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ANALYSIS OF VEHICLE FUEL EFFICIENCY AND SURVIVAL PATTERNS FOR THE PREDICTION OF TOTAL ENERGY CONSUMPTION FROM GROUND TRANSPORTATION IN KOREA

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ABSTRACT−In this study, correlation between vehicle fuel efficiency and total fuel energy consumption is analyzed to support the energy consumption and greenhouse gas (GHG) emissions reduction master plan in Korea. The background and highlights of recently amended fuel economy regulations and fuel efficiency labeling standards in Korea are also introduced. 18 representative vehicle groups, classified by class, type, size, and fuel, are selected by investigating vehicle distribution statistics based on market penetration and registration data sets in order to reflect and predict total fuel energy consumption in the overall ground transportation sector in Korea. Validity of the vehicle survival patterns modeled and vehicle classification rules are confirmed by comparing national fuel energy consumption statistics to the total amount of fuel consumed by each selected representative vehicle group. The latter figures are approximated from representative number of registrations, weighted average fuel economy, and average annual distance traveled.

KEY WORDS : Fuel efficiency, Fuel energy consumption, Representative vehicle groups, Vehicle survival patterns

NOMENCLATURE

E : predicted annual fuel energy consumption, l
R : number of vehicle registration
D : average distance traveled, km
F : weighted average fuel economy, km/l
C : CO_2 emission, g/km

1. INTRODUCTION

Total energy consumption in Korea gradually has increased almost six-fold over the past 30 years as shown in Table 1, where population growth was only two-fold over the same period. Even though the rate of increase has slowed from 8.5 % in the 1980s to 3.1 % in the 2000s, the rate of total energy consumption is still increasing faster than the rate of Korea's economic growth, unlike in other developed countries such as the U.S., United Kingdom, and Germany. Korea's total energy consumption growth relative to economic growth is the highest among the 34 nations of the Organization for Economic Cooperation and Development (OECD). In particular, primary energy imports were increasing more rapidly than energy consumption in the 2000s, reaching a 16.7 % annual increase due to the persistent rise of the oil price. In 2012, primary energy imports in Korea reached 37 % of the total imports, which is 1.4 times the value of total exports of the chief exports such as semiconductors, cars, and sea vessels (KEEI, 2013).

Energy source-based statistics indicate that fossil fuels like oil, coal, and gas formed 85.5 % of the total energy consumption in 2012, as shown in Table 2. This issue has become a major obstacle to Korea meeting the United Nations Framework Convention on Climate Change (UNFCCC) by reducing climate warming GHG emissions such as CO_2. According to the national final energy consumption and outlook by sector (KEEI, 2013), energy demand of the transportation sector has reached 21.0 % in 2006, affected by the rapid increase of oil price after 2003, after which it gradually decreased to 17.9 % then 17.8 % in 2011 and 2013, respectively. However, within the

Table 1. Primary energy consumption and imports between 1981 and 2012.

	1981	1991	2001	2012
Energy consumption (million TOE)	45.7	103.6	198.4	277.6
Annual growth rate (%)	-	8.5	6.7	3.1
Energy imports (100 million $)	78	128	339	1,853
Annual growth rate (%)	-	5.1	10.3	16.7

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transportation sector, composed of ground, rail, air, and water, the ground transportation counted for the largest portion of energy demand occupying 77 % of the total sector energy consumption and 17 % of the total GHG emissions. Consequently, the Korean government plans transportation GHG emissions cuts of 34.3 %, which is higher than the 26.9 % from the building sector, 26.7 % from power generation, 25.0 % from the public sector, 18.5 % from industry, 12.3 % from waste, and 5.2 % from agriculture and fisheries (MOE, 2014a). Reducing total energy consumption from the ground transportation sector is, therefore, a matter of great urgency for Korea as one of the most heavily motorized countries, with 2.59 people per car in the first half of 2014 as shown in Figure 1 (MOLIT, 2014). In addition to being a major consumer of cars, Korea was the fifth biggest manufacturer in the world for the nine consecutive years up to 2013, producing 5.2 % of the world's new cars in that year (KAMA, 2014).

In order to establish more effective fuel economy regulations that embrace the entire ground transportation sector, it is beneficial to divide the sector into representative vehicle groups with reasonable classification rules. Total energy consumption obtained by analyzing registration data sets, average fuel efficiency, and average distance traveled of those representative vehicle groups would then be validated with national energy consumption statistics as suggested in our previous study (Choi and Lee, 2014). In the long term, it is desirable to make full use of predicted ripple effects of various energy-efficient technologies related to vehicle fuel efficiency improvements for drawing-up regulations and policies by constructing a technology database with regular updates.

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Table 2. Energy consumption profile in 2012.

	Oil	Coal	Gas	Nuclear	Renewable
Portion (%)	38.2	29.2	18.1	11.4	3.1

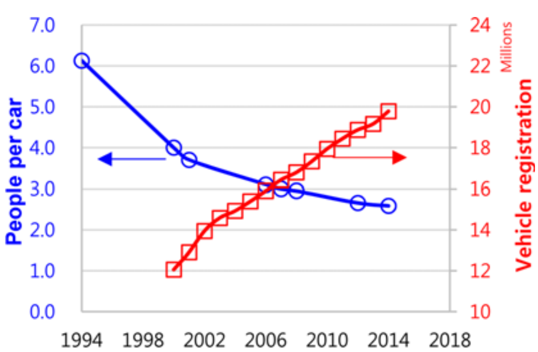

Figure 1. Vehicle ownership and registration trends in Korea.

