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2050 Carbon neutrality measures and costs in the road transport sector of South Korea

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ABSTRACT

The South Korean government delineated carbon-neutral scenarios for the road transport sector in 2021, envisioning a more than 97% transition to battery electric vehicles (BEVs) and hydrogen fuel cell electric vehicles (FCEVs) by 2050. This study employs the Model for Energy Transition and Emission Reduction to examine changes in vehicle types, greenhouse gas emissions, and economic costs in the road transport sector until 2050. A comparison between the carbon-neutral (CN) and business-as-usual (BAU) scenarios, maintaining current policy levels, is conducted to derive policy implications. The attainment of carbon neutrality in the road transport sector hinges significantly on the widespread adoption of BEVs and FCEVs, with a crucial policy to ban the sales of internal combustion engine vehicle by the 2030s. A comparison of the two scenarios highlights the significant differences in the choice of BEVs and FCEVs between the non-business and business sectors. The direct costs, encompassing investment, operating, and fuel costs, are higher in the CN scenario than in the BAU scenario. However, when external costs related to greenhouse gas emissions and vehicle travel are factored in using carbon and vehicle miles traveled taxes, the total costs of the CN scenario are lower than those of the BAU scenario. Analyzing its economic viability by incorporating external costs enhances the policy's feasibility of achieving carbon neutrality.

Key words: 2050 Carbon Neutrality, Road transport Sector, Scenario Analysis, Battery Electric Vehicles, Hydrogen Fuel Cell Vehicles, Carbon Neutrality

1. Introduction

A worldwide consensus emphasizes the necessity in restraining the global atmospheric temperature rise to within 1.5℃, above pre-industrial levels, compelling a collective effort to achieve carbon neutrality by 2050. Commencing in 2019, with the European Union and the United Kingdom, declarations committing to achieving carbon neutrality by 2050 have proliferated, with over 140 countries endorsing such commitments as at 2022 (Climate Action Tracker, 2023). Aligning with this global objective, the South Korean government announced its commitment to achieving carbon neutrality by 2050, and subsequently finalized a scenario for achieving this goal a year later in October 2021 (Ministry of Environment, 2021a).

In accordance with the national carbon neutrality scenario announced by the South Korean government in 2021, the transport sector, which is the focus of this study, is expected to undergo significant transformations. This scenario involves replacing conventional modes of transport, such as automobiles, railways, and ships, with those that utilize electricity or hydrogen as its energy source. Additionally, measures to reduce transport

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demand, including the expansion of public transport and promotion of cycling and walking, have been incorporated (CCNGG, 2021).

The road transport sector, which accounts for approximately 97% of greenhouse gas (GHG) emissions in the transport sector, hold significant importance. Two scenarios are presented based on the extent of the transition to battery electric vehicles (BEVs) and hydrogen fuel cell vehicles (FCEVs). Scenario A envisions BEVs and FCEVs occupying over 97% of the total vehicle fleet, whereas Scenario B proposes an occupation of over 85%, with other vehicles relying on alternative fuels such as biofuels and E-fuels. The choice between these scenarios determines the government's means of implementation. For instance, pursuing Scenario A would necessitate a policy to stop the sale of internal combustion engine vehicles (ICEVs) by the mid-2030s. However, Scenario B introduced uncertainty regarding the timing of implementing such a policy. While intensity differences exist in the level of penetration of zero-emission vehicles by 2050 compared with the scenarios proposed by the International Energy Agency (IEA), European Union (EU), and Germany, the overall direction aligns. The emphasis lies on expeditiously transitioning the majority of the vehicle fleet to electric and hydrogen vehicles for optimal energy source composition and efficiency.

Key measures include policies for ceasing ICEV production or sales, technological development of zero-emission vehicles, and infrastructure expansion (European Commission, 2018; IEA, 2021; Prognos et al., 2021). Furthermore, policies are proposed to reduce the demand for car usage by expanding alternatives such as cycling, walking, ride-sharing, telecommuting, and railway transport, along with the introduction of congestion charges. The implementation of these various policy tools to achieve carbon neutrality in the transport sector by 2050 requires considering diverse aspects. The process of transformation, which entails transitioning around 25 million operational vehicles to zero-emission vehicles and establishing extensive infrastructure like electric charging stations, comes with substantial administrative and economic costs. Societal awareness and acceptance of these costs are crucial. Additionally, considering that the transport equipment manufacturing and petroleum refining industries, which produce gasoline, diesel, etc., collectively account for approximately 20% of Korea's manufacturing value-added, achieving carbon neutrality in the transport sector is of significant industrial importance according to the Korean Statistical Information Service (KOSIS).[1]

