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Basis for Hydrogen Freight Vehicle Activation Policy

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Carbon neutrality is essential to limit global warming. The promotion of hydrogen cars in the transportation sector may be consistent with this policy. Hydrogen cars, because of their shorter charging time and longer operating distance per charge than electric vehicles, are suitable replacement for vehicles that emit air pollutants, such as large trucks. In this study, the basis for the Hydrogen Freight Vehicle (HFV) activation policy was prepared by quantitatively predicting the distribution trend and effect of HFV. The scenarios were classified based on the level of achievement of the Korean government's hydrogen vehicle supply targets. The survival curve was used to predict the number of HFV actually operating annually. In addition, routes with a high utilization ratio of HFV were predicted by dividing the traffic patterns of passenger and freight cars. In the future, routes with a high truck operation ratio would be identified and presented as areas that require intensive infrastructure expansion. Using the emission coefficients by vehicle type and speed, the reduction in air pollutants and the reduction in air pollution costs owing to the introduction of HFV was calculated. Our results predicted that 111,626 HFV may be operated based on the 2030 target. The proportion of HFV was high in the Goesan IC to Yeonpung IC section of the Jungbu Naeryuk Highway and it is expected that there will be more HFV in the future. As a result, the amount of air pollutants, CO_2, Nox, CO, VOC, and $PM_{2.5}$, CO_2 saved could be 17,006.96 – 42,501.99 Mt by 2030. The cost-reduction benefits, of air pollution, increases to 89.7.11 billion KRW by 2030. The results of this study can be used as a basis for policy judgment when establishing and implementing policies to encourage the supply of HFV.

1. Introduction

Achieving carbon neutrality by reducing greenhouse gas emissions is a trend in global environmental policy (Lee et al., 2020). Carbon dioxide emissions in the global transportation sector were 24.6 % (as of 2018) of the total emissions from automobiles. Therefore, focus is in the transportation sector (OH and Lee, 2021). Among automobiles, freight cars primarily use diesel as fuel source that contributes to pollutant emissions. The proportion of registered truck is only 14.9 % (Korea Ministry of Land, 2020), but it accounts for 42.9 % of all fine dust (PM_{10}) emissions and 57.9 % of greenhouse gas emissions; it is urgent to replace fossil fuelled trucks. To address this issue, interest in eco-friendly vehicles, such as electric vehicles, is increasing, with development and distribution underway (Yoo et al., 2021). Although many technological advances have been made, there are technical limitations for electric vehicles (large battery volume and low power) to be applied to large trucks (Richardson, 2013).

Hydrogen fuelled vehicles have the potential to address the technical limitations of electric vehicles (Davis et al., 2018). Because Hydrogen Freight Vehicle (HFV) has a shorter charging time than an electric truck, trucks can be charged during the loading time enabling efficient operation (Yan et al., 2022). The mileage per charge is longer, making it suitable for application to trucks with a longer mileage per operation (Lee et al., 2018). To promote hydrogen vehicles with eco-friendly effects, many countries have implemented policies to revitalize use of hydrogen vehicles. Unlike electric vehicles, research on hydrogen vehicles is insufficient and quantitative evidence for policy establishment is lacking (İnci et al., 2021).

In this study, in the scenario where internal combustion engine trucks are replaced by HFVs, the reduction in the amount of pollutants and air pollution costs savings were predicted based on the HFV supply scenario. Since the reduction of air pollution costs is presented as a monetary amount, it is easy to compare with the cost

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required for HFV activation policies and can be used as a quantitative basis for policy implementation. To promote HFV, it is necessary to expand the related infrastructure. The areas that need to expand infrastructure to achieve the goal of supplying hydrogen vehicles were presented. Study site was located in Republic of Korea. Republic of Korea is the first country in the world to expand the fuel cell electric vehicle (FCEV) market (Stangarone, 2021). The government supports, in policy, the use of hydrogen cars. Korea is number one in hydrogen car sales (Wang et al., 2019), making it suitable as a research subject as it is expected to commercialize hydrogen cars quickly.

