International Journal of Automotive Technology, Vol. 4, No. 2, pp. 101−108 (2003)

1229−9138/2003/012−06

EXPERIMENTAL ANALYSIS OF DRIVING PATTERNS AND FUEL ECONOMY FOR PASSENGER CARS IN SEOUL

J. S. SA[1)], N. H. CHUNG[2)] and M. H. SUNWOO[2)*]

[1)]Dept. of Automobile, Seoil College, Seoul 131-702, Korea
[2)]Department of Automotive Engineering, Hanyang University, Seoul 133-791, Korea

(Received 18 September 2002; Revised 15 March 2003)

ABSTRACT−There are a lot of factors that influence automotive fuel economy such as average trip time per kilometer, average trip speed, the number of times of vehicle stationary, and so forth. These factors depend on road conditions and traffic environment. In this study, various driving data were measured and recorded during road tests in Seoul. The accumulated road test mileage is around 1,300 kilometers. The objective of the study is to identify the driving patterns of the Seoul metropolitan area and to analyze the fuel economy based on these driving patterns. The driving data which was acquired through road tests was analyzed statistically in order to obtain the driving characteristics via modal analysis, speed analysis, and speed-acceleration analysis. Moreover, the driving data was analyzed by multivariate statistical techniques including correlation analysis, principal component analysis, and multiple linear regression analysis in order to obtain the relationships between influencing factors on fuel economy. The analyzed results show that the average speed is around 29.2 km/h, and the average fuel economy is 10.23 km/L. The vehicle speed of the Seoul metropolitan area is slower, and the stop-and-go operation is more frequent than FTP-75 test mode which is used for emission and fuel economy tests. The average trip time per kilometer is one of the most important factors in fuel consumption, and the increase of the average speed is desirable for reducing emissions and fuel consumption.

KEY WORDS : Fuel economy, Driving pattern, Modal analysis, Multivariate statistical technique, Correlation analysis, Principal component analysis, Multiple linear regression analysis, FTP-75 mode

1. INTRODUCTION

The amount of automobiles in Korea has constantly increased due to the enlargement of the national economic scale and the growth of the national income. Since the increase of the registered number of automobiles has showed the highest record in 1988, the increasing rate of the registered number of automobiles was 30.7% in 1989. Since then, the yearly mean of the increasing rate of the number of automobiles was 16.4% up to 2000. As a result of this rapid increase, the registered number of automobiles was about 13 million in 2001. Meanwhile, the increasing rate of registered passenger cars was 18.9% based on yearly mean from 1987 to 2001. The registered number of passenger cars has reached around 9 million in 2001.

Therefore, the air pollution caused by automotive emissions has increased. In 2000, the discharging proportion of automotive emissions out of whole air pollutants was 50.5% all over the nation, and 85.7% in the city of Seoul (Koh, 2000). The emission standards of our country were adopted for the first time in 1978 and reinforced to the level of advanced countries through successive amendments.

There are several methods to reduce automotive emissions including technical developments to produce low emission vehicles and institutional improvements such as tax reform and environmental share of expenses. But the improvement of fuel economy is also the method to reduce automotive emissions. Therefore, in order to know the fuel economy of the Seoul metropolitan area, and influencing factors on fuel economy, the driving data was measured and recorded through road tests. The accumulated road tests mileage is around 1,300 kilometers. The driving data was analyzed to identify the driving patterns of urban areas and the interrelationships among the driving variables by multivariate statistical techniques.

2. EXPERIMENTAL DETAILS

2.1. Test Routes

Three test routes in the Seoul metropolitan area were selected to cover various urban driving conditions. These

**Corresponding author.* e-mail: msunwoo@hanyang.ac.kr

Table 1. Test driving routes.