2. FUEL ECONOMY STANDARDS IN KOREA

Korea is one of the few countries in the world, including the U.S., Japan, Canada, Australia, China, India, and the E.U., to have adopted mandatory vehicle fuel economy standards that are based on an engine size classification system. For the certification drive cycle, the Constant Volume Sampling 75 (CVS-75) mode, which is identical to the Federal Test Procedure 75 (FTP-75) mode developed by the U.S. Environmental Protection Agency (EPA) in 1975, has been applied in all Korean test procedures. Since the mode is basically representing city driving conditions in Los Angeles, there has been a considerable gap between the certified fuel economy and real-world gas mileage, often resulting in controversial issues between car makers and owners. In addition, the previous regulations that have remained unchanged for nearly four decades were unable to take into consideration the fuel efficiency of vehicles with alternative powertrain systems, such as hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), battery electric vehicles (BEV), or fuel cell electric vehicles (FCEV). This was so even though market penetration and resulted impacts on national energy consumption and CO_2 reduction kept increasing along with technology level, as revealed in many countries (Pasaoglu *et al.*, 2012; Yabe *et al.*, 2012; Wu *et al.*, 2012; Tang *et al.*, 2013). To resolve the problems, the Korean Ministry of Knowledge Economy (MKE) extensively revised previous standards and promulgated new fuel economy regulations in 2011 based on the Energy Use Rationalization Act (MKE, 2011). The standards regulate vehicles manufactured after January 1, 2013, in order to prevent consumer confusion, meet information demands, and appropriately reflect advanced vehicle technologies.

Under the revised standards, the CVS-75 mode is used combined with the Highway Fuel Economy Test (HWFET) mode, a highway drive cycle developed in the U.S. Fuel efficiency measured in each drive cycle is then calibrated with formulas representing the so-called 5-Cycle Tests – city test, highway test, high speed/quick acceleration test, air conditioning test, and cold temperature test – to better approximate typical conditions and behaviors in real-world driving. The final drive cycle weightings are set to 55 % and 45 % for the CVS-75 and the HWFET modes,

(a) Subcompact vehicles

(b) Compact, medium, and large-sized vehicles

Figure 2. Fuel economy label of Korea.

Table 3. Vehicle energy efficiency labeling standard (unit: km/l).

Class	1	2	3	4	5
Combined fuel efficiency	16.0 or above	13.8 ~ 15.9	11.6 ~ 13.7	9.4 ~ 11.5	9.3 or below

(Subcompact vehicles and electric vehicles are excluded.)

respectively. As shown in Figure 2, the certified fuel efficiency information is printed in a newly designed fuel economy label. It shows vehicle class, combined fuel economy and CO_2 emissions of the vehicle, and separated fuel economy results expected in each mode. The vehicle fuel energy efficiency labeling standards have also been tightened, as shown in Table 3.

Based on the Motor Vehicle Management Act (MOLIT, 2011), which provided vehicle classification rules, new fuel economy standards regulate passenger cars in all size variations and compact buses and trucks, powered by gasoline, diesel, LPG, CNG, and/or electricity.

The fuel economy label of the passenger cars and the compact buses contains both fuel economy, defined as distance traveled per unit of fuel consumed, expressed as kilometers per liters (km/l), and an energy efficiency labeling standard that shows fuel economy only for compact trucks. For BEVs, the fuel economy, which is defined as distance traveled per unit of energy equivalent to one kilowatt of power expended for one hour (km/kWh), and the maximum drivable range on one charge are shown together in the label.

The fuel economy and GHG emissions of MHD commercial buses and trucks have never been regulated in Korea and are also excluded in the revised standards. This was mainly due to the difficulties in measurement caused by diverse and customized specifications of those commercial vehicles. However, regulating fleet efficiency has become a worldwide trend recently as shown in Table 4, and Korea started developing a new fuel economy regulations and GHG emissions standards for the MHD fleets in 2013 (Noda *et al.*, 2003; Lee *et al.*, 2011; Zheng *et al.*, 2011; Fontaras *et al.*, 2013; Kim *et al.*, 2011). In order to phase in the new standards starting in 2017, the Korean government currently is analyzing fuel efficiency regulations legislated in foreign countries and is also developing a vehicle system-level model, named Korean Energy Efficiency Simulator (KEES), and relevant test procedures (KEA, 2011b; KEA, 2012; Lee *et al.*, 2015).

3. METHODOLOGY

In this work, vehicle classification rules established under the Motor Vehicle Management Act (MOLIT, 2011) were basically applied to the processes of selecting representative vehicle groups of 2010. Based on the rules, all ground vehicles are classified into three classes first: passenger car, bus, and truck. Then the vehicles classified in each class are grouped by fuel used (e.g. gasoline, diesel, LPG, and CNG) and size (e.g. subcompact, compact, medium, large or heavy). Finally, the vehicles multi-grouped by class, fuel, and size are divided into 3 types; general, special, and multi-purpose vehicle (MPV).

Driven by the shale gas development boom started in the U.S. and China in the early 2000s, liquefied natural gas (LNG) vehicle development has also accelerated with CNG vehicles. However, in Korea, LNG vehicle development seems to have lost momentum since the LNG truck conversion program and diesel to LNG dual-fuel engine conversion program promoted by the government in 2008 have finally ended without successful results. Sustained market penetration for LNG cars in Korea is impossible without strong policy as well as car makers overcoming several technological constraints in LNG vehicles development; as neither condition is being met, the authors excluded the LNG vehicles in this study. The vehicles powered mainly or partially by electricity, such as HEV, PHEV, BEV, or FCEV, are also excluded from the selection due to their negligible market share as of 2010.