2. Methodology

2.1 Forecasting the prevalence of new technologies

Ayyadi (2018), compared three diffusion models (Gompertz, logistic, and Bass models) to predict the spread of electric vehicles in Morocco. Based on the R-square and average absolute percentage error (MAPE), the Bass diffusion model was selected as the optimal model. Morocco's electric vehicle market is expected to reach its maximum sales in 14 y the decline in battery prices could expand the of the EV market. Future electric vehicle sales data predicted in this study was different from the current trend of electric vehicle supply because the prediction was based on insufficient sales data. Singh et al. (2020) estimated the number of private cars owned per 1,000 people in India by 2050 by applying the per capita GDP growth rate to the Gompertz function. In the 2050 scenario, the trend of personal automobile penetration showed a growth rate along the S-shaped curve, with the current automobile ownership population increasing 3-4 times and the number of vehicles increasing 9-14 times. Uncertainty in the results was owing to the application of India's high economic growth scenario and lack of data accuracy. Xian et al. (2022), predicted the prevalence of hydrogen cars based on the generalized Bass model, considering the impact of the levelled cost (LCD) reduction and hydrogen charging station (HRS) configuration in China. Development of hydrogen cars in China is divided into three stages: initial, development, and maturity. The number of delivered hydrogen vehicles is predicted to be approximately 1.43 M by 2030, and 10.41 M by 2040. In previous studies errors occurred owing to data uncertainty; the characteristics of each vehicle was considered using the application of the survival cycle of the vehicle. In this study, the annual hydrogen vehicle supply target set by the Korean government and the survival rate according to the model year of each vehicle were estimated using the survival curve. The actual number of HFV operating per year was forecasted. In many cases, the government's policy goals are not accurately observed. Uncertainty was corrected by dividing the scenario into cases where the government goal was achieved by 50 %, 75 %, 100 % and 125 %. The hydrogen truck survival curve Eq(1) developed by Liu et al. (2021), was used to estimate the survival rate according to the model year of HFV. The curve is a type of logistic curve, and it has a modified form (Figure 1) with a sharp drop in the survival rate at a certain point in time. It is often used to estimate the life of a product. The number of supplied HFV was calculated by applying the ratio of cargo trucks to the total number of vehicles per year, to the estimated number of hydrogen vehicles per year.

$$r(j) = \frac{1}{1+8.76\left(\frac{j}{8.15}-1\right)} \quad (1)$$

where $r(j)$ is survival rate after j years and j is lapse of years.

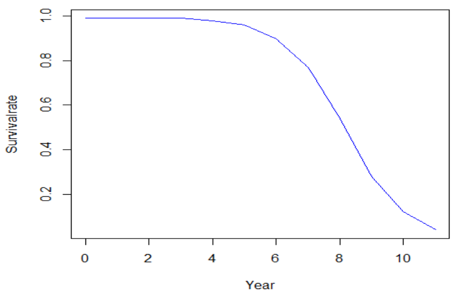

Figure 1: Hydrogen Truck Survival Curve Developed by Liu

2.2 Eco-friendly effects of transportation policies

Han et al. (2019), studied the environmental and economic effects of the spread of electric vehicles and hydrogen vehicles through a computable general equilibrium model (CGE). It was suggested that the introduction of electric and hydrogen vehicles had a positive effect on the gross domestic product. It was argued that hydrogen cars have reduced carbon dioxide emission; the increase in gross domestic product is because the emission coefficient of city gas is relatively lower than that of electric vehicles. There are limitations in vehicle characteristics, such as speed deviation based on the route of each vehicle type, are not reflected closely. (Kim et al., 2020) analysed, in the road transportation sector, the forecast of greenhouse gas emissions and potential reductions. Based on the energy demand and CO_2 emissions forecast model, the domestic road transportation sector's energy demand is expected to be 36,759,000 t, and CO_2 emissions will be 102,442,000 t by 2030. In addition, it is estimated that CO_2 emissions could be reduced by approximately 23.2 % by 2030 by applying carbon dioxide reduction technologies and appropriate policies. Statistical data, such as electricity usage of passenger cars, did not exist, so the analysis did not reflect the market share forecast for the detailed classification stage. Kluschke et al. (2019) predicted the impact of the introduction of next-generation alternative energy sources, such as biofuels, hydrogen, and electricity, applicable to large vehicles (HDVs), such as trucks. It was predicted that truck usage would increase to 30 % by 2050; the CO_2 emissions from trucks, using alternative fuels, would be reduced by more than 40 %. These limitations have been extensively reviewed for various alternative energy sources but have not been reviewed in depth for each energy source, focusing on comparison of various energy sources. In summary, the characteristics of alternative energy sources were reflected, but there was a limitation in that a specific solution could not be derived through a detailed analysis by vehicle type and region.