Driving mode	Course	Distance
Commuter (DC)	Yangjae•Namdaemun	15.1 km
Circulation (DL)	Hanyang univ.•Hanyang univ.	18.8 km
Highway (DH)	Samseong-dong•Bundang	22.1 km

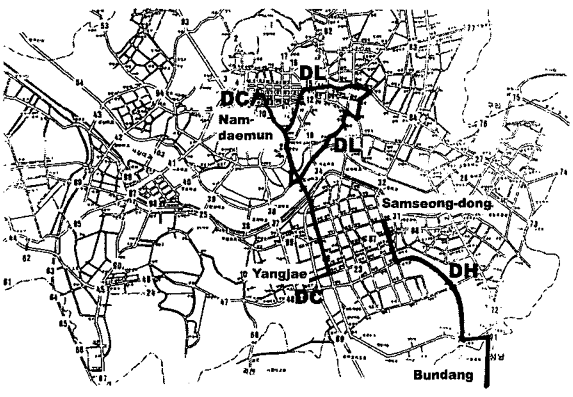

Figure 1. The map of test driving routes.

test routes were some of the test routes which had been selected to evaluate the fuel economy by Korea Institute of Energy Research (KIER) in 1993 (Lee *et al.*, 1995). These routes were on behalf of commuter, circulation, and highway modes of Seoul. The driving distances of the test routes are between 15.1 and 22.1 kilometers. The test routes which have been chosen were summarized in Table 1 and shown in Figure 1.

Test runs were carried out by 45 drivers who have a passenger car with manual transmission and driving experiences over three years. The number of male and female drivers is 37 and 8 respectively. Test driving was conducted three times per day including rush hours.

2.2. Test Vehicle and Sensors

The test vehicle was a SONATA III 2.0 DOHC equipped with a manual transmission and ABS system having a cumulated mileage of 19,500 km. Measured signals were vehicle speed, engine revolution, fuel consumption, gear engaged, etc., which are summarized in Table 2. Vehicle speed was measured by the signal from ABS rear wheel speed sensor and engine revolution was measured by the signal from crank angle sensor. The amount of fuel consumption was measured by the injector driving signal, and engine load was measured by using the signal from throttle position sensor. Optical sensors were attached at the gearshift lever in order to measure the engaged gear signal.

Table 2. Measured signals.

Signal	Sensing position
Vehicle speed	Rear wheel speed sensor
Engine revolution	CAS signal from ECU (C21)
Fuel consumption	Injection signal from ECU (B1)
Gear engaged	Optical sensors at gearshift lever
Acceleration pedal	TPS signal from ECU (C19)

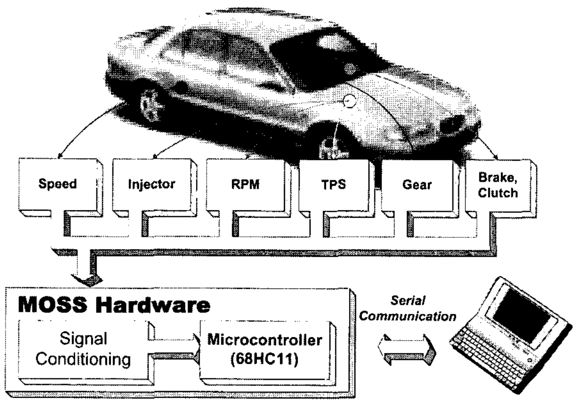

Figure 2. MOSS schematic diagram.

2.3. Data Acquisition System

The mode survey system (MOSS) was developed to measure and record the driving data during test runs. The MOSS received the driving signals from sensors and the ECU, temporarily stored the measured signals after signal conditioning, and sent them to personal computer (PC) for data recording. The MOSS was mounted into the trunk of the test vehicle during test driving and connected to the wheel speed sensor, the optical sensors, and the engine control unit (ECU) for receiving the measured signals. Figure 2 represents the schematic diagram of the MOSS.

The MOSS consists of hardware and software. MOSS hardware is designed to operate safely in the presence of electrical noise due to electromagnetic interference, which frequently appears during vehicle operation. It is also durable enough to withstand vibrations of the vehicle as well. The hardware can be installed without physically deforming any part of the test vehicle, and the operator can be easily aware of the current state of operation. The hardware structure of MOSS can be divided into 2 subsystems.

