector performance is evaluated in terms of both the uniformity of the fuel injection rate and the dynamic flow range (DFR) by repetitively injecting fuel during a certain injection period [1-2]. That is, the injector assembled in a rig that measures the injection rate repeatedly injects fuel several times with an identical pattern. The average injection quantity per injection is calculated by dividing the total weight of the collected fuel by the total number of injections. Evenness of the average injection quantity when evaluating injectors is important. The DFR curve is obtained by measuring the fuel injection rate using the measuring method described above while increasing the fuel injection period at regular intervals, thereby allowing an evaluation of the linearity of the injected fuel quantity with an increase in the injection period.

However, it is impossible to measure the amount of fuel injected by an injector in the transient state of an actual vehicle with the traditional method. Therefore, there is a need for a method capable of evaluating the performance of an injector by measuring the fuel injection rate under transient operating conditions as the vehicle travels. Evaluating the fuel consumption of a vehicle driven in a specific running mode is also necessary.

Recently, in order to evaluate different vehicle parts, including injectors, while a vehicle is being driven, one tendency has been to evaluate the connection with the ECU. Many studies have attempted to evaluate the main parts of vehicles, including injectors, at the laboratory level using the ECU and a data acquisition (DAQ) system without actually driving the vehicle [3-6]. These studies mainly focused on evaluating ECUs.

Oh and Lee [7] measured the injected fuel quantity while a vehicle was being driven. They used an ECU and a DAQ system to measure the quantity of injected fuel when the vehicle was being driven and used an FPGA board and a real-time OS to supply various vehicle sensor signals with precise synchronized timings to the ECU. Oh and Lee [7] used mess cylinders and a camcorder to measure the amount of fuel injected from an injector. However, Oh and Lee [7] could not determine the fuel injection quantity instantly at the point of measurement, as the injected fuel quantity was determined by analyzing recorded images of the liquid level in the mess cylinder after the experiment had ended. Cho and Lee [8] measured the fuel injection quantity using a load cell to overcome the problem encountered by of Oh and Lee [7] who had measuring the injection quantity using a camcorder.

Cho and Lee [8] measured the fuel quantity collected in the mess cylinder in real time using a load cell. Cho and Lee [8] used computer simulations of the engine speed, vehicle speed, throttle valve opening amount, and

VOL. 13, NO. 1, JANUARY 2018 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences



intake air amount with GT-Suite. In this study, the cumulative injected fuel mass (CIFM) over time in a vehicle driving condition is repeatedly measured using the method of Cho and Lee [8] and the experimental results are analyzed statistically. The CIFM was measured at intervals of 0.05 seconds when certain vehicle sensor signals, in this case the engine speed, vehicle speed, throttle opening amount, and intake air amount in the FTP-75 driving mode were input to the ECU. The mean and standard deviation of the CIFM were obtained and an uncertainty analysis was conducted using the t-distribution function.

## EXPERIMENTS

The vehicle driving performance metrics of the engine speed, throttle valve opening angle, and mass flow rate of the intake air were simulated with a computer using GT-Suite when the vehicle is driven in Phase 1 of the FTP-75 driving mode [9]. Figure-1 shows a schematic diagram of the computer simulation process of the vehicle driving performance using GT-Suite. The engine part load data set, the vehicle transmission map, the automatic transmission shift map, and the vehicle specifications of the K-factor and torque ratio data of the torque converter and the transmission gear ratio are used as input data in the GT-Suite simulation. The simulation results of the engine speed, mass flow rate of the intake air, and the throttle opening angle are also shown in Figure-1 when the vehicle is driven in the FTP-75 mode. By changing the vehicle driving pattern, the corresponding driving performance can also be simulated. Vehicle sensor signals corresponding to the engine speed, throttle valve opening angle, and mass flow rate of the intake air were generated using a FPGA board and the LabView real-time OS.

Figure-2 shows a schematic diagram of an experimental apparatus capable of measuring the CIFM when a vehicle is in a running condition on a laboratory scale. The experimental apparatus consists of an ECU, a fuel rail, injectors, a fuel supply system, a computer system and a measurement system to measure the cumulative quantity of injected fuel. Each vehicle sensor signal corresponding to the vehicle performance simulation data was generated using both a host PC and a PXI-7833R board operating with a real-time OS. The vehicle sensor signals of TPS (throttle position sensor), TDC (top dead center), CPS (crank position sensor), AMF (air mass flow), VSS (vehicle speed sensor), ATS (air temperature sensor), and WTS (cooling water temperature sensor) generated by the PXI-7833R board are supplied to the ECU via a terminal block, and the ECU drives three injectors, as occurs when the vehicle is driven. In this case, the fuel injected by each injector was collected in a mess cylinder whose weight was measured with a load cell and a dynamic strain amplifier. Table-1 summarizes the specifications of the DAQ boards and the PXI in this study. The process of generating the vehicle sensor signals is identical to that used by Oh and Lee [7].