In this study, different traffic information was obtained for each vehicle type by classifying the traffic patterns of general passenger cars and trucks. The major routes used were classified according to the traffic pattern to analyze the areas of truck concentration. The amount of air pollutants according to the operating speed was estimated by modelling the speed on each path. These paths and speeds would change owing to future population movements; they must be tracked to add credibility to future change predictions. Changes in future conditions were addressed by considering the changes in future traffic characteristics and networks from 2020 to 2030. The amount of reduction in air pollutant was calculated by applying the air pollutant emission unit and air pollution cost unit (Table 1) of the Korea Development Institute (KDI) to the estimated route and speed of each vehicle type. Regardless of the size of the vehicle, the lower the operating speed, the higher the air pollutant emissions (Figure 2). The benefits of reducing air pollutants were calculated by considering these characteristics.

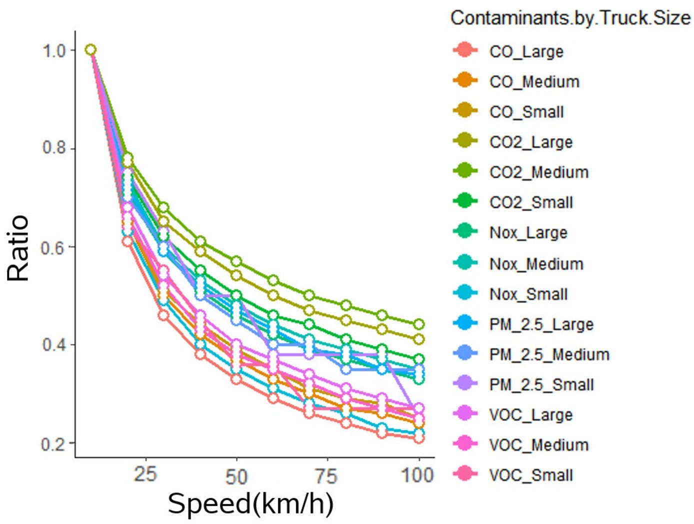

Figure 2: Air Pollutant Emission Ratio by Speed Compared to Operating Speed of 10 km/h

Air pollution cost reduction benefits are defined as the difference between air pollution costs incurred when internal combustion engine trucks are not replaced by HFV and costs incurred when they are partially replaced by HFV (Eq(2) and (3)). The costs were calculated using the unit of cost by speed and region (Table 1).

$$VOPCS = VOPC_{Not\ Replaced} - VOPC_{Partially\ Replaced} \quad (2)$$

$$VOPC = \sum_l \sum_{k=1}^{3} D_{lk} \times VT_k \times 365 \quad (3)$$

where *VOPC* is the valuation of pollution cost saving, D_{lk} is the total travel distance (veh·km) by link(*l*), by vehicle type(*k*), VT_k is the air pollution cost (KRW/km) of the link speed by vehicle type (*k*), *k* is the vehicle type (1: auto, 2: bus, 3: freight).