Table 4. Global trends in MHD commercial vehicles fuel efficiency and GHG emissions regulations.

Country	Year*	Certification tool	Certification drive cycles
Japan	2005	Simulation, HILS (for HEV)	JE05 (ED12)**, Interurban
U.S.	2011	Simulation	ARB***, 55 and 65MPH constant
China	2013	Simulation with chassis dyno test	C-WTVC****
E.U.	2015	Simulation (under development)	10 types of driving patterns defining vehicle target speed versus distance
India	2019	TBD	TBD

* Year for standard proposal.
** A transient test mode introduced in Japanese 2005 emission standards based on Tokyo driving conditions, applicable to diesel- and gasoline-powered heavy vehicles of gross vehicle weight (GVW) above 3.5 ton
*** A transient test mode of Heavy Heavy-Duty Diesel Truck Schedule (HHDDTS) developed by the California Air Resources Board (CARB) with the cooperation of West Virginia University
**** A modified version of Worldwide-harmonized Transient Vehicle Cycle (WTVC or WHVC) allowing under-power vehicles to follow the cycle

3.1. Passenger Car

In order to make a selection of representative passenger cars, registration data sets in 2010 (Korea Transport Database, 2010) and new-car sales record over the 1996 ~ 2010 period (KEA, 2011a) are analyzed, and all passenger cars are categorized according to the criteria defined in the Act (MOLIT, 2011). Then, the vehicles registered and sold in relatively large numbers were chosen to be the representative vehicles. One exception is MPV that is treated as one of the size criteria instead of type criteria in diesel and LPG passenger cars for convenience.

Due to the negligible portion of MPVs and special-type vehicles in sales, gasoline passenger cars are all classified as general-type, then are divided into four size variations. On the contrary, diesel passenger cars are all classified to medium-sized MPVs as they account for 86.4 % of total sales. Similarly, LPG passenger cars are considered medium-sized general-type vehicles. Even though the sales records of LPG MPVs and LPG special-type vehicles were not significant in 2010, as shown in Table 5, the annual average sales between 2001 and 2010 were found to be 30,000, making the cumulative number of registrations considerable. Therefore, it was also necessary to select both types and include them in the LPG MPV category.

Table 5. Passenger car sales of Korea in 2010.

Type	Size	Fuel		
		Gasoline	Diesel	LPG
General	Subcompact	151,895	0	8,564
	Compact	277,426	7,089	6,293
	Medium	217,973	15,053	125,161
	Large	187,059	2,802	18,365
MPV	Subcompact	0	0	0
	Compact	0	0	0
	Medium	6,494	167,848	0
	Large	8,765	37,189	476
Special	Subcompact	0	0	0
	Compact	0	0	0
	Medium	20,795	1,208	5,005
	Large	71	6,009	124

3.2. Bus and Truck

In general, model diversity of compact buses and of trucks is similar to that of passenger cars. Especially, 87 % of compact buses, defined as having the capacity of 15 passengers or below under Motor Vehicle Management Act (MOLIT, 2011), are general-type. Therefore, the compact general-type bus would be the only representative vehicle among all of the bus variations if the same classification rules were applied in the selection process, considering market share and sales volume. However, buses and trucks differ from passenger cars, especially in their usage, which is clearly set within each size variation. In addition, the national standards of dividing vehicle size defined in the Act are too rough to reflect the usage of those vocational vehicles. Moreover, the importance of relative share can be limited, especially when the total volume itself is not significant (i.e., a small Korean domestic market share). For these reasons, the MHD vehicles were also investigated in this study. Like other countries, the MHD buses and trucks in Korea are mostly custom-made, manufactured under small quantity batch production systems, resulting in a wide range of variations (KEA, 2011b). Thus, both registration statistics in 2010 (Korea Transport Database, 2010), shown in Table 6 and Table 7, and new-car sales data in 2012 (KAMA, 2012), are analyzed. Then, the vehicles found to be in the majority are selected as representative MHD buses and trucks.

Table 6. MHD bus registration numbers in Korea in 2010.

Type		Variation	Registration
General		General subtotal	1,034,839
		Urban	29,225
		Interurban	21,893
		Chartered	36,923
		Express	421
		Farming and fishing village	0
		Shuttle	0
	Others	Others subtotal	946,377
		15 passengers or less	904,142
		25 passengers or less	15,927
		35 passengers or less	10,426
		50 passengers or less	15,239
		Above 51	643
Special		Special subtotal	14,886
		Rescue	7,453
		Funeral	625
		Bloodmobile	35
		Broadcasting	111
		Tow trailers	676
		Others	5,986
Total			1,049,725

Table 7. MHD truck registration in Korea in 2010.

Type			Registration
General		General subtotal	2,173,961
		Pickup	121,018
	Cargo	Cargo subtotal	2,052,943
		1 ton or less	1,625,851
		3 ton or less	183,971
		5 ton or less	105,095
		8 ton or less	71,090
		10 ton or less	9,593
		12 ton or less	13,363
		Above 12 ton	43,980
Dump		Dump subtotal	46,227
		1 ton or less	22,263
		5 ton or less	17,088
		12 ton or less	6,489
		Above 12 ton	387
Van		Van subtotal	653,338
		1 ton or less	645,863
		5 ton or less	7,160
		Above 5 ton	315
Special			330,282
Total			3,203,808

In terms of fuel used in vehicle powertrains, diesel bus holds the vast majority within all of size variations. LPG bus is an unusual case since the total number of registrations is high, reaching 312,319 in 2010, while the sales record is low, totaling 66,477 between 2002 and 2010. From this fact, the authors concluded that there is a considerable number of LPG buses currently registered that were initially diesel buses at point of sale. It is reasonable deduction when considering the diesel to LPG engine conversion program, depicted in Figure 3, promoted by the government's policy since 2005 to improve metropolitan air quality (MOE, 2014). Accordingly, compact- and medium-sized LPG buses are selected as the representative vehicles considering significant registration and important characteristics of the fuel in energy and environment industry, despite lower new-car sales.

