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COMPARATIVE STUDY BETWEEN KOREA AND UK: RELATIONSHIP BETWEEN DRIVING STYLE AND REAL-WORLD FUEL CONSUMPTION

J. SON[1)*], M. PARK[1)], K. WON[1)], Y. KIM[1)], S. SON[1)], A. MCGORDON[2)], P. JENNINGS[2)] and S. BIRRELL[2)]

[1)]HumanLab, DGIST (Daegu Gyeongbuk Institute of Science and Technology), Daegu 42988, Korea
[2)]WMG, University of Warwick, Coventry, CV4 7AL, UK

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ABSTRACT–It is known that differences in driving styles have a significant impact on fuel efficiency and driving styles are affected by various factors such as driver characteristics, street environment, traffic situation, vehicle performance, and weather conditions. However, existing knowledge about the relationship between driving style and fuel consumption is limited. Thus, the aim of this study was to analyze the relationship beteen driving style and fuel consumption. The analysis presented in this paper used data from three on-road experiments were conducted independently in two different countries, i.e. South Korea and the United Kingdom. In this study, 91 participants, consisting 44 UK drivers and 47 Korean drivers, were asked to drive approximately 28 km of UK road and 21 km of Korean road, respectively. Driving data, including real-time fuel consumption, vehicle speed, and acceleration pedal usage were collected. The results suggested that driving styles including average vehicle speed and average throttle position were highly correlated with the real-world fuel consumption, and the cultural factors, e.g. road environment, traffic design, and driver's characteristics affected the driving styles and, consequently, fuel efficiency.

KEY WORDS : Driving style, Fuel consumption, Cross-cultural difference, Traffic environment, Field operation test

1. INTRODUCTION

The combustion of fossil fuels such as gasoline and diesel for transportation was the second largest source of greenhouse gas (GHG) emissions in 2011 (Mitropoulos and Prevedouros, 2014). Currently, increasing numbers of research on reducing GHG emissions and improving fuel efficiency have been actively conducted. Ericsson (2000) found that various factors including vehicle, road environment, and driving style affect the fuel efficiency of vehicles. Among those factors, Cleaves (1997) found that the fuel consumption varies according to driving pattern and suggest the eco driving style. Klunder *et al*. (2009) also suggested that changing driving style may increase the fuel efficiency up to 20 % with relatively lower cost comparing with other factors. Therefore, Orofino *et al*. (2010) emphasized the driving style related enhancement should be addressed prior to other considerations. In eco-driving assistance perspective, Birrell *et al*. (2014) showed real-world improvements in fuel efficiency when using an in-vehicle eco driving application of 4.1 %. However, few previous eco-driving studies considered the cross-cultural variability of driving style.

Human factors in driving can be classified into two separate components, i.e., driving skills (or driving performance) and driving style (or driver behavior) (Özkan *et al*., 2006). Driving style refers to the ways drivers choose to habitually drive, for example, the choice of driving speed, habitual level of general attentiveness, and gap acceptance (Elander *et al*., 1993; Son *et al*., 2010). From previous study results, drivers in the UK across all age groups were found to show a tendency for aggression, appraising other drivers as hostile and coping confrontationally, a style of coping linked to both anger and dangerous driving (Matthews *et al*., 1996). Son *et al*. (2013) found that drivers' characteristics, e.g. age and gender, significantly affected fuel efficiency. They suggested that drivers of late middle age recorded higher fuel efficiency than young drivers, and female drivers higher than male drivers.

In addition, the variation in driving style could be influenced not only by the drivers' characteristics but also by the external conditions such as street type, traffic conditions, and the type of car. Lyons *et al*. (1990) suggested that driving patterns are connected with urban structure and local environment. Smidfelt-Rosqvist (1998) also found that fuel consumption was highly correlated to street design and structure.

**Corresponding author.* e-mail: joonwooson@gmail.com

Thus, the present paper aimed at analyzing the relationship between driving style and fuel consumption, and its impact on the real-world fuel consumption across two different countries, South Korea and the United Kingdom.

2. METHOD

2.1. Participants

In order to compare the effects of driving styles on fuel economy between UK and Korean drivers, a total of 91 drivers were recruited as shown in Table 1. The gender of Korean drivers was counterbalanced but the UK was not. The average age of Korean drivers was slightly older than the UK drivers, but not significant.

2.2. Experimental Vehicle

As shown in Table 2, three different vehicles were used to collect drivers' behaviors, e.g. throttle usage, and driving data, e.g. vehicle speed, acceleration, and engine speed.