Table 1: Air Pollution Cost Unit by Truck Size and Speed (Units: KRW/km)(obtained from KDI. (2021))

Classification	Speed (km/h)	CO	NOx	VOC	$PM_{2.5}$			CO_2	Sum
					Urban	Suburb	Provinces		
Small	10	0.14	16.36	0.26	34.95	9.09	3.64	20.86	72.56
	50	0.05	5.68	0.11	14.87	3.87	1.55	10.47	31.17
	100	0.03	3.6	0.07	10.3	2.68	1.08	7.8	21.8
Medium	10	0.64	89.97	2.27	86.75	22.56	9.02	34	213.62
	50	0.23	43.17	0.86	38.86	10.11	4.05	19.26	102.39
	100	0.16	31.49	0.57	27.59	7.18	2.87	15.07	74.89
Large	10	1.17	420.84	4.04	336.78	87.58	35.03	68.46	831.29
	50	0.38	192.95	1.62	156.32	40.65	16.26	36.77	388.05
	100	0.24	138.75	1.1	112.95	29.37	11.75	28.14	281.18

3. 3. Results

3.1 Estimation of the number of HFV operations by year

The number of HFV operating in future years was predicted using the annual supply of hydrogen vehicles set by the Korean government in the 4th Basic Plan for Eco-friendly Vehicles (Table 2); the survival rate was estimated through the survival curve. In many cases, the government's policy goals have not been accurately implemented. Uncertainty was corrected by classifying the scenario into cases where the government goal was achieved by 50 %, 75 %, 100 % and 125 %. The number of HFVs actually operating by year was calculated by applying the ratio of trucks among currently operating vehicles(Table 3).

Table 2: Target Number of Hydrogen Vehicles Supplied by Year set by the Korea Government (Units: veh)

Year	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Hydrogen vehicles	5,083	6,000	16,800	27,600	38,400	49,200	60,000	80,000	100,000	120,000	140,000	160,000

Here, 2019 is the actual number of registered hydrogen vehicles and the government's policy goal is from 2020.

Table 3: Actual Operating Number of HFV by year according to scenario(Units: veh)

Attainment rate	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
50 % achieved	1,200	2,447	4,493	7,335	10,963	15,346	21,104	28,139	36,358	45,644	55,830
75 % achieved	1,423	3,293	6,363	10,630	16,079	22,675	31,363	42,004	54,429	68,421	83,728
100 % achieved	1,645	4,139	8,234	13,924	21,195	30,005	41,623	55,870	72,500	91,198	111,626
125 % achieved	1,868	4,986	10,104	17,219	26,311	37,334	51,882	69,735	90,571	113,975	139,524

3.2 Areas for intensive expansion of HFV infrastructure

Figure 3a compares the main routes of passenger cars and trucks by 2030. Areas marked in red are routes with a high ratio of trucks to passenger cars. It can be seen in Table 4. In the case of route, the proportion of trucks among all vehicles used was more than 40 %.

Table 4: Truck Concentrated Route (Units: veh/d)

Classification	Section	2020 Truck traffic (A)	2030 Passenger car traffic (B)	2030 Truck traffic (C)	2030 Traffic of Sum(D) (B+C)	2030 Truck ratio (C/D)	The rate of change in truck traffic (C/A)
Jungbu-Naeryuk Highway	Goesan IC ~ Yeonpung IC	17,221	25,954	22,287	48,241	46.2 %	129.4 %
Cheonan-Nonsan Highway	Gongju IC ~ South Gongju IC	19,557	28,306	19,348	47,654	40.6 %	98.9 %

Jungbu-Naeryuk Highway will have more truck traffic in the future. Figure 3b shows a comparison of the number of trucks used between 2020 and 2030. The red route is the route where the number of trucks used increased in 2030, and the Jungbu-Naeryuk Highway Goesan IC to Yeonpung IC is expected to not only have a high rate of truck use but also a steady increase in the future. There are many policy effects such as the amount and benefits of air pollutant reduction through the supply of HFV in this region. It is possible to achieve the target of supplying HFV by expanding the related infrastructure, such as charging stations in the relevant area.