It is known that CNG fuel is not appropriate for vehicles requiring long distance travel due to the lower energy density than liquefied fuel. Thus, CNG-fueled vehicles are developed and distributed by government's policy mainly for intracity buses – 25,671 of 28,720 total registration as of 2010 – in Korea since 2000;, therefore, the heavy-duty CNG bus, shown in Figure 4, is selected as a representative vehicle in this study.

Figure 3. Diesel to LPG engine conversion work.

Even though the situations of trucks and buses in Korea are alike in terms of size distribution in registration, because compact trucks are found to account for 80.7 % of total truck registration, MHD trucks are also selected as representative vehicles by applying the same reasoning as

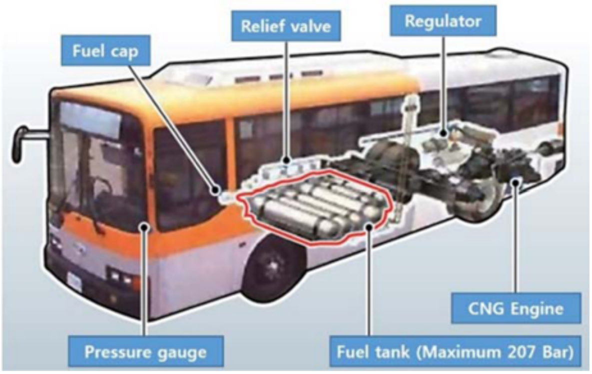

Figure 4. CNG powered intracity bus run in Korea.

used in selecting representative buses. In fact, annual distance traveled of heavy-duty trucks is more than twice that of compact trucks. It means that the heavy-duty fleets have the greater influence on total amount of fuel consumed; therefore it is reasonable to take the MHD trucks into consideration for the objective of this study. However, due to the exceptional characteristics of trucks, type variations is not considered for trucks in this work.

3.3. Representative Vehicle Group

The 18 representative vehicle groups selected in this study, based on the principal methodologies and classification rules previously described, are shown in Table 8.

4. RESULTS AND DISCUSSION

Feasibility of each of the 18 representative vehicle groups selected in this study for predicting the amount of fuel energy consumed in transportation sector are analyzed using Equation (1);

$$E[l] = \sum_{\text{Vehicle group}} \frac{R \times D[km]}{F[km/l]} \tag{1}$$

where E represents predicted annual fuel energy consumption, R is the number of vehicle registrations, D is average distance traveled, and F is weighted average fuel economy. The results for each representative vehicle group are added-up, then each total is compared to the total fuel energy consumption statistics from the national database system. In order to estimate the total amount of GHG emission from ground transportation sources in Korea, Equation (2) is used;

$$GHG[g] = \sum_{\text{Vehicle group}} \left(R \times D[km] \times C\left[\frac{g}{km}\right] \right) \tag{2}$$

where C is average CO_2 emission per kilometer of each representative vehicle group selected.

The overall schematic of procedure flow for processing data in this study is illustrated in Figure 5.

Table 8. 18 representative vehicle groups selected in this study.

No	Class	Fuel	Size
1	Passenger car	Gasoline	Subcompact
2			Compact
3			Medium
4			Large
5		Diesel	MPV
6		LPG	Medium
7			MPV
8	Bus	Diesel	Compact
9			Medium
10			Heavy
11		LPG	Compact
12			Medium
13		CNG	Heavy
14	Truck	Diesel	Compact
15			Medium
16			Heavy
17		LPG	Compact
18			Medium

4.1. Representative Vehicle Registrations

4.1.1. Passenger car

While total numbers of registrations of passenger car group estimated in this study are based on statistics from national database system (Korea Transport Database, 2010), following five key assumptions were also made due to the unavailable data sets in the statistics.

1. Diesel-fueled passenger cars are all MPVs in terms of size criterion.
2. Subcompact and compact passenger cars in the database are all gasoline-fueled vehicles.
3. Of LPG passenger cars, 80 % are medium-sized general-type and the rest 20 % are MPVs, considering that cumulative sales of general-type and MPV or special-type show a ratio of 78 to 22.
4. Number of registrations of gasoline medium-sized passenger cars is calculated by subtracting LPG medium-sized passenger cars registrations, approximated in the assumption 2, and half of LPG MPVs and diesel MPVs registrations from the total number of medium-sized passenger car registrations in the database.
5. Number of registrations of gasoline large-sized passenger cars is calculated by subtracting half of the LPG MPVs and diesel MPVs registrations from the total number of

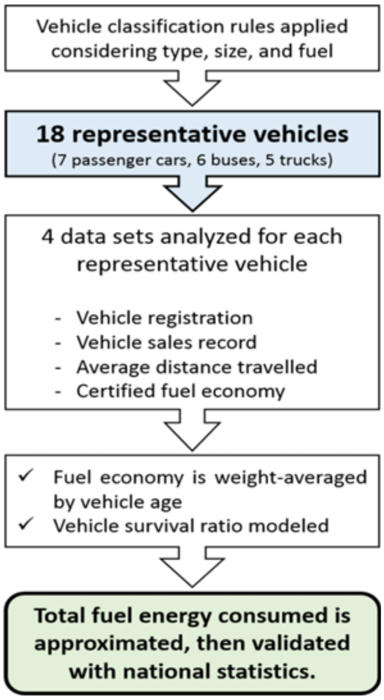

Figure 5. Schematic of procedure flow for data processing.

large-sized passenger car registrations in the database.