Numerous studies have investigated future GHG reduction scenarios in the South Korean transport sector, including Jeong et al. (2011), Koo and Shin (2012), Lee et al. (2018), Kwon et al. (2018), Kim et al. (2020), Ahn et al. (2021), and Im et al. (2022). However, studies that specifically analyze policy tools and effects to achieve carbon neutrality by 2050 are limited to Ahn et al. (2021) and Im et al. (2022). Ahn et al. (2021) focused on the road transport sector and investigated changes in vehicle stock and policy tools centered on BEVs and FCEVs until 2050, but did not consider economic costs. However, Im et al. (2022) had limitations in that they only analyzed the non-business passenger car sector. Additionally, Ahn et al. (2021) and Im et al. (2022) failed to analyze the differences in vehicle composition, GHG emissions, and economic costs between achieving carbon neutrality by 2050 and maintaining current policies.

This study aims to compare the implementation of the carbon neutrality A scenario presented by the South Korean government for the road transport sector by 2050 (Carbon Neutrality [CN] scenario) with the scenario of maintaining current policies (business-as-usual [BAU] scenario). This study compares the year-by-year trajectories of changes in vehicle stocks and GHG emissions to identify crucial policy measures for carbon neutrality. Additionally, the direct costs required for the adoption and operation of BEVs and FCEVs between the two scenarios were compared separately for passenger and freight transport. Furthermore, this study analyzed the impact of introducing carbon and

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1) The transport equipment manufacturing industry, which produces automobiles and related components, accounts for approximately 13%, whereas the petroleum refining industry holds around 6.3% of the manufacturing value added (2021, approximately 195.9 trillion won) (KOSIS, 2023).

driving taxes proposed in the CN scenario on the overall costs. To achieve this, the Model of Energy Transition and Emission Reduction (METER) (used by Ahn et al., 2021) for the road transport sector, was employed. This study divides the road transport sector into passenger and freight segments and quantitatively analyzes changes in vehicle composition, GHG emission reduction prospects, and associated costs until 2050.

The subsequent sections of this paper are outlined as follow. Chapter 2 presents an international comparison of the 2050 CN scenario for the road transport sector, along with a review of previous studies on the road transport sector of South Korea. Section 3 explains the characteristics of the METER used in this study and provides the definitions and assumptions for the CN and BAU scenarios used in the model analysis. Chapter 4 analyzes the changes in vehicle composition, GHG emissions, and direct and external costs of both passenger and freight transport. Chapter 5 presents the implications that policymakers must consider. Section 6 summarizes the findings and proposes directions for future research areas.

2. Literature review

This study quantitatively compares and analyzes CN scenarios in the road transport sector, focusing on cases that have been quantitatively presented globally, such as the International Energy Agency's (IEA) study which covers the entire world, the European Union (EU) which implemented the most advanced GHG reduction policies, and Germany, which boasts an annual automobile production performance similar to that of South Korea. Additionally, this study reviews previous studies that have explored future scenarios for the road transport sector of South Korea.

2.1. Comparative review of international scenarios for the road transport sector

To analyze the CN scenarios in the domestic and international road transport sectors, scenarios from South Korea were compared with global scenarios. South Korea’s scenario, denoted Scenario A, was finalized by the 2050 Presidential Commission on Carbon Neutrality and Green Growth in 2021. This was juxtaposed with the IEA’s Net Zero Roadmap for the Global Energy Sector by 2050 released in 2021, the European Union’s (EU) Long-Term Analysis Report on a climate-neutral economy published in 2018, and the German climate neutrality strategy for 2045 presented by a private German research institute (CCNGG, 2021; European Commission, 2018; IEA, 2021; Prognos et al., 2021).

The key policy direction of the four CN scenarios was to transition the majority of the existing ICEVs to BEVs and FCEVs by 2050. This requires significant technological advancements in transport vehicles utilizing electric and hydrogen energy-sourced technologies, resulting in completely overhauling the overall vehicle composition. For instance, in the South Korean CN scenario A, the projection is that by 2050, over 80% of the entire operating vehicle fleet should be BEVs, with over 17% being FCEVs (CCNGG, 2021).