The vehicle speed sensor is mounted on the vehicle transmission housing and generates four pulses each time the vehicle wheel makes one revolution. The frequency of the vehicle speed sensor pulses ($Freq_{DAQ\ for\ Vss}$) as generated by the DAQ board in response to the vehicle speed ($V_{ss}$) simulation data obtained by GT-Suite can be calculated by Equation (1).

$$Freq_{DAQ\ for\ Vss} = \frac{V_{ss}(\frac{km}{h}) \times 1000000(\frac{mm}{km}) \times 4}{\pi \times 647.5(mm) \times 3600(\frac{sec}{h})} \quad (1)$$

Here, the diameter of the vehicle tire is 687.5 mm.

The relationship between the voltage ($V_{TPS}$) and the throttle opening angle of the throttle position sensor (TPS) has a linear characteristic. If the throttle valve position is idle, the sensor voltage is 0.525 V. The sensor voltage is 4.4V when the throttle valve is fully open (WOT). The relationship between throttle valve position and voltage can be expressed by Equation (2) and is programmed such that the FPGA boards generate an electrical signal.

$$V_{TPS} = 0.043 \times TPS_{opening\ angle} + 0.525 \quad (2)$$

The sensor signal corresponding to the mass flow rate of intake air is obtained by the curve fitting of the relationship between the intake air mass flow rate of the actual vehicle and the voltage of the intake airflow sensor. The intake airflow sensor is generated from the analog output terminal of the FPGA board, similar to the manner used to obtain the throttle position sensor signal.

$$V_{AFS} = 2.3895 \times \log(\dot{m}_{air\ flow}) - 2.023 \quad (3)$$

The cooling water temperature and intake air temperature were maintained as a constant value of 20.3℃. The sensor voltage corresponding to the constant temperature of 20.3℃ is generated using a potentiometer due to the insufficient number of analog output channels on the FPGA board.

**Table-1.** Summary of DAQ system used.

| PXI model | NI PXI-1042 |
|---|---|
| DAQ board | NI PXI-7833R |
| | NI PXI-6220 |
| Software | LabView® |

The fuel rail pressure is maintained at a constant pressure of 4 $kg/cm^2$. In an actual vehicle, the fuel is injected into the intake port. Therefore, in the actual vehicle driving condition, the ambient pressure during the injection of the fuel is the manifold absolute pressure (MAP) pressure. However, in this study, the fuel is injected into the mess cylinder; that is, the ambient