2.3. Experimental Road Scenario

Figure 1 presents overall driving routes of three separate experiments. The WMG study was conducted in Warwickshire in the UK for the verification of a driver model generated.

The MIRA study was conducted for investigating the effects of using in-vehicle information systems. The DGIST study was conducted in Daegu in South Korea for analyzing the relationship between driving styles and fuel efficiency.

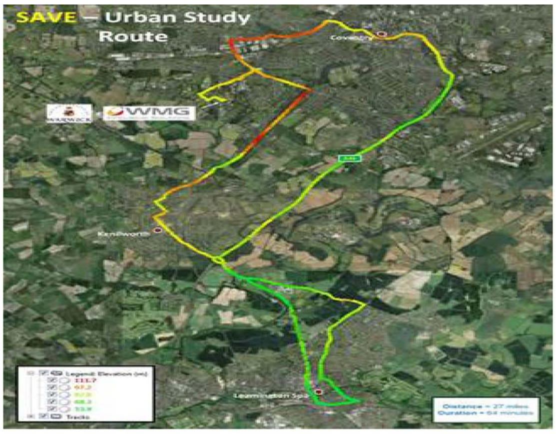
As shown in Table 3, the driving length of Korean scenario was shorter than the UK and the overall

Table 1. Participants overview.

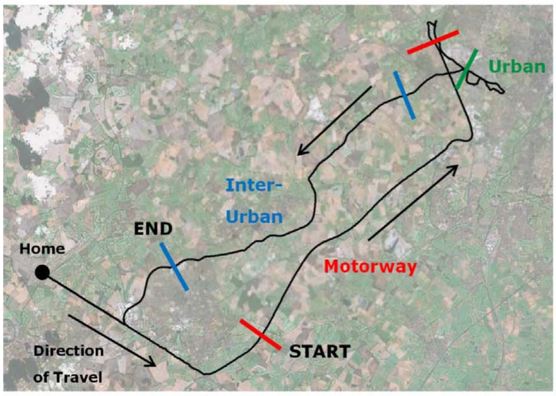
	WMG (UK)	MIRA (UK)	DGIST (Korea)
N	19	25	47
Age	35.8	41.9	43.9

Table 2. Overview of vehicle parameters.

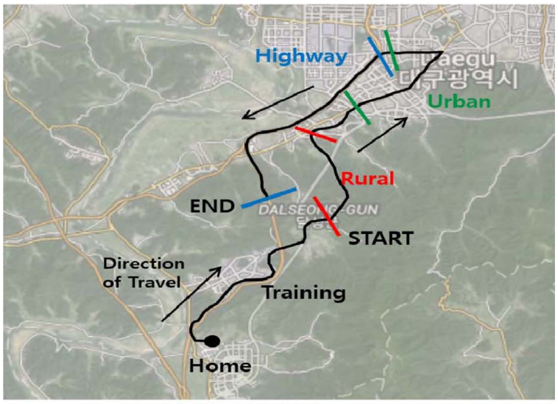
	WMG (UK)	MIRA (UK)	DGIST (Korea)
Model (Maker)	Freelander (Land Rover)	Focus (Ford)	Genesis (Hyundai)
Fuel type	Diesel	Diesel	Petrol
Engine size (ℓ)	2.2	1.6	3.3
Engine power (HP)	148	104	262
Fuel efficiency (km/liter)	15.9	23.8	10.1
Transmission	Manual	Manual	Automatic



(a) WMG driving route



(b) MIRA driving route



(c) DGIST driving route

Figure 1. Driving routes of three experiments.

Table 3. Experimental roadway conditions.

	WMG (UK)	MIRA (UK)	DGIST (Korea)
Length (km)	27.3	28.3	20.9
Driving time (minutes)	65.8	50.1	31.7
Speed ≥ 100 km/h	17.9 %	40.6 %	45.7 %
50 km/h ≤ Speed < 100 km/h	47.0 %	50.3 %	54.3 %
Speed < 30 mph	35.1 %	9.2 %	0.0 %

Table 4. Driving style parameters.

Category	Parameters	Description
Acceleration	Max acceleration (m/s^2)	Acceleration with strong power demand
	Max deceleration (m/s^2)	Extreme deceleration by braking
Engine speed	Average engine speed (rpm)	Normal engine speed
	Max engine speed (rpm)	Late gear change
Vehicle speed	Average speed (km/h)	Normal speed
	Max speed (km/h)	Extreme speed
	S.D.* of speed (km/h)	Speed oscillation
Driver input	Average throttle position (%)	Normal throttle usage
	Max throttle position (%)	Extreme throttle usage
	S.D.* of throttle position	Throttle oscillation

*S.D. means a standard deviation.

distribution of speed limit was different. For example, the portions of highway driving, i.e. the speed limit was equal or higher than 100 km/h, were 17.9 %, 40.6 % in the UK WMG and MIRA experiments, and 45.7 % in Korean scenarios.