The EU scenario provides a more detailed breakdown according to vehicle type. For passenger cars and small buses, in 2050, the operating vehicle composition is projected to be 80% BEVs, 16% FCEVs, 2% plug-in hybrid electric vehicles (PHEVs), and 1% ICEVs. For buses and small trucks, the composition is expected to be 92% BEVs and FCEVs and 3% PHEVs. For medium-sized trucks, it is estimated to be 10–15% BEVs and FCEVs, 15–28% PHEVs, and 51–77% ICEVs (European Commission, 2018).

Germany’s 2045 CN scenario outlines the operating vehicle composition for passenger cars and small buses as 92% BEVs, 5–6% FCEVs, and 2–3% PHEVs and ICEVs. For medium-sized trucks, it is projected to be 91% for BEVs, 7–8% for FCEVs, and 1–2% for ICEVs. Large trailers and freight trucks are expected to consist of 69% BEVs, 30% of FCEVs, and 1–2% of ICEVs (Prognos et al., 2021).

In contrast, the IEA scenario, which covers the entire globe, provides a breakdown of the share of each vehicle type among new car sales by 2050. Passenger cars and small buses comprise 90% BEVs, 8–9% FCEVs, and approximately 1% PHEVs. Medium-sized trucks are projected to comprise 65% BEVs, 23% FCEVs, and 1–2% PHEVs (IEA, 2021).

In contrast to the Korea's scenario, which does not differentiate based on vehicle types, such as passenger cars, buses, and trucks, the scenarios presented by the IEA, EU, and Germany show variations based on characteristics such as battery development level and driving range. The transition to electric or hydrogen vehicles occurs more rapidly in passenger cars. Notably, medium- and heavy-duty trucks exhibited a higher prevalence of FCEV adoption than passenger cars. The EU scenario predicts that the share of ICEVs using biofuels or e-fuels will remain relatively high in heavy-duty trucks.

All scenarios emphasize the need for technological solutions, such as the expansion of electric and hydrogen charging infrastructure, advancements in battery technology, and a decrease in zero-emission vehicle costs, to achieve a comprehensive shift toward electric and hydrogen vehicles. Additionally, to accelerate the transition, policies such as the introduction of mandatory adoption measures for BEVs and FCEVs in the 2020s and a ban on the sale of ICEVs by the mid-2030s are highlighted.

Each CN scenario incorporated a reduction in transport demand. The Korea's scenario assumes a 15% reduction in the private passenger car travel compared to the 2018 levels, driven by changes in behavior. The IEA scenario also assumes a 10% reduction in energy consumption owing to behavioral changes. The German scenario includes a strategy to expand the use of bicycles, walking, and other non-car modes of transport to reduce car demand without affecting overall mobility. The EU scenario assumes a decrease in transport demand through the activation of the digital economy, increased online conferencing, and the utilization of shared-economy services. Furthermore, these scenarios incorporate strategies to diversify the transport demand for buses, railways, and water transport, which have higher energy efficiencies and greater GHG reduction effects than cars. For the passenger sector, scenarios include expanding public transport infrastructure and implementing congestion, fuel, and driving taxes to reduce vehicle operations. In the freight sector, suggestions include improving facilities at railway stations and ports, and introducing financial incentives to promote the use of rail and water transport methods.

2.2. Review of previous research on the South Korea case

In this case study, we examined medium- to long-term GHG emission scenarios in South Korea's road transport sector. Jeong et al. (2011) conducted a case study on the GHG reduction potential of the transport sector in South Korea following the establishment of its first national GHG reduction goal by 2020 (a 30% reduction compared with BAU). This study focused on five transport demand management policies, including fuel taxes, and congestion charges, utilizing a transport-mode share model to analyze scenarios based on the intensity of policy implementation. The analysis indicated that implementing a high-intensity strategy could lead to an annual reduction of 7.6 million tCO2eq. in GHG emissions.

Koo and Shin (2012) utilized a traffic demand model based on origin-destination travel volume to analyze the reduction in travel distance for six transport demand management policies. These policies include telecommuting, carpooling, promotion of cycling, enlargement of freight vehicles, improvement of loading rates, and transport modal shifts. The study assessed the extent of travel distance reduction under these policies and calculated the potential GHG emission reductions for 2016 and 2021. The analysis indicated that the change in the transport mode share had the most significant reduction effect compared to the other measures.

Lee et al. (2015) classified 23 GHG reduction policies in the transport sector into three types: avoid, shift and improve. Using an Analytic Hierarchy Process (AHP) analysis, they selected seven policies and utilized a travel demand forecasting model to analyze GHG reduction amounts from 2017 to 2027. They concluded that policies such as a rotation system for no driving, penetration of compact cars, early retirement of diesel cars, and promotion of BEVs were effective in achieving GHG reduction. Lee et al. (2018) employed a classification method similar to that used in previous studies to analyze GHG reduction measures in the transport sector. They quantitatively calculated the reduction effects of five measures. This study concluded that promoting eco-friendly driving and enhancing bus utilization are more cost effective than other measures.