(1) Signal conditioning subsystem

(2) Microcontroller subsystem

The signal conditioning subsystem converts the driving signals received from sensors and the ECU into stable signals through filtering and sends them to the

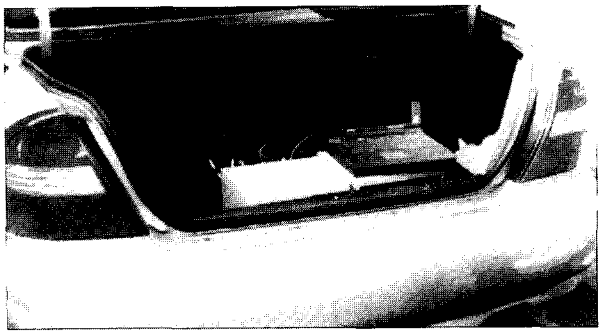

Figure 3. MOSS mounted in the test vehicle.

microcontroller. This subsystem receives electrical power from the built-in battery and supplies the sensors with the electrical power of ±12 and +5 volts.

The Motorola 68HC11 was chosen as a micro-controller. The signals from the signal conditioning subsystem were sampled at 0.125-second interval and stored in the form of 8 bit data packet. The current state of the system is displayed on the LCD panel with background light for convenience. The stored data was transferred to a personal computer through RS-232 serial communication at a transmitting rate of 9.6 kbps. Figure 3 represents the appearance of MOSS installed in the trunk of the test vehicle.

The development of the MOSS software was focused on accuracy and convenience. The MOSS software is composed of a microcontroller assembly program and application program for analyzing the signals.

The assembly program reads the signals from sensors and the ECU, and uses the controller's timer feature to sample the signals at every 0.125 second. The initiation and termination of the test are controlled by the Start/ Stop toggle switch in front of the MOSS. In the post processing mode, the data was stored in the internal memory of the MOSS during the test and transferred to the PC upon completion of the driving test.

The application program receives driving data from the microcontroller and displays the measured signals in various forms. This program can also be used for statistical analysis. Figure 4 shows one of the display formats.

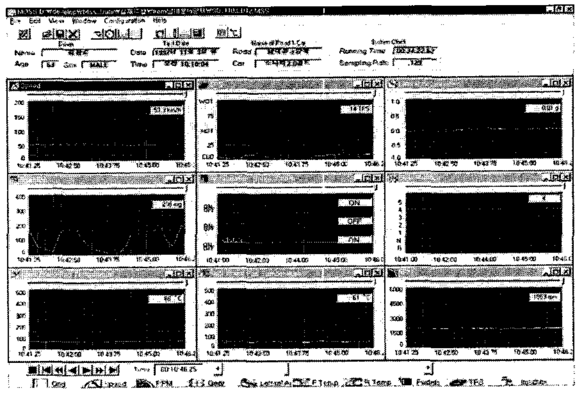

Figure 4. MOSS display in graph mode.

3. ANALYSIS

3.1. Modal Analysis

Modal analysis provides a very efficient method in studying the driving patterns. A modal analysis involves a statistical study on the driving data. For the present analysis, four major driving modes are considered and each mode is identified as follows (Shima, 1981);

(1) Acceleration mode is defined as the condition under which the vehicle speed is greater than 3 km/h and the acceleration of a vehicle is greater than 0.3 m/s^2;

(2) Deceleration mode is defined as the condition under which the vehicle speed is greater than 3 km/h and the acceleration of a vehicle is less than -0.15 m/s^2;

(3) Cruise mode is defined as the condition under which the vehicle speed is greater than 3 km/h and the acceleration of a vehicle is greater than -0.15 m/s^2 and less than 0.3 m/s^2;

(4) Idle mode is defined as the condition under which the vehicle speed is less than 3 km/h.

The analyzed results of the driving data were compared with the FTP-75 test mode and the results of early test, that is, '93 Seoul test which was conducted by KIER in 1993. Figure 5 shows a comparison of three test results for the modal distributions based on time duration. The percentages of time that the test vehicle spends in idle (33.2%), accelerating (21.8%), and decelerating (25.1%) are the highest among three test results. Therefore, the time percentage of cruising is the lowest value of 19.9%. The percentages of time that the FTP-75 test mode spends in accelerating and decelerating are 19.2% and 24.2% respectively which are lower than the results of this test by 0.9~2.6% points. But the percentages of time that the FTP-75 test mode spends in idle and cruising are

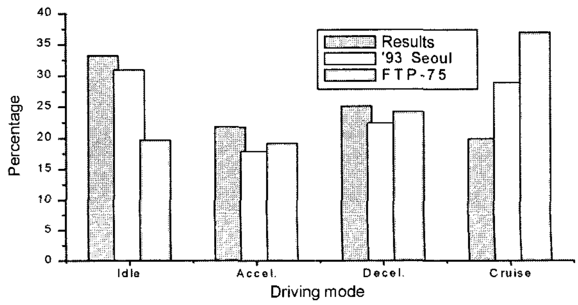

Figure 5. Modal distribution based on time duration.