4.1.2. Bus and truck

Numbers of registrations of buses and trucks are obtained based on the same database system and methodologies used in the passenger cars with the six key assumptions as follows.

1. CNG buses are all heavy-duty in terms of size criterion.
2. Of LPG buses, 90 % are all compact-sized and the rest 10 % are medium-duty, considering that total registration number of LPG compact bus and LPG medium-duty bus are shown a ratio of 94 to 6.
3. Of LPG trucks, 85 % are all compact-sized and the rest 15 % are medium-duty, considering that total registration number of LPG compact truck and LPG medium-duty truck are shown a ratio of 87 to 13.
4. Number of registrations of diesel heavy-duty buses is calculated by subtracting number of CNG heavy-duty bus registrations, which is approximated in assumption 1, from total number of heavy-duty bus registrations in the database.
5. Numbers of registrations of diesel compact trucks and diesel medium-duty trucks are calculated by subtracting LPG compact truck and LPG medium-duty truck registrations, respectively, from total number of compact and medium-duty truck registrations, respectively.
6. Numbers of registrations of diesel compact buses and diesel medium-duty buses are calculated by subtracting LPG compact bus and LPG medium-duty bus registrations, respectively, from total number of compact and medium-duty bus registrations.

4.2. Weighted Average Fuel Economy

In order to approximate the average fuel economy of each representative vehicle group, representative value of fuel economy for each group is classified by vehicle age which is defined in the Equation (3), then the results are weight-averaged by the vehicle age distribution taking vehicle scrappage rate into account. In this work, fuel economy records of all vehicles in each group are analyzed by utilizing accumulated big data sets (KEA, 2011a), which indicate certified fuel economy of all passenger cars, compact buses, and compact trucks since 1996. The data sets based on previous fuel economy standards are calibrated to become suitable to the current regulations. In case of MHD buses and trucks, real world driving fuel economy 2010 data reported by the Korea Energy Economics Institute (KEEI, 2011) are used due to the unavailability of certified fuel economy data.

$$\textit{Vehicle age} = 2010 - \textit{vehicle model year} + 1 \qquad (3)$$

In this work, average fuel economy of each representative vehicle group is obtained by developing vehicle survival ratio models and weight-averaging the modeled registration against vehicle age where the vehicle survival ratio is defined in the Equation (4). In case of passenger cars, for instance, the survival patterns are modeled by comparing total number of passenger car registrations sorted by vehicle age (Korea Transport Database, 2010) to total new-car sales records sorted by year (KEA, 2011a). It is estimated that the average life spans of passenger cars, LPG vehicles, and heavy-duty CNG buses are 14.5, 14.4, and 15 years, respectively. It is interesting to notice that the model result for passenger cars is identical to the reference value previously reported (Hao *et al.*, 2011).

$$\text{Vehicle survival ratio [\%]} = \frac{\text{Total registration of specific model year}}{\text{New car sales at specific year}} \qquad (4)$$

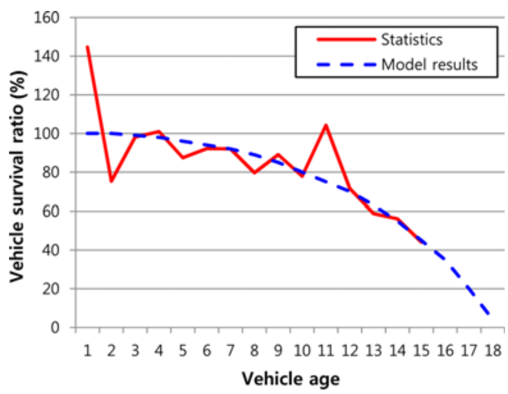

Figure 6. Vehicle survival ratio model validation for passenger cars.

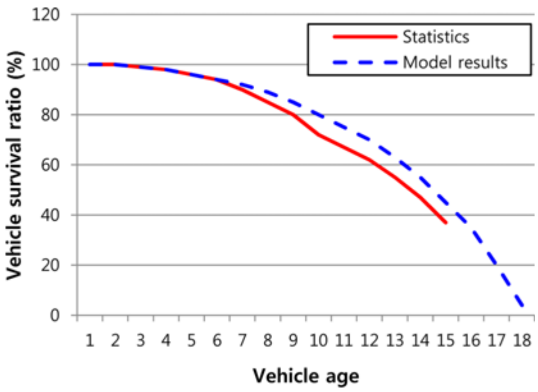

Figure 7. Vehicle survival ratio model validation for LPG vehicles.

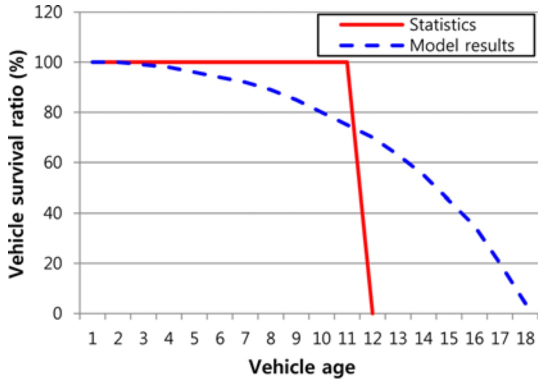

Figure 8. Vehicle survival ratio model validation for heavy-duty CNG buses.