Kim et al. (2016) utilized the Long-range Energy Alternative Planning system (LEAP)[2] model to analyze energy demand projections and GHG reduction potential in the road transport sector. Examining the effects of three policy measures–the Low Carbon Car Subsidy Fund, fuel efficiency improvement policies, and driving behavior enhancements–the study concluded that the Low Carbon Car Subsidy Fund had the most favorable impact on GHG reduction.

Ahn and Lee (2017) analyzed a bottom-up road transport model. The model included variables such as the number of cars, total travel distance, and selection of new cars. Six scenarios were designed by combining three policy measures that influence new-car selection: discount rate (DR), carbon price (CP), and behavioral change (BC). The analysis focused on the GHG reduction effects until 2050, with the scenario combining DR and CP showing the most significant increase in the adoption of electric cars by 2050.

Kwon et al. (2018) utilized the Avoid Shift Improve (ASI) structure. They categorized vehicles into 23 vehicle types, determined the registration numbers for each type, calculated the annual travel distances for each vehicle type, and assessed the energy intensity per distance traveled and energy consumption. Using econometric models for each category, this study analyzed the changes in vehicle types and energy consumption until 2050. It examined the effects of population decline, fuel efficiency improvement policies, and the penetration of ecofriendly vehicles on changes in energy consumption. The study concluded that these factors significantly influenced the reduction in energy consumption.

Park et al. (2018) divided the South Korean transport sector into the road, railway, waterway, and aviation subsectors. They quantitatively analyzed the GHG reduction effects and marginal mitigation costs of six technological reduction scenarios compared to the BAU scenario for the period 2017 ~ 2030. The model used for the quantitative analysis was the bottom-up Integrated MARKAL-EFOM System (TIMES) model. Among the subsectors, the road sector, further subdivided into 52 vehicle types, applied four reduction scenarios, which included the promotion of zero-emission vehicles and an energy efficiency improvement scenario for passenger cars, an energy efficiency improvement, and electric bus penetration scenarios for buses and trucks. A scenario for increasing the biodiesel blending ratio was also examined.

Kim et al. (2020) employed an ASI structure and regression analysis to forecast vehicle registration numbers, vehicle type-specific travel distances, and fuel efficiency improvements. In contrast to previous studies, they categorized vehicles into 22 types based on combinations of non-business/business, car/bus/truck, and fuel types. This study calculated the BAU GHG emissions until 2030 and analyzed the reduction effects of three GHG reduction measures (expanding the adoption of eco-friendly vehicles, behavioral improvements, and promoting public transport) in comparison to the BAU scenario.

Ahn et al. (2021) utilized the METER to analyze the changes in vehicle types and travel distances in road transport from 2020 to 2050. They formulated six scenarios, differentiated by the extent of zero-emission vehicle adoption in 2030 and level of fuel efficiency technology improvement, and examined whether energy usage and GHG emission reduction in each scenario aligned with South Korea's CN scenario. The METER categorized vehicles into 84 technologies, making it the most detailed model among previous domestic studies. It calculated the changes in vehicle types, travel distances,

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[2] The LEAP model was renamed "Low Emission Analysis Platform."

energy usage, GHG emissions, and other factors under minimum-cost conditions.

Im et al. (2022) aimed to achieve carbon neutrality in the transport sector by 2050, by focusing on the transition of non-business passenger vehicles from ICEVs to BEVs. They created an integrated model combining the Computable General Equilibrium (CGE) and vehicle stock models to analyze the scenarios influencing the replacement of vehicle stock composition. The scenarios included carbon taxes in the energy sector, banning the sale of ICEVs, introducing taxes on vehicle miles traveled, and managing vehicle demand. They analyzed the macroeconomic effects, levels of BEV adoption, and impacts on transport tax revenue for each scenario. Among the four scenarios, banning the sale of ICEVs has the most significant impact on BEV adoption. However, this study has limitations, such as excluding vehicles other than non-business passenger cars from the analysis and not examining the cost implications of each scenario.

By reviewing domestic research cases, studies in the fields of transport demand management, enhancement of vehicle energy efficiency, and the transition to zero-emission vehicles, such as BEVs and FCEVs, can be identified. These studies have employed different models depending on their objectives, and recent studies have tended to utilize more technical data when investigating vehicle transitions.