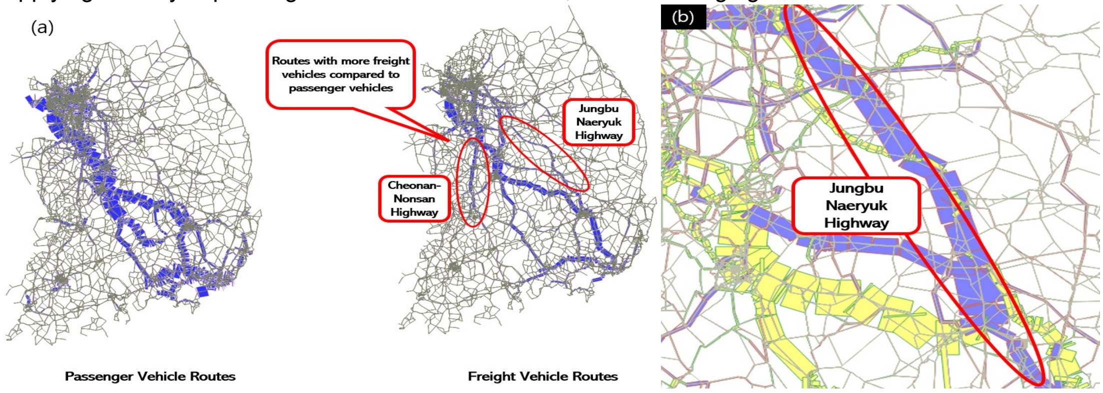

Figure 3: (a) Main Route used by Vehicle Type (2030), and (b) Route of Increasing Future Truck Usage

3.3 Estimation of air pollution reduction and air pollution cost savings by year

There was substantial reduction in the calculated air pollutant levels. The reduction was in the order of CO_2, Nox, CO, VOC, and $PM_{2.5}$ (Table 5). Savings by 2030 were estimated to be 17,006.96 to 42,501.99 M t for CO_2, and 110.49 to 276.12 M t for NOx.

Table 5: Amount of Air Pollutants by Scenario (Units: Mt)

Classification	CO	NOx	VOC	$PM_{2.5}$	CO_2
2020	0.95~1.48	2.38~3.7	0.2~0.32	0.1~0.16	367.24~571.75
2025	12.22~29.72	30.62~74.49	2.61~6.35	1.29~3.14	4,726.08~11,497.97
2030	44.25~110.6	110.49~276.12	9.44~23.6	4.65~11.63	17,006.96~42,501.99

The benefits of reducing air pollution costs are listed in Table 6. As the number of operating HFV increase, the benefits of reducing air pollution costs based on the target scenario will increase from 13.25 billion KRW in 2020 to 89.11 billion KRW in 2030.

Table 6: Benefits of air pollution cost reduction in different scenarios (Units: 1,000M)

Classification	50 % achieved	75 % achieved	100 % achieved	125 % achieved
2020	9.67	11.46	13.25	15.05
2025	124.41	183.83	243.25	302.67
2030	448.69	672.90	897.11	1,121.32

4. Conclusions

This study presents the basis for policy implementation for the activation of HFV. The scenarios were classified according to the level of achievement of the Korean government's policy goals. The number of HFV operating in the future was forecasted, and the routes of concentration and increase in freight trucks were predicted. The amount of air pollutants saved and the benefits of reducing air pollution costs are estimated. By 2030, 111,626 HFV are expected to be supplied. The intensive used routes of trucks and the area of future increases were predicted to be the section between Goesan IC and Yeonpung IC on the Jungbu-Naeryuk Highway. The amount of air pollutants saved was in the order of CO_2, Nox, CO, VOC, and $PM_{2.5}$. CO_2 was reduced by 17,006.96 Mt to 42,501.99 Mt by 2030. As the number of HFV operations increases, the air pollution cost-reduction benefits would increase from 13.25 billion KRW in 2020 to 89.11 billion KRW in 2030. To increase the supply HFV, it is necessary to establish an operating environment by the establishment of infrastructure, such as charging stations, and a subsidy payment policy to offset high price resistance. In addition, HFV have different routes from passenger cars because of the nature of trucks, so it is effective to preemptively identify these characteristics and expand the related infrastructure in the region. The results of this study can be used as a basis for policy judgment when establishing and implementing policies to encourage the supply of HFV. In the future, if it is possible to obtain specific data such as the number of HFV supplied by year or type, it is possible to analyze the trend closely through the application of statistical models such as time series models or diffusion models. In addition, it is possible to provide international policy solutions beyond the national level by predicting, comparing, and analyzing the effects of introducing HFV in countries other than Korea.

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