As seen in Figure 6, the actual vehicle survival ratio, obtained from registration statistics divided by sales record, fluctuates considerably, even showing unrealistic values such as 140 % for 1-year-aged passenger cars. This is primarily due to the statistical error, such as the gap between the times of purchasing and registering the vehicles, altering the vehicle age in many cases. In vehicle survival ratio model development, initial value of 100 % is set to be gradually decreased starting from 3-year-aged vehicles in order to correct the error. Table 10 shows the model results of number of registrations in each representative vehicle group by vehicle age. Figures 7 and 8 are plotted to show vehicle survival ratio model validation for LPG vehicles and heavy-duty CNG buses, respectively. It should be noted that taxis, which account for around 70 % of total LPG vehicles, have diffused since 1998, and their service life is defined as 9 years. Similarly, intracity buses have come into wide use since 2000, and

Table 9. Average fuel economy of representative vehicle groups by vehicle age (km/l for Gasoline, Diesel and LPG; km/m^3 for CNG).

Class	Fuel	Size	Vehicle age																	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Passenger car	Gasoline	Sub-compact	16.12	15.53	15.39	15.06	15.09	15.25	15.21	14.94	14.94	14.94	14.94	14.94	14.94	14.94	14.94	14.94	14.94	14.94
		Compact	13.97	13.29	12.43	12.22	11.89	11.43	11.41	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43	11.43
		Medium	11.42	10.57	10.25	9.87	9.79	9.53	9.02	8.87	8.87	8.87	8.87	8.87	8.87	8.87	8.87	8.87	8.87	8.87
		Large	9.07	8.93	8.41	8.22	8.10	8.01	7.54	7.36	7.36	7.36	7.36	7.36	7.36	7.36	7.36	7.36	7.36	7.36
	Diesel	MPV	12.97	12.23	11.23	10.99	10.91	10.73	10.06	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21	9.21
	LPG	Medium	6.58	6.22	6.15	6.03	5.93	5.74	5.51	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50	5.50
		MPV	5.77	5.75	5.81	5.69	5.47	4.85	4.89	4.96	4.96	4.96	4.96	4.96	4.96	4.96	4.96	4.96	4.96	4.96
Bus	Diesel	Compact	10.22	9.65	9.61	9.34	9.14	8.97	9.01	8.63	8.63	8.63	8.63	8.63	8.63	8.63	8.63	8.63	8.63	8.63
		Medium	6.46	6.46	6.46	6.46	6.46	6.46	6.46	6.46	6.46	6.46	6.46	6.46	6.46	6.46	6.46	6.46	6.46	6.46
		Large	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66	3.66
	LPG	Compact	4.66	4.66	4.63	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62	4.62
		Medium	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26	3.26
	CNG	Large	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39	2.39
Truck	Diesel	Compact	10.06	10.07	10.06	9.43	9.26	9.06	8.86	8.91	8.91	8.91	8.91	8.91	8.91	8.91	8.91	8.91	8.91	8.91
		Medium	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75	4.75
		Large	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17	2.17
	LPG	Compact	4.55	4.45	4.89	4.45	4.44	4.45	4.48	4.37	4.25	4.25	4.25	4.25	4.25	4.25	4.25	4.25	4.25	4.25
		Medium	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19	3.19

Table 10. Modeled registration number of representative vehicle groups by vehicle age (thousands).

Class	Fuel	Size	Vehicle age																	
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Passenger car	Gasoline	Sub-compact	85.7	85.7	84.8	83.9	82.2	80.5	78.8	76.2	72.8	68.5	64.2	60.0	54.0	47.1	38.5	30.0	17.1	3.4
		Compact	178.0	178.0	176.2	174.4	170.9	167.3	163.8	158.4	151.3	142.4	133.5	124.6	112.1	97.9	80.1	62.3	35.6	7.1
		Medium	289.7	289.7	286.8	283.9	278.1	272.3	266.5	257.8	246.3	231.8	217.3	202.8	182.5	159.3	130.4	101.4	57.9	11.6
		Large	132.2	132.2	130.9	129.6	126.9	124.3	121.6	117.7	112.4	105.8	99.2	92.5	83.3	72.7	59.5	46.3	26.4	5.3
	Diesel	MPV	216.7	216.7	214.6	212.4	208.1	203.7	199.4	192.9	184.2	173.4	162.5	151.7	136.5	119.2	97.5	75.9	43.3	8.7
	LPG	Medium	138.6	138.6	137.2	135.8	133.0	130.2	124.7	117.8	110.8	99.8	92.8	85.9	76.2	0.0	0.0	0.0	0.0	0.0
		MPV	33.3	33.3	33.0	32.7	32.0	31.3	30.7	29.7	28.3	26.7	25.0	23.3	21.0	0.0	0.0	0.0	0.0	0.0
Bus	Diesel	Compact	49.1	49.1	48.6	48.2	47.2	46.2	45.2	43.7	41.8	39.3	36.9	34.4	31.0	27.0	22.1	17.2	9.8	2.0
		Medium	1.9	1.9	1.9	1.8	1.8	1.8	1.7	1.7	1.6	1.5	1.4	1.3	1.2	1.0	0.8	0.7	0.4	0.1
		Large	3.7	3.7	3.7	3.7	3.6	3.5	3.4	3.3	3.2	3.0	2.8	2.6	2.3	2.0	1.7	1.3	0.7	0.1
	LPG	Compact	24.6	24.6	24.4	24.1	23.6	23.2	22.7	21.9	20.9	19.7	18.5	17.2	15.5	0.0	0.0	0.0	0.0	0.0
		Medium	2.7	2.7	2.7	2.7	2.6	2.6	2.5	2.4	2.3	2.2	2.1	1.9	1.7	0.0	0.0	0.0	0.0	0.0
	CNG	Large	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	2.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Truck	Diesel	Compact	183.9	183.9	182.1	180.3	176.6	172.9	169.2	163.7	156.4	147.2	138.0	128.8	115.9	101.2	82.8	64.4	36.8	7.4
		Medium	27.7	27.7	27.5	27.2	26.6	26.1	25.5	24.7	23.6	22.2	20.8	19.4	17.5	15.3	12.5	9.7	5.5	1.1
		Large	17.1	17.1	17.0	16.8	16.4	16.1	15.8	15.2	14.6	13.7	12.8	12.0	10.8	9.4	7.7	6.0	3.4	0.7
	LPG	Compact	17.1	17.1	16.9	16.7	16.4	16.0	15.7	15.2	14.5	13.7	12.8	11.9	10.8	0.0	0.0	0.0	0.0	0.0
		Medium	3.0	3.0	3.0	3.0	2.9	2.8	2.8	2.7	2.6	2.4	2.3	2.1	1.9	0.0	0.0	0.0	0.0	0.0