Considering the findings from comparative analyses of domestic and international carbon-neutral scenarios, the fundamental measures for achieving carbon neutrality in the road transport sector involve the electrification and hydrogenation of vehicle power sources. Recent studies are also aligned with this trend. Additionally, studies have suggested policy measures such as carbon taxes or vehicle miles traveled (KRW/vehicle·km) taxes as solutions to compensate for the reduction of fuel tax imposed on gasoline and diesel under the transition to the carbon neutral transport sector (Kim et al., 2021; Park et al., 2021).

However, with the 2050 carbon neutrality target set by the Korean government, the existing literature has limitations, and further studies are required to address them. First, to assess the policy implications of achieving the 2050 CN scenario in the transport sector, analyzing the differences between the carbon neutral and BAU scenarios, where current policies are maintained, is necessary. Second, a more detailed and realistic analysis of the implementation strategies, and associated energy and GHG reduction effects over different periods up to 2050 is required. This requires a detailed breakdown of technological measures by vehicle type, potential improvements in the energy efficiency for each vehicle, and updated information. Third, when evaluating the feasibility of scenario implementation, analyzing the economic costs involved is crucial. The transition toward all electric- or hydrogen-based vehicles by 2050 incurs costs related to vehicle purchase, operation, and energy use. Additionally, the introduction of carbon or vehicle miles traveled (VMT) taxes should be considered in terms of the associated costs.

Therefore, this study aims to analyze and compare the carbon-neutral scenario A proposed by the Korean government with the BAU scenario while maintaining current policies. The analysis focused on annual changes in vehicle composition, GHG emissions, and the associated economic costs in the process of carbon neutrality, considering passenger and freight transport separately within the road transport sector.

3. Methods and data

3.1. Analysis methods[3]

The analysis method employed in this study is based on the METER used by Ahn et al. (2021) for the road transport sector. The METER is a bottom-up partial equilibrium model that simulates the energy supply and consumption sectors. The METER, as elucidated by Jang et al. (2022), functions as a linear optimization model aimed at minimizing the overall cost within the analyzed

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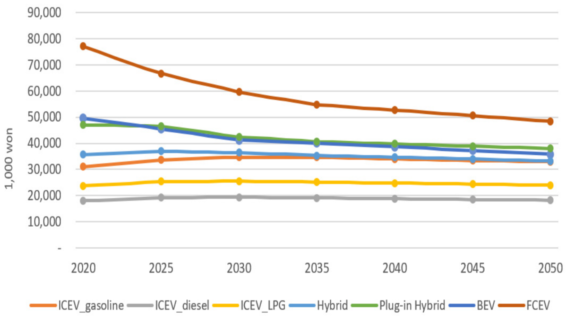
[3] The description of the METER for the road transport sector is based on the work of Ahn et al. (2021).

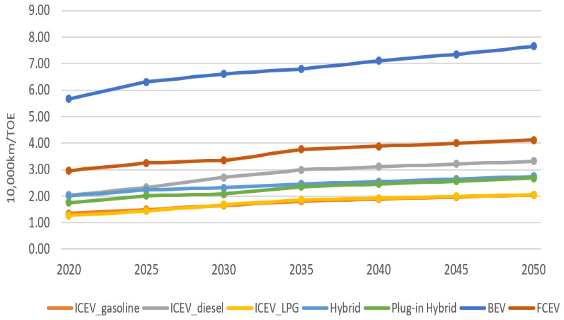
system. In this study, the METER for the transport sector projects the vehicle stocks by powertrain technology type for both passenger and freight road transport in each scenario. It then calculates the energy consumption and GHG emissions by multiplying the average distance traveled per vehicle by applying conditions such as fuel efficiency improvements. The model calculates the number of vehicles and travel distances for each powertrain technology type that satisfies the condition of minimizing total cost. However, while Ahn et al. (2021) included only three components (investment, fixed operating, and fuel costs) in the total cost, this study included carbon and VMT taxes in the total cost calculation. In this study, the carbon tax is interpreted as the cost of the external effect of GHG emissions caused by road transport, and VMT taxes are assumed to represent the external effect cost of congestion by vehicle use and degradation of transport infrastructure. The key features of the METER are summarized as follows.