2.4. Data Collection and Normalization

As shown in Table 4, the driving style parameters were selected based on the findings of Ericsson (2000) which were shown as having the most significant impact on fuel consumption and their categories within. The mean, maximum and standard deviation of each parameter were calculated for each participant. Data from fifteen participants in MIRA (UK) experiments were excluded from the analysis due to technical issues with collecting data.

Due to the difference in vehicle characteristics and roadway environment of three experiments in the UK and Korea, a normalization method was applied to the raw data. A raw score was transformed into a standard score using z-score function (1) which is one of the most commonly used score normalization technique (Jain *et al*., 2005);

$$Z = \frac{(X-\mu)}{\sigma} \quad (1)$$

where μ is the arithmetic mean and σ is the standard deviation of the given data.

3. RESULTS

The data were analyzed with descriptive statistics, a one-way ANOVA, and multiple linear regression analysis using SPSS version 17.

3.1. Descriptive Comparisons

As shown in Table 5, descriptive statistics showed significant differences between the UK and Korean drivers. In general, the fuel economy of the UK drivers was much higher than that of Korean drivers. However, that was contributed by the difference of the engine types, i.e. diesel engines for the UK cars (certified fuel economy for Land Rover Freelander and Ford Focus diesel: 15.9 and 23.8 km/*l*) and a gasoline engines for the Korean car (certified fuel economy: 10.1 km/*l*). Overall fuel efficiency results of all three studies were lower than the certified fuel efficiency, i.e. 18.6 % and 18.0 % in the UK and 14.3 % in Korean study, respectively. Most of the driving behavior parameters were significantly different. Especially, the primary differences appeared in the standard deviation of throttle position, average throttle position, maximum deceleration and average speed (see Table 5).

3.2. Regression Model for Fuel Consumption

A multiple linear regression models on the fuel economy and driving style were constructed, and the contributions of specific driving parameters to increase or decrease the fuel efficiency were analyzed as shown in Table 6. The explanatory power of the multiple linear regression models using the whole data sets from the three studies was 88.3 % (R Square = 0.883). However, the data sets were collected from different vehicle types and road environments. Thus, the z-score normalization procedure was conducted prior to comparative analysis.

The regression model fitness using the normalized data was reduced to 54.2 % (R Square = 0.542), which may not be the optimal model. However, the regression coefficients were sufficient for analyzing the relative contributions of each variable within the regression models.

According to the contribution of the driving style parameters in the overall regression model using data from the whole three studies, 61.2 % of the fuel economy model was explained by the average speed (+24.2 %), average throttle position (−24.1 %) and maximum acceleration (−12.9 %) as described in Table 6. In the UK studies, the R^2

Table 5. Descriptive statistics and ANOVA results.

Category	Parameters	Descriptive results*						ANOVA**	
		WMG (UK)		MIRA (UK)		DGIST (Korea)		F-ratio	p
Fuel economy	Fuel Efficiency (km/*l*)	12.94	(1.14)	19.52	(1.13)	8.66	(0.44)	1352.529	.000
Acceleration	Max acceleration (m/s^2)	3.88	(1.14)	3.63	(0.77)	3.50	(0.49)	1.782	.174
	Max deceleration (m/s^2)	-4.03	(1.00)	-3.35	(0.52)	-5.43	(1.23)	36.358	.000
Engine speed	Average engine speed (rpm)	1428.95	(159.41)	1550.89	(98.05)	1222.06	(50.39)	103.515	.000
	Max engine speed (rpm)	3417.58	(520.00)	2904.56	(381.39)	2621.40	(282.76)	31.547	.000
Vehicle speed	Average speed (km/h)	41.06	(2.01)	55.02	(2.45)	39.95	(2.92)	287.011	.000
	Max speed (km/h)	124.42	(13.48)	118.47	(7.97)	106.94	(9.05)	25.187	.000
	S.D. of speed (km/h)	28.93	(1.99)	34.74	(1.77)	31.02	(1.86)	57.193	.000
Driver input	Average throttle position (%)	8.89	(0.97)	18.12	(1.70)	11.00	(0.55)	502.537	.000
	Max throttle position (%)	76.49	(20.12)	52.16	(13.49)	48.63	(8.11)	32.578	.000
	S.D. of throttle Position	10.99	(2.43)	2.20	(0.22)	6.70	(1.10)	228.284	.000

*Average with standard deviation in parentheses.
**The degree of freedon in the ANOVA test is (2, 88).