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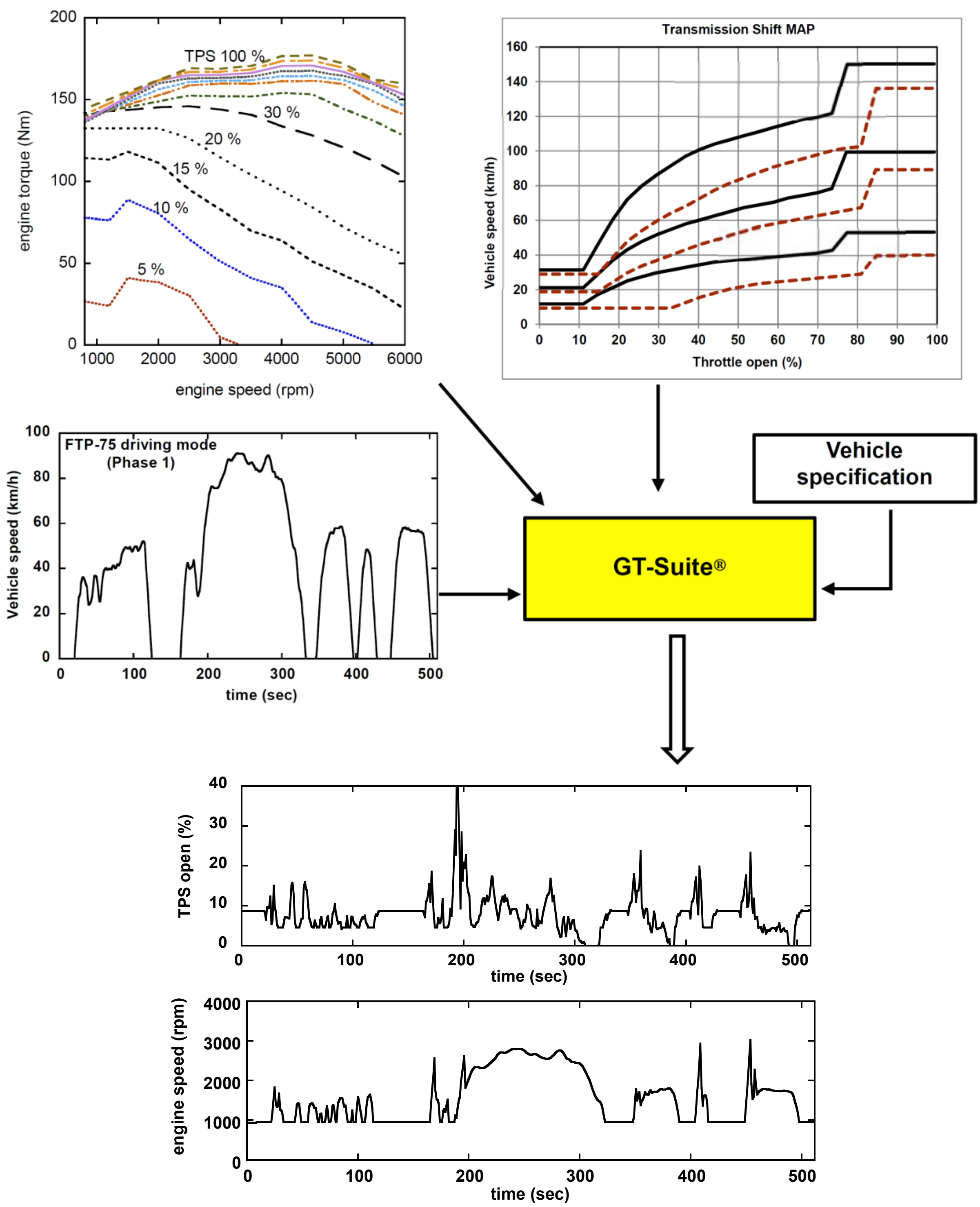
pressure during the injection of the fuel is atmospheric. Therefore, the ambient pressure during the fuel injection step differs slightly from that of the actual vehicle driving condition.

Figure-2 shows that the vehicle sensor signals generated by the FPGA board are input to the ECU. By connecting an ECU scanner device to the serial port in the ECU, the vehicle sensor signals input to the ECU could be monitored. Through the ECU scanner, it could be confirmed that the vehicle sensor signals are supplied to the ECU, as expected.



 ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences



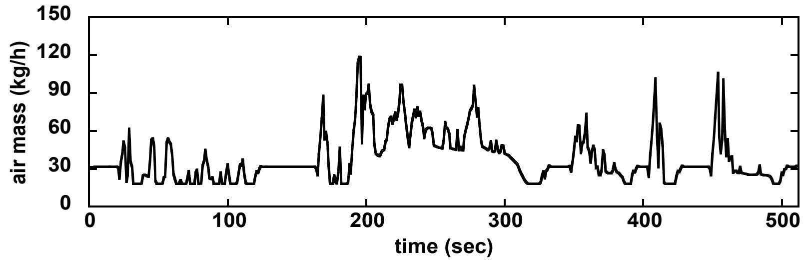




**Figure-1.** Conceptual diagram for simulating the vehicle performance using GT-Suite.

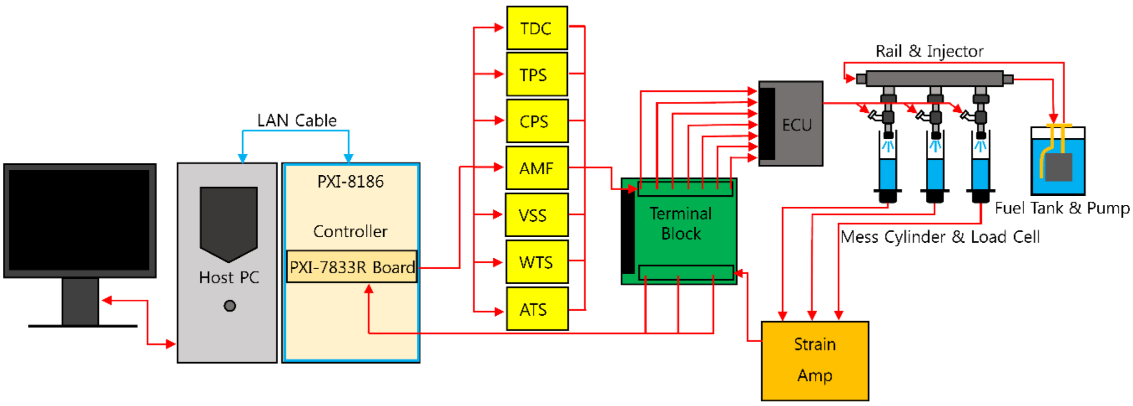



**Figure-2.** Experimental setup for measuring the cumulative injected fuel mass.

The vehicle sensor signals are supplied to the ECU, which drives the injectors, and the injected fuel is collected into each mess cylinder correspondent to the injector. Each mess cylinder is mounted on a circular disk, and the circular disk is mounted on a load cell. In this study, the CIFM was measured using a load cell. The load cell is the CBCL-1L model from Curitec Inc. The weight range of the load cell is 0~1 kgf. A signal amplifier (strain amplifier) was used to amplify the load cell signal. The strain amplifier is the 2300 system from Measurements Group Co. Ltd. The load cell signal was calibrated using precision weights.

## RESULTS AND DISCUSSIONS

When the vehicle sensor signals are input into the ECU in the range of 0-512 seconds during Phase 1 of the FTP-75 vehicle driving mode, the injector driving signal is output from the ECU to inject the fuel. In this study, three injectors were driven and the fuel injected from each injector was collected in each respective mess cylinder.