The METER's objective function aims to minimize the total cost during the modeling period. The total cost used in this study is calculated by distinguishing the direct costs associated with the supply and use of cars, such as investment costs, fixed operating costs, fuel costs, and external costs of car operation. Investment cost refers to the expenses required to purchase new vehicle technologies, such as ICEVs, hybrid electric vehicles (HEVs), BEVs, and FCEVs. For the analysis, investment costs for the same duration as the modeling period are required. This study forecasts investment costs using the growth rate of investment cost prediction data for automotive technologies from the National Renewable Energy Lab (NREL, 2020) (Fig. 1[a]). The investment costs for the base year are determined by selecting an appropriate model from among Korean car models and referencing the model's selling price data. Furthermore, in the computations, a cost recovery factor (CRF) is incorporated, accounting for the average lifespan of the technology. Fixed operating costs represent the fixed costs incurred for the maintenance of a vehicle throughout its lifespan. By applying a discount rate, we assume that 5% of the initial vehicle investment cost is used annually until the vehicle is scrapped. The probability of vehicle survival is assumed to follow a Weibull distribution (Plotz et al., 2012).

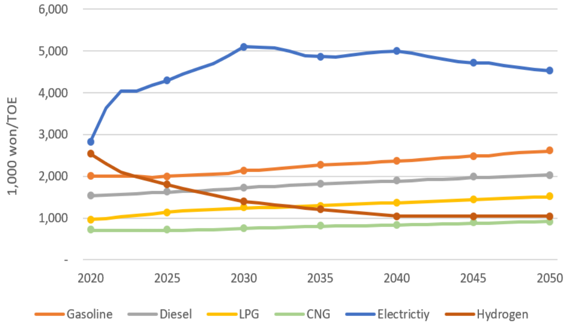
Fuel costs are the expenses related to fuel consumption during a vehicle's survival period. These costs are determined based on the fuel efficiency, driving distance, and fuel price of each vehicle. The methodology employed for the estimation of fuel efficiency paralleled the approach utilized for assessing investment costs(Fig. 1[b]). They were assumed to remain constant throughout the vehicle's lifespan. The estimation of driving distance relies on annual driving distance values for each vehicle



(a) Investment cost



(b) Fuel efficiency



(c) Fuel price

Fig. 1. Input data for direct costs

type derived from the regression analysis of GDP and population. Fuel prices were applied based on forecast figures from the Energy Information Administration (EIA, 2020). However, in the case of electricity prices, the forecast value of electricity prices derived from METER's conversion sector model (Jang et al., 2022) was used, and the target price suggested by the Government of the Republic of Korea (2019) was used for hydrogen (Fig. 1[c]). External costs were calculated by applying carbon and VMT tax rates, as explained in Section 3.2. When making cost optimization decisions, the analysis is based on the addition of external and direct costs.[4]

3.2. Scenario definition

We define two scenarios, BAU and CN, to forecast the future of the road transport sector until 2050 (Table 1). The BAU scenario assumes no additional constraints on GHG emissions or policies promoting BEVs or FCEVs. This follows the principle of minimizing the costs of vehicle selection. The CN scenario encompasses the 2030 Nationally Determined Contribution (NDC) and CN scenario A for 2050, raised in South Korea in October 2021. CN Scenario A aims for over 80% of BEVs and more than 17% of FCEVs in all passenger and freight vehicles by 2050.

Regarding the demand management of car travel, the BAU scenario assumes that the current level is maintained without additional policy measures. In contrast, the CN scenario includes a 4.5% reduction in passenger car traffic by 2030 and a 15% reduction by 2050 compared with 2018. Additionally, legislation related to renewable energy was revised in 2021 to include biofuels in automotive fuels. This law stipulates that the mandatory inclusion rate should increase from 3% in 2020 to 5% by 2030. The BAU scenario adheres to these regulations and maintains a mandatory inclusion rate until 2050. In the CN scenario, it is assumed that this rate will increase to 8% by 2030 and will be sustained at 8% until 2050.

The CN scenario includes a policy considered the most robust for the transition to BEVs and FCEVs, which is the prohibition of ICEV sales in Table 2. To analyze this, different application timings were applied for each vehicle technology type, as designed by the CN scenario analyses, both domestically and internationally. While the South Korean government's CN scenario mentions measures to prohibit the sale of ICEVs, it does not specify a concrete timing. In this study, a policy for ceasing the sale of ICEVs by vehicle type was implemented, considering references from Ahn et al. (2021), CN scenario cases from domestic and international contexts, carbon neutrality declarations from the domestic automotive

Table 1. Scenario definition

Scenario	Key features
BAU	• No constraints on the penetration of eco