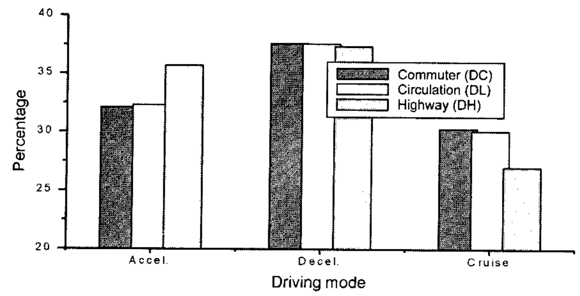

Figure 6. Modal distribution based on traveled distance.

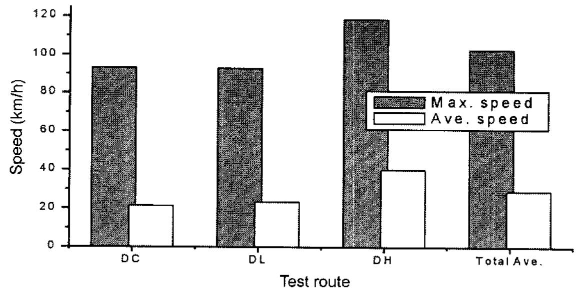

Figure 8. Maximum and average speeds according to the driving routes.

19.7% and 36.9% respectively which show great differences from the results of this test. As a consequence of this analysis, the FTP-75 test mode simulates the driving conditions of high average vehicle speed and small number of times of vehicle stationary.

Figure 6 shows a comparison of the test results of three routes for the modal distribution based on traveled distance. In case of commuter driving mode (DC), the proportions of accelerating, decelerating, and cruising mode are 32.1%, 37.6%, and 30.3% respectively. These proportions are similar to those of circulation driving mode (DL) which are 32.3%, 37.6%, and 30.3% respectively. In case of highway driving mode (DH), the proportions of accelerating, decelerating, and cruising mode are 35.7%, 37.4%, and 27.0% respectively. Therefore, the proportions of decelerating mode for the three test courses are nearly the same amount but the proportions of accelerating and cruising mode for DC and DL mode show differences from those of DH mode. This feature is because the average speed of the highway mode is higher than those of commuter and circulation mode.

3.2. Speed Analysis

In speed analysis, the maximum and average speeds are analyzed according to the three tests and the three test routes. Figure 7 shows the maximum and average speeds for the three tests. While the average speed of this test is 29.2 km/h, the average speeds of the '93 Seoul test and the FTP-75 test mode are 22 km/h and 34.1 km/h respectively. Therefore, the average speed of this test is higher than that of the '93 Seoul test and lower than that of the FTP-75 test mode. Also, the maximum speed of this test is the highest value of 103 km/h among other test results.

Figure 8 shows the maximum and average speeds for the three test routes. The maximum and average speeds of commuter (DC) and circulation (DL) mode are nearly the same amount, and the results of the highway (DH) mode show the highest values. This feature is because the proportion of accelerating mode for DH is higher than those of DC and DL mode. Moreover, the number of stops per unit distance for DC and DL mode is 2.63 and 1.75 times/km, respectively and for DH mode is 1.0 times/km.

Figure 9 is a three dimensional surface of probability percentage of the speed-acceleration matrix of this test. This graph shows that the maximum value of probability percentage is located in the region of speed under

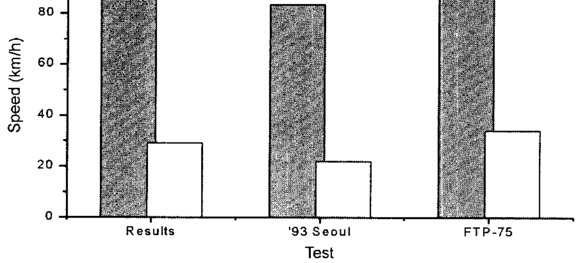

Figure 7. Maximum and average speeds for the three tests.