Table 6. Multiple linear regression model for fuel consumption.

		Total			WMG (UK)			MIRA (UK)			DGIST(Korea)		
		R^2	Bata	Contri-bution	R^2	Bata	Contri-bution	R^2	Bata	Contri-bution	R^2	Bata	Contri-bution
Models	Models	0.542			0.952			0.606			0.797		
Acceler-ation	Max acceleration (m/s^2)		-0.172	-9.7 %		0.426	8.6 %		-0.234	-10.1 %		0.18	5.7 %
	Max deceleration (m/s^2)		0.048	2.7 %		0.731**	14.8 %		-0.116	-5.0 %		0.201*	6.4 %
Engine speed	Average engine speed (rpm)		0.063	3.6 %		-0.217	-4.4 %		0.17	7.3 %		-0.478*	-15.2 %
	Max engine speed (rpm)		-0.229	-12.9 %		-0.524	-10.6 %		-0.162	-7.0 %		-0.062	-2.0 %
Vehicle speed	Average speed (km/h)		0.429***	24.2 %		0.238	4.8 %		0.248	10.7%		1.122***	35.7 %
	Max speed (km/h)		0.429	-6.7 %		-0.37	-7.5 %		-0.072	-3.1 %		-0.138	-4.4 %
	S.D. of speed (km/h)		0.429	-9.3 %		0.406	8.2 %		-0.252	-10.8 %		-0.079	-2.5 %
Throttle	Average throttle position (%)		0.429**	-24.1 %		-1.144**	-23.2 %		-0.709	-30.5 %		-0.166	-5.3 %
	Max throttle position (%)		0.429	3.1 %		0.079	1.6 %		-0.052	-2.2 %		0.114	3.6 %
	S.D. of throttle position		0.429	-3.7 %		0.797**	16.2 %		0.31	13.3 %		-0.601**	-19.1 %

*$p<.05$, **$p<.01$, ***$p<.001$

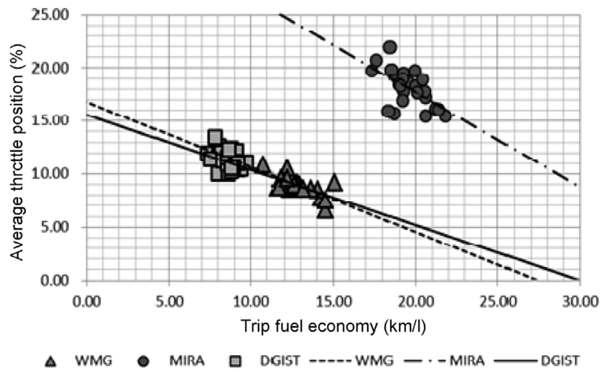
value for the WMG study was 95.2 %, suggesting a high goodness-of-fit, and the MIRA study result was 60.6 %, suggesting reasonable model fitness. The results from the UK studies indicated that the most significant driving style parameter on the fuel efficiency was average throttle position, which contributed to decrease fuel efficiency by 23.2 % and 30.5 % in the regression models. However, the results from the Korean study showed that the most significant parameter was average vehicle speed. The vehicle speed contributed to increase fuel efficiency by 35.7 % in the Korean regression model.

4. DISCUSSION

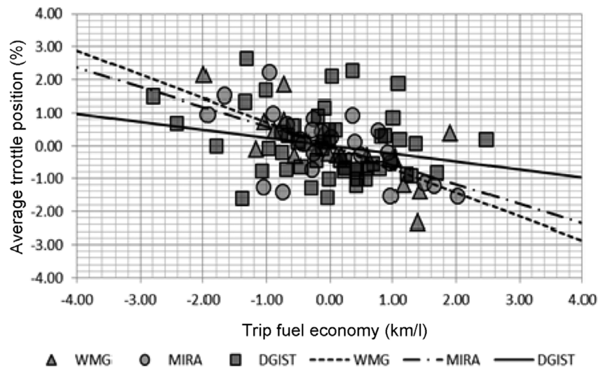
4.1. Normalization Method for Comparing a Non-homogeneous Data Set

As mentioned, data from three completely separate studies were used for the analysis. The non-homogeneous extended data were collected using different vehicles and drivers over entirely different real-world driving scenarios. It was found that the z-score normalization method effectively merged three separated data sets into one unified data set, as shown in Figure 2.