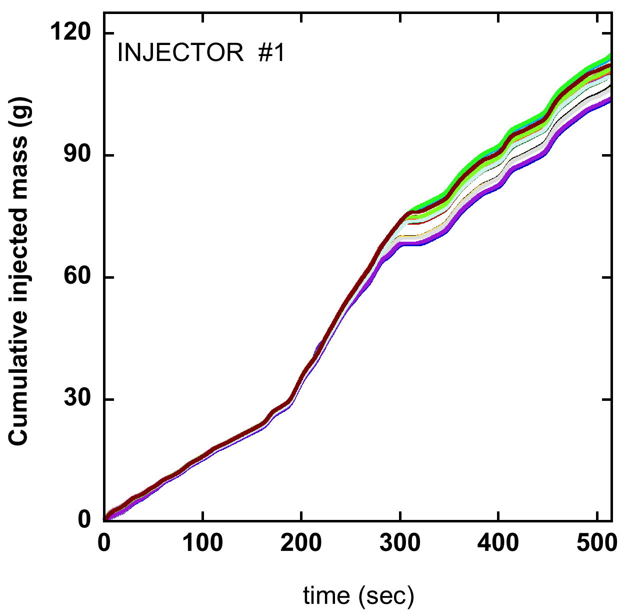



**Figure-3.**20 times measured CIFM for injector #1.

ISSN 1819-6608
ARPN Journal of Engineering and Applied Sciences



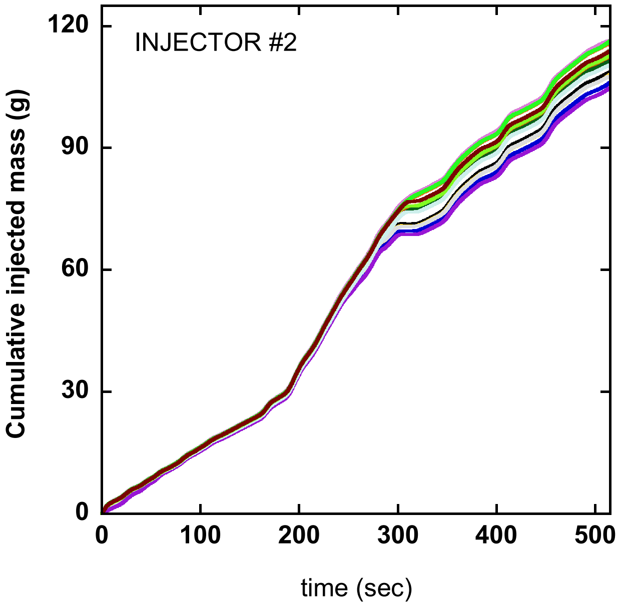




**Figure-4.** 20 times measured CIFM for injector #2

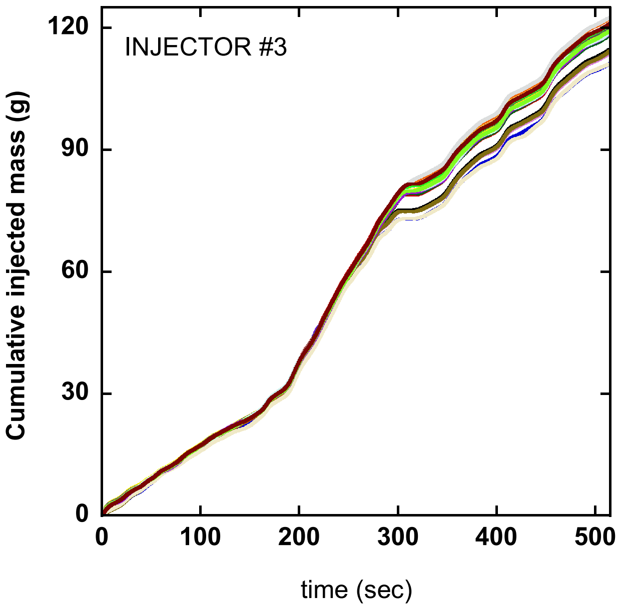



**Figure-5.** 20 times measured CIFM for injector #3.

The cumulative weight of the collected fuel was measured at 0.05 second intervals using the load cell. The experiment was repeated 20 times for a statistical analysis. The CIFM was measured 20 times each for injectors # 1, # 2, and # 3 and the results are shown in Figures 3, 4 and 5, respectively. In the 0-200 second driving range, the CIFM tended to increase linearly, and its variation during the 20 repeated measurements was low because the vehicle speed change is relatively smooth. Moreover, the CIFM value is very small due to the early stage of the driving range. The CIFM tends to increase linearly during the 200-300 second driving range, also. The slope of the CIFM curve for the 200-300 second interval is larger than that for 0-200 sec interval. The change in the vehicle speed was not significant when the interval was 200-300 seconds; however, the vehicle speed was greater, which resulted in larger intake air mass. Therefore, the slope of the CIFM curve was larger than that for the interval of 0-200 seconds. It can be seen that the fluctuation of the CIFM from the repetitive measurement is very small when the driving range is 0-300 seconds. The fluctuation of the CIFM when the driving range exceeds 300 seconds is greatly increased. The increased fluctuation of the CIFM past the driving range of 300 seconds is related to the acceleration and deceleration pattern of the vehicle speed, as shown in Figure-1. That is, the vehicle speed rapidly decreases in the driving range of 300-330 seconds, after which three steep peaks in the vehicle speed curve appear for a short time, indicating that the vehicle speed varied steeply compared to the driving range of 0-300 seconds. The steep variation of the vehicle speed means that the fuel is injected from the injector under a highly transient condition. Therefore, the fluctuation of the CIFM after 300 seconds is increased. The CIFM fluctuation after 300 seconds was increased in all injectors, i.e., # 1, # 2, and # 3.

Figure-6 shows the results when averaging the CIFM from 20 measurements with injectors # 1, # 2 and # 3.The CIFM of injectors #1 and #2 with time nearly