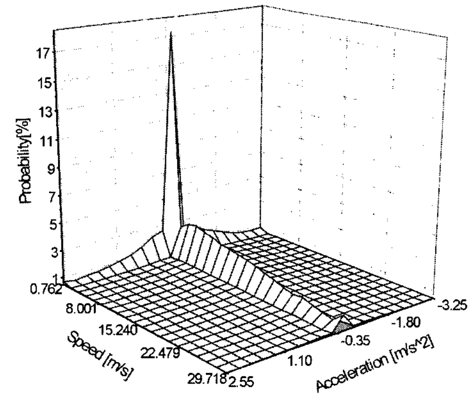

Figure 9. Surface of probability percentages for speed-acceleration matrix.

0.762 m/s and acceleration between -0.2 and 0.105 m/s^2. As both the speed and the absolute value of acceleration increase, the probability percentage shows decreasing tendency.

3.3. Multivariate Statistical Analysis

Since each test driving reflects nearly all cases of driving situations, the trip data of three test routes is used for statistical analysis. The driving data which was obtained from road tests was arranged into 74 sample data for statistical analysis. The minimum average speed of the sample data was 10.4 km/h and the maximum average speed 54.7 km/h, and the average speed 29.2 km/h. From a list of 36 variables examined in a preliminary analysis, 18 traffic variables were selected for the correlational analysis. The variables are defined in the appropriate way and listed in Table 3. The correlation coefficients between 18 variables are given in Table 4. Most of the traffic variables are highly correlated with fuel consumption. Table 5 shows the eigenvalues of the principal components as a result of principal component analysis. The first four principal components represent over 92 percent of the total variances in the data.

The multiple linear regression analysis was used to obtain the best one, two, three, etc., traffic variable subsets for the estimation of fuel consumption. The variable subsets and the coefficients of determination (r^2) for each subset of 1 to 3 independent variables are shown in Table 6. For the single variable, the average trip time per kilometer (X_3) accounts for a large portion of the variance in fuel consumption (X_{18}). For the two variables, the best regression involves average trip time per kilometer (X_3) and average acceleration (X_4), and for the three variables, the best regression involves standard deviation of trip speed (X_2), average trip time per kilometer (X_3), and average acceleration (X_4). The more variables were involved in the subsets, the higher coefficient of determination resulted in. The coefficients of determination represent the proportion between the total variance of the measured fuel consumption and the variance of the estimated fuel consumption. The values of the coefficients of determination are between 0 and 1. The high value of the coefficients of determination means that the estimated fuel consumption is close to the measured value.

Figure 10 shows the scattering diagram between fuel

Table 3. Traffic variables used in analysis.

No	Variable	*Unit*	*Formula*
1	Average trip speed	km/h	$\bar{v} = (1/T)\int_0^T v(t)dt$
2	Standard deviation of trip speed	km/h	$\sqrt{(1/T)\int_0^T (v(t)-\bar{v})^2dt}$, $v(t)>0$
3	Average trip time per kilometer	sec/km	
4	Average acceleration	g	$\bar{a} = (1/T)\int_0^T a(t)dt,\ a(t)\geq 0,\ v(t)>0$
5	Standard deviation of acceleration	g	$\sqrt{(1/T)\int_0^T (a(t)-\bar{a})^2dt}$, $a(t)\geq 0,\ v(t)>0$
6	Time fraction of vehicle stationary	%	$v(t)<3$km/h
7	Time fraction of acceleration	%	$v(t)\geq 3$km/h, $a(t)\geq 0.3$m/s^2
8	Time fraction of cruising	%	$v(t)\geq 3$km/h, $-0.15\leq a(t)<0.3$m/s^2
9	Time fraction of deceleration	%	$v(t)\geq 3$km/h, $a(t)<-0.15$m/s^2
10	Acceleration energy per kilometer	$(m/s)^2$/km	$(1/D)\int_0^T a(t)\cdot v(t)dt,\ a(t)>0$
11	Number of times of vehicle stationary per kilometer	times/km	
12	Time of vehicle stationary per kilometer	sec/km	
13	Acceleration time per kilometer	sec/km	
14	Cruising time per kilometer	sec/km	
15	Deceleration time per kilometer	sec/km	
16	Acceleration sum per kilometer	(km/h)/km	$(1/D)\int_0^T a(t)dt,\ a(t)>0$
17	Square velocity per kilometer	(m^2/s)/km	$(1/D)\int_0^T v^2(t)dt,\ a(t)>-0.15$m/s^2
18	Fuel consumption	cc/km	