The unified data set could be used to construct a regression model on the cross-cultural fuel economy and driving behavior. Although the explanatory power of the regression model was not sufficient enough, i.e., 54.2 % (R Square = 0.542), two significant driving parameters, including average vehicle speed and average throttle position, were observed. Each parameter represented each



(a) Original throttle position



(b) Z-score normalized throttle position

Figure 2. Example of original and normalized data sets.

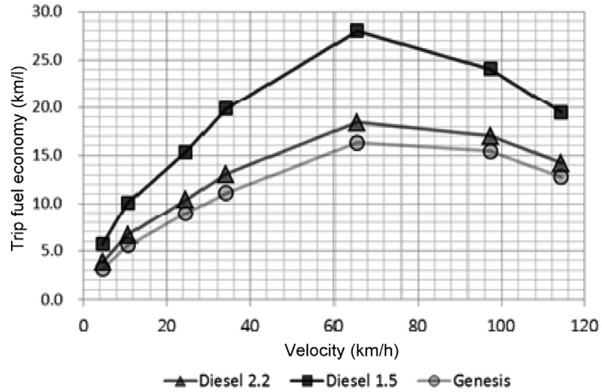


Figure 3. Example profiles of speed-based fuel economy by engine size and types.

countries dominant variable, i.e., throttle position for UK studies and vehicle speed for Korean study. The difference could be explained by the experimental conditions such as vehicle types, roadway environment and driving behavior.

4.2. Effects of Vehicle Performance

The vehicles used in the three studies had different performance specifications. The vehicle used in the Korean study had the most powerful engine but the vehicle for the MIRA study in the UK had the lowest engine power. The WMG vehicle had a medium engine size between the MIRA and DGIST vehicles. Thus, the results of the average throttle position were relatively higher in the MIRA study than that of the DGIST study. Interestingly, the average throttle position of the WMG study was similar to the result of DGIST, but the contribution of the average throttle position was much closer to the MIRA model than the DGIST model.

The difference in the vehicle performance also affected the relationship between the vehicle speed and fuel efficiency. Figure 3 depicts the correlation between vehicle speed and fuel efficiency based on engine displacement. As in Figure 3, the profile of the 2.2 liter diesel engine, i.e., the same engine size of the WMG vehicle was closer to the DGIST vehicle profile.

4.3. Effects of Driving Styles

Regarding the difference in driving styles between the UK and Korea, it was found that driving style was related to urban structure and local environment (Lyons *et al*., 1990) and fuel consumption were highly correlated to street design and structure. However, overall speed limit profiles of the MIRA study and the Korean study were likely to be the same, but the WMG study was significantly different. That meant that the environment factors may not have a significant difference between the UK and Korean studies, at least, the MIRA and the DGIST studies.

When considering the cross-cultural differences, it was found that drivers in the UK across all age groups were found to show a tendency for aggression (Matthews *et al*., 1996). Driving style referred to the level of driving aggressiveness and included the effects of the vehicle, driver, and driving environment. Driving style can be thought of as the accumulated velocities and accelerations used during a specific type or mode of driving (Berry, 2010). In the country-wise analysis, the results indicated drivers in the UK were more aggressive than the Korean drivers. The maximum speeds of the UK studies were higher by 16.3 % (WMG) and 10.8 % (MIRA) than the DGIST study result. The maximum accelerations were also higher by 10.9 % (WMG) and 3.7 % (MIRA) compared to the DGIST result (see Table 5). The findings supported that the findings of the UK drivers' aggressiveness (Matthews *et al*., 1996) and suggested that the external differences, e.g. road environment, traffic design, and drivers' behaviors affected on driving styles and, consequently, fuel efficiency.

5. CONCLUSION

In this study, it was examined whether driving style was influenced by various factors such as the driver characteristics, the road environment, the traffic flow and the vehicle type. In order to understand the effect of these sources on driving style and fuel economy, driving experiments were conducted on an actual road in the UK and Korean roadway.

A cross-cultural comparison using different data sets which were collected from the different vehicle types (i.e. gasoline and diesel) and countries (i.e. the UK and South Korea), was conducted through z-score normalization method. A regression model from the normalized data was created with the explanatory power of 54.2 %. The results indicated different variables as dominant factors that affected fuel consumption in a different country, e.g. average throttle position for the UK model and average vehicle speed for Korean model. The findings showed that the external differences such as traffic design and road environment have affected driving style, and highly correlated with the real-world fuel consumption consistent with the findings of previous studies (Lyons *et al*., 1990; Smidfelt-Rosqvist, 1998).

The results of this study suggested that automotive manufacturers need to consider cultural differences in driving style which affect fuel efficiency when designing an eco-driving assistant system.

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