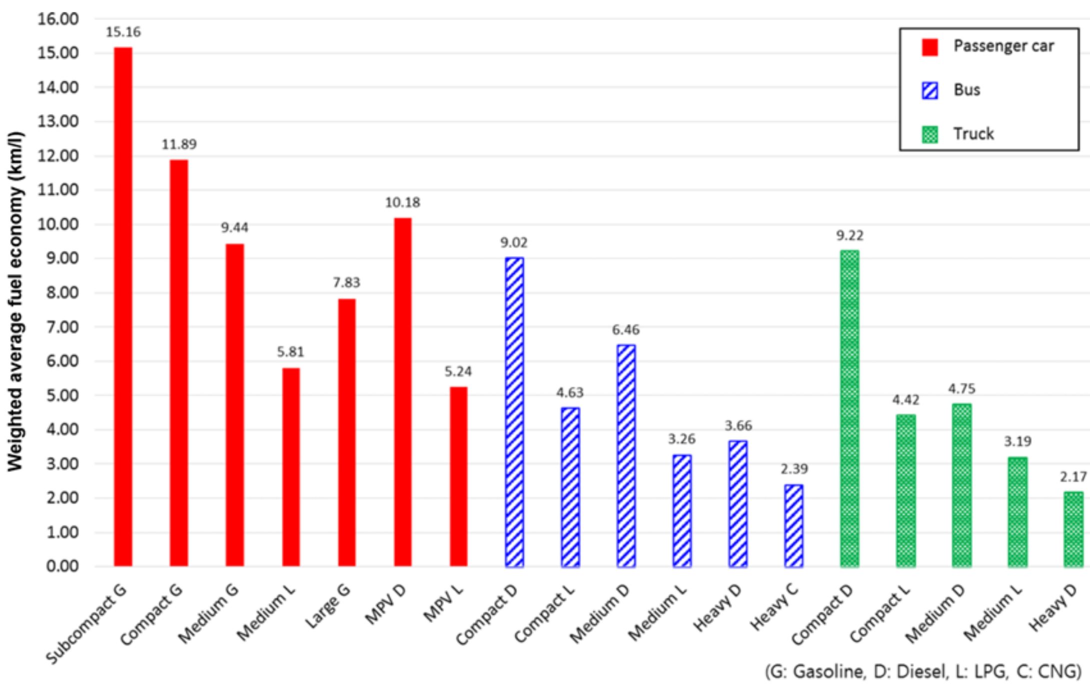

Figure 9. 2010 weighted average fuel economy of the 18 representative vehicle groups selected.

Table 11. Registration, 2010 weighted average fuel economy, and averaged annual distance traveled of representative vehicle groups.

Class	Fuel	Size	Representative vehicle registration in 2010	Weighted average fuel economy (km/l) or (km/m^3)*	Average annual distance traveled (km)
Passenger car	Gasoline	Subcompact	1,113,562	15.16	9,198
		Compact	2,313,979	11.89	9,271
		Medium	3,766,339	9.44	11,790
		Large	1,718,677	7.83	14,199
	Diesel	MPV	2,817,399	10.18	15,732
	LPG	Medium	1,521,402	5.81	19,470
		MPV	380,350	5.24	15,732
Bus	Diesel	Compact	638,765	9.02	11,133
		Medium	24,521	6.46	17,228
		Large	48,449	3.66	70,974
	LPG	Compact	281,087	4.63	11,133
		Medium	31,231.9	3.26	17,228
	CNG	Large	25,671	2.39*	105,487
Truck	Diesel	Compact	2,391,339	9.22	15,403
		Medium	360,680	4.75	24,200
		Large	222,694	2.17	40,048
	LPG	Compact	194,731	4.42	15,403
		Medium	34,364	3.19	24,200

their service life is 11 years. The 2010 weighted average fuel economy of each representative vehicle group, obtained from the Equation (5) is shown in Figure 9.

$$F\left[\frac{km}{l}\right] = \frac{R_{2010}}{\Sigma_{1993}^{2010}\frac{R}{Representative\ fuel\ economy}} \tag{5}$$

where F is the 2010 weighted average fuel economy.