(Note) T: trip time, D: trip distance

Table 4. Correlation coefficient matrix.

Var.	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	1.00	0.83	-0.90	-0.38	-0.43	-0.83	0.89	0.29	0.80	0.18	-0.75	-0.81	-0.93	-0.88	-0.93	-0.82	0.91	-0.75
2		1.00	-0.66	-0.35	-0.31	-0.51	0.61	0.10	0.48	0.21	-0.45	-0.52	-0.80	-0.74	-0.80	-0.68	0.97	-0.49
3			1.00	0.39	0.49	0.88	-0.90	-0.36	-0.84	-0.18	0.93	0.98	0.90	0.88	0.92	0.83	-0.74	0.89
4				1.00	0.60	0.32	-0.33	-0.31	-0.15	0.36	0.34	0.36	0.41	0.27	0.51	0.52	-0.41	0.60
5					1.00	0.47	-0.48	-0.27	-0.38	0.01	0.48	0.50	0.40	0.37	0.48	0.43	-0.34	0.56
6						1.00	-0.93	-0.57	-0.92	-0.17	0.84	0.92	0.72	0.68	0.73	0.67	-0.59	0.73
7							1.00	0.25	0.93	0.38	-0.78	-0.89	-0.74	-0.85	-0.79	-0.61	0.69	-0.74
8								1.00	0.24	-0.53	-0.47	-0.46	-0.31	0.07	-0.33	-0.52	0.18	-0.34
9									1.00	0.43	-0.76	-0.86	-0.66	-0.79	-0.64	-0.50	0.52	-0.68
10										1.00	-0.04	-0.17	-0.02	-0.42	-0.02	0.31	0.11	0.06
11											1.00	0.95	0.80	0.74	0.82	0.80	-0.56	0.86
12												1.00	0.80	0.79	0.83	0.75	-0.61	0.86
13													1.00	0.86	0.97	0.93	-0.89	0.82
14														1.00	0.85	0.66	-0.78	0.76
15															1.00	0.92	-0.89	0.84
16																1.00	-0.79	0.81
17																	1.00	-0.60
18																		1.00

Table 5. Eigenvalues of principal components.

Principal component	Eigenvalue	% of variance	Cumulative %
1st	11.0668	65.1	65.1
2nd	2.2156	13.0	78.1
3rd	1.5007	8.8	87.0
4th	0.9963	5.9	92.8
5th	0.5099	3.0	95.8
6th	0.3342	2.0	97.8
7th	0.1886	1.1	98.9

Table 6. Best to 7th best linear regression.

Rank	1 variable		2 variables		3 variables	
	Var.	r^2	Var.	r^2	Var.	r^2
Best	3	0.7853	3,4	0.8613	2,3,4	0.8870
2nd	12	0.7412	4,11	0.8408	3,4,17	0.8824
3rd	11	0.7316	4,12	0.8381	3,4,7	0.8761
4th	15	0.7136	3,10	0.8374	1,3,4	0.8756
5th	13	0.6750	15,17	0.8312	3,4,10	0.8735
6th	16	0.6530	3,5	0.8054	4,11,14	0.8734
7th	14	0.5719	3,7	0.8041	8,10,12	0.8729

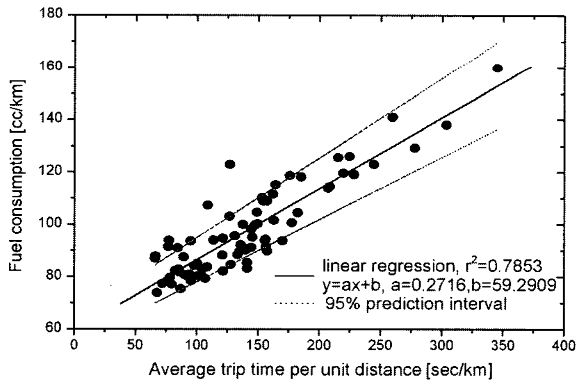

Figure 10. Relationship between fuel consumption and average trip time per kilometer.