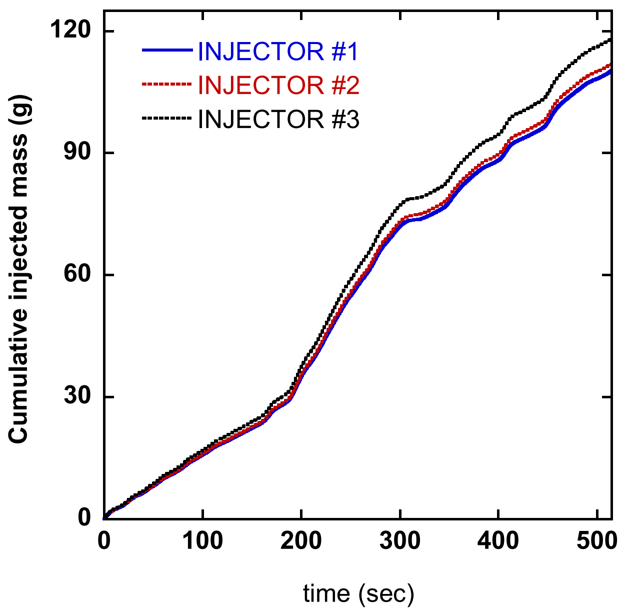



**Figure-6.** Averaged CIFM for each injector #1, 2, 3.

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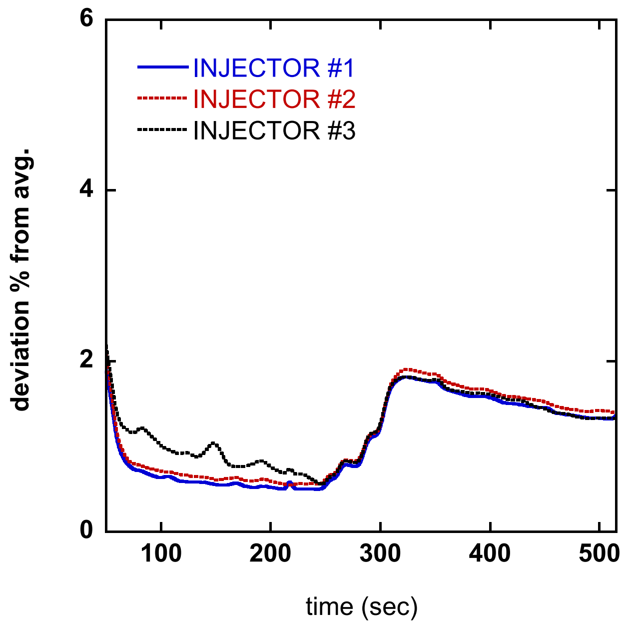


**Figure-7.** Deviation % from each average CIFM of Injector #1, 2, 3 with 95 % confidence level.

coincides over the entire running range. The # 3 injector has a slightly larger CIFM over the entire measurement time as compared to the # 1 and # 2 injectors, and the difference gradually increases with the driving time. These results indicate that there is a clear difference in the CIFM values between the injectors.

Figure-7 shows the percentage of deviation of the CIFM from the average value with a 95% confidence level at the respective driving times. Given that the CIFM is not large at the beginning of the vehicle driving time, the percentage of deviation from the average value is calculated from 50 seconds, by which point a certain amount has accumulated. The error distribution function used in this study is the t-distribution. The percentage of deviation from the average value of the CIFM is approximately 1% at the 95% confidence level for the driving time of 300 seconds, and there is a deviation of 1.5 ~ 2% thereafter. Injectors # 1 and # 2 have nearly identical deviation percentages over the entire running time. Injector # 3 exhibits a slightly larger deviation percentage comparing to those of injector # 1 and # 2 with the 300-second driving time, showing deviation percentages nearly identical to injectors #1 and #2 past the driving time of 300 seconds. The variation of the deviation with the driving time is related to the acceleration and deceleration pattern of the vehicle speed, as explained previously. This result implies that a new means of measuring the CIFM of the injector when the vehicle is in the driving condition is needed. The new method of measuring the CIFM of the injector can also be used to measure the quantity of fuel injected in the transient condition of the injector.

In addition to measuring the CIFM, another important point is that the new method can evaluate the CIFM difference between the injectors. The CIFM between the injectors must be minimized such that the fuel injection amount between the engine cylinders is minimized. This minimizes the difference in the torque output between the engine cylinders. The CIFM in Figure-6 shows that there is a clear difference between the injectors in the vehicle driving condition.

## CONCLUSIONS

An injector evaluation system was used to measure the CIFM from injectors in the FTP-75 vehicle driving mode. The CIFM was measured 20 times and the results were statistically analyzed.

a) In the driving range of 0-300 seconds in the FTP-75 mode, the CIFM showed a linear characteristic, and the slope of the CIFM in the driving range of 0-200 seconds was smaller than that in the driving range of 200-300 seconds. The difference in the slope of the CIFM curve with the driving time range is related to the speed of the vehicle as it is driven.

b) In the driving range of 0-300 seconds in the FTP-75 mode, the CIFM results when measured 20 times showed a small amount of variation. In the driving range of 300-512 seconds, the variation of the CIFM increased greatly. These results are related to the acceleration or deceleration pattern of the vehicle.

c) The deviation from the average value of the CIFM at a 95% confidence level is approximately 1% in the driving range of 0-300 seconds and about 2% in the driving range of 300 to 512 seconds.

d) The measurement method of the CIFM when the vehicle is being driven can be used effectively to evaluate the variation of the CIFM under a transient operating condition of an injector.

## ACKNOWLEDGEMENT

This study was supported by the research program funded by Seoul National University of Science and Technology.

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