4.3. Average Annual Distance Traveled

To obtain average annual distance traveled for each representative vehicle group, the national statistical database system (TS, 2011) was analyzed. The database is a high-reliable system as it is based on survey sampling results obtained from 30 % of all vehicles surveyed on their regular inspection. However, the Korea Energy Economics Institutes' report (KEEI, 2011) refers exclusively to heavy-duty CNG buses due to the unavailable traveled distance information for the intracity buses. It should also be noted that vehicle classification rules applied to the database systems and this study differ from each other in some cases. For example, in case of medium-sized LPG passenger cars, which includes most of taxies in Korea, the gap of annual distance traveled between taxies and typical passenger cars is huge. To resolve the discrepancy, average annual distance traveled of both taxied and typical passenger cars are weighted against registration number of each category.

4.4. Model Validation

Table 11 shows representative vehicle registration, 2010 weighted average fuel economy, and average distance traveled modeled in this study for the 18 representative vehicle groups.

Using Equation (1) and the national statistical data

Table 12. Total amount of fuel consumed by overall ground transportation of Korea in 2010 (KEEI, 2013).

Fuel	Unit	National statistics	Model results	Error (%)
Gasoline	kl	10,622,500	10,301,742	3.0
Diesel	kl	16,722,652	16,088,772	3.8
LPG	kl	8,121,212	8,023,021	1.2
CNG	m^3	1,054,028	1,132,089	7.4

reported (KEEI, 2013), model results of total fuel energy consumed by overall ground transportation sector in Korea are validated to confirm the reliability of the 18 representative vehicle groups selected in this study. As shown in Table 12, it showed good agreement, with errors ranged between 1.2 % to 7.4 %. Therefore, we can utilize the representative vehicle groups and the vehicle survival patterns for predicting the total fuel energy consumption.

5. CONCLUSION

The objective of this research is to support national fuel energy consumption and GHG emissions reduction master plan in Korea, identify potential of reduction, confirm validity of vehicle survival patterns modeled, and make recommendations for future policy making to ensure realistic and productive strategies to reduce nationwide foreign oil consumption. Specifically, correlation between vehicle fuel efficiency and total fuel energy consumption is analyzed by categorizing ground vehicles into 18 representative vehicle groups and using the survival ratio models. The background and highlights of the Korean fuel economy regulations amendment, including test method schemes, drive cycles, and fuel economy labeling standards, are also introduced. The following conclusions and policy implications can be drawn from this study;

(1) Due to the wide range of vehicle types, making a selection of representative vehicle groups and constructing a relevant vehicle technology database are crucial to establish effective policies and agreeable regulations. In this paper, 18 representative vehicle groups are selected based on vehicle classification rules taking into account the following factors: registration data sets; new-car sales record and market penetration statistics; distribution status of vehicles by fuel, class, type, and size; and current standing and future prospects of vehicle technologies.

(2) Three versions of the vehicle survival ratio model are developed to account for statistical vehicle distribution against vehicle age. Total amount of national energy consumption by fuel estimated by utilizing the modeled survival patterns with registration statistics, 2010 weighted average fuel economy, and average annual distance traveled, showed good agreement with statistics in the national database system, with errors ranged between 1.2 % to 7.4 %.

(3) Despite the lower number of registrations, total energy consumption of diesel is much higher than that of gasoline, implying higher distance traveled by MHD commercial vehicles, which is, in most cases, a means of living for the owner. In this situation, higher oil price results in not only higher economic burden to the owner but also higher price of commodity products. Therefore, the government must take stronger policy measures to curb the country's fossil fuel consumption and to blunt the impact of high oil prices.

(4) Vehicles with advanced powertrain systems like HEV, PHEV, BEV, and FCEV have emerged as an alternative to conventional vehicles. In Korea, the market share of those vehicles are also gradually increasing; however, definitions of fuel economy for those vehicles are under debate among researchers in many countries, especially for the vehicles that utilize both stored energy from the electric grid on board and conventional fuel occasionally. Establishing standard methodologies for evaluating fuel consumption is challenging not only for the electrified vehicles but also for conventional vehicles with innovative technologies such as dual-fuel (also called bi-fuel) internal combustion (IC) engines, which utilize two different fuels at the same time for initiating in-cylinder combustion. In fact, even for the CNG or LNG vehicles that have existed in Korea for more than a decade, the fuel economy standards of those vehicles are still not clarified primarily due to the different physical characteristics of fuel in measuring. Therefore, the government must set policies to direct such fast-paced technological advancements in a timely manner before they become more widespread to maximize the effect of advanced vehicular technologies on reducing national energy consumption and hazardous emissions.

(5) The fuel economy-gap between official and real-world figures has been significant in Korea, even with the new regulations enacted in 2011. This means car makers have optimized their vehicles to the specific test environments, including the certification drive cycle, which was not originally intended to be used in Korea. The growing gap affects not only consumer confidence in both domestic and global markets, but also government tax revenues under a proposed tax code revision that, if adopted, will change annual vehicle taxation criteria from an engine size-basis to a CO_2-basis. Therefore, in the long term, it is desirable to develop new test procedures and certification drive cycles to reduce the discrepancy for restoring consumer confidence, as recently done for the World-Harmonized Light-duty Vehicles Test Procedure (WLTP) development by the United Nations Economic Commission for Europe (UNECE) in cooperation with many other countries (ICCT, 2013, 2014).

(6) Fuel economy standards for measuring GHG emissions of passenger cars, compact buses, and compact trucks are well established in Korea. On the other hand, regulations for MHD commercial vehicles are currently under development and are expected to be introduced in 2017. Therefore, the results of this study will have to be revised with a wider scope upon establishment of the regulations for the MHD buses and trucks. Further, it is recommendable to adopt payload-dependent standards, such as gram per mile (or gallon per 1,000 ton-mile), that are generally used in many countries (EPA, 2011), because convenience in

multidisciplinary research involves carrying-power of various transportation means.

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