consumption and average trip time per kilometer which has the highest value of coefficient of determination (r^2). The solid line represents the result of linear regression estimation of fuel consumption, and the dotted lines represent 95 percent intervals of the estimated values. There is an almost linear relationship between fuel consumption and average trip time per kilometer.

Figure 11 shows the average trip time per kilometer, and fuel consumption for the three test routes. The fuel consumptions of the commuter mode (DC) and the circulation mode (DL) are 107.4, and 104.5 cc/km

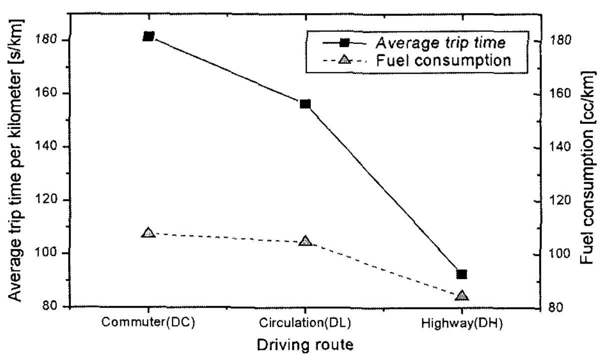

Figure 11. Fuel consumption and average trip time per kilometer according to driving routes.

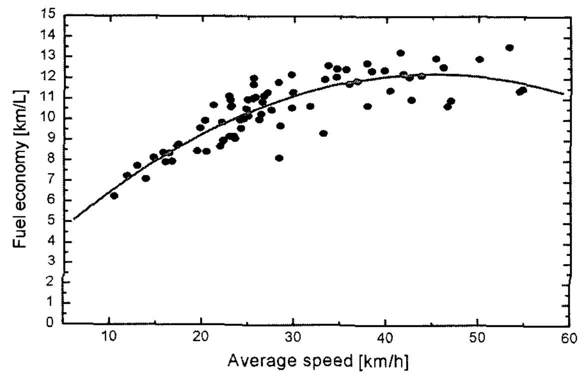

Figure 12. Relationship between fuel economy and average speed.

respectively and these values are higher than the average fuel consumption of 97.8 cc/km. As for the highway mode (DH), the fuel consumption is 84.2 cc/km, which is lower than the average fuel consumption. Therefore, it is known that the fuel consumption is proportional to the average trip time.

3.4. Analysis of Fuel Economy

Figure 12 shows the scattering diagram between fuel economy and average speed. The solid line represents the curve fitting result using the least square method. The fuel economy is a reciprocal of the fuel consumption, and has an increasing tendency according to the increase of the average speed. Therefore, it is necessary to increase the average velocity in order to reduce CO_2 emission and improve fuel economy.

Figure 13 shows the analyzed result of the fuel economy according to drivers gender. While the total average fuel economy is around 10.23 km/L, the average fuel economy of male drivers 10.12 km/L, and the average fuel economy of female drivers 10.69 km/L. Therefore, the average fuel economy of female drivers is higher than that of the male drivers by 5.6% points.

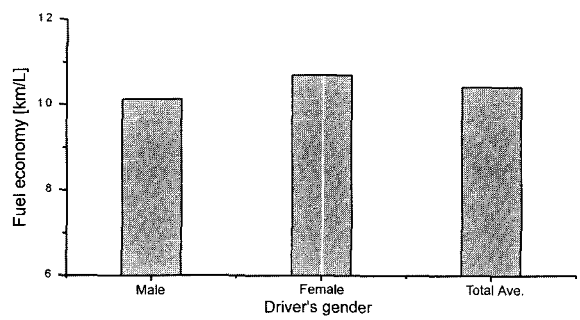

Figure 13. Fuel economy according to driver's gender.

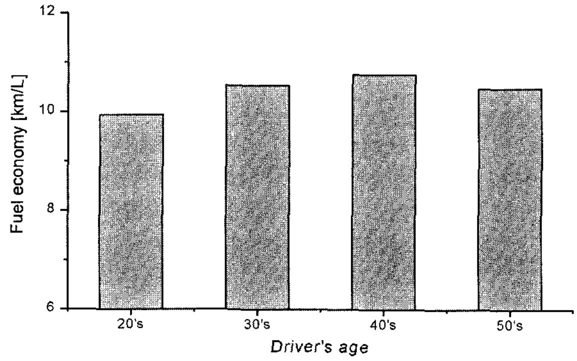

Figure 14. Fuel economy according to driver's age.

Figure 14 shows the analyzed result of the fuel economy according to drivers age. The fuel economy of the Forties is the highest value of 10.75 km/L, and the fuel economy of the Twenties is the lowest value of 9.93 km/L.

4. CONCLUSION

The driving data which has been obtained from road tests was analyzed statistically to obtain driving patterns and fuel consumption.

The average speed of Seoul is around 29.2 km/h, and the number of stops per kilometer is 1.83 times/km, and the average fuel economy is 10.23 km/L. The maximum acceleration and the maximum deceleration are 0.709 g and -0.554 g respectively.

As a consequence of the 4-mode analysis based on time duration, the sum of acceleration and deceleration mode is 46.9 percent which is similar to the FTP-75 test mode. The idle mode is 33.2 percent, and the cruise mode is 19.9 percent. The idle and cruise mode are different from the FTP-75 test mode, which are 19.7, and 36.9 percent respectively. Therefore, the vehicle speed of the Seoul metropolitan area is slower, and the stop-and-go operation is more frequent than the FTP-75 test mode.

The multiple linear regression analysis was carried out to obtain the best one, two, three traffic variable subsets for fuel consumption estimation. For the single variable, the average trip time per kilometer is one of the most important factors to fuel consumption. For the two variables, the average trip time per kilometer and the average acceleration are the most important subset, and for the three variables, the average trip time per kilometer, the average acceleration, and the standard deviation of trip speed are the most important subset.

As a result of the principal component analysis, the first four principal components represent over 92 percent of the total variances in the data.

Under 45 km/h of vehicle speed, fuel economy is nearly proportional to the vehicle speed, but over 45 km/h, the increase of fuel economy with speed becomes blunt.

As a result of analyzing fuel economy according to the drivers gender, the average fuel economy of female drivers is 10.69 km/L, and higher than that of male drivers, 10.12 km/L.

As a result of analyzing fuel economy according to drivers age, the fuel economy of the Forties is the highest value of 10.75 km/L, and the fuel economy of the Twenties is the lowest value of 9.93 km/L.

ACKNOWLEDGEMENT–The present research has been conducted by the Research Grant of Seoil College 2002.

REFERENCES

Bata, R., Yacoub, Y., Wang, W., Lyons, D., Gambino, M. and Rideout, G. (1994). Heavy duty testing cycles: survey and comparison. *SAE Paper No.* 942263, 29–41.

Evans, L., Herman, R. and Lam, T. (1976). Multivariate Analysis of traffic factors related to fuel consumption in urban driving. *Transportation Science* **10**, **2**, 205–215.

Hellman, K. H. and Murrell, J. D. (1984). Development of adjustment factors for the EPA city and highway MPG values. *SAE Paper No.* 840496, 1–8.

Koh, K. (2000). *An Environmental White Paper in 2000–Environment in Seoul.* Seoul Metropolitan Government.

Lee, Y. J., Kwon, O. S. and Koh, C. J. (1995). Analysis of the driving patterns concerned with fuel economy in Seoul metropolitan area. *Transactions of KSAE* **3**, **2**, 1–15.

Sunwoo, M. H., Lee, J. I., Lee, W. T., Lee, S. J., Ju, W. C., Choi, S. H., Lee, S. T., Lee, H. S. and Lee, K. M. (1998). Development of an in-vehicle driving data acquisition system. *Spring Conference Proceedings of KSAE*, 391–396.

Shima, J. (1981). Detailed analysis on the actual driving condition and fuel economy. *Automotive Technology* **35**, **10**, 1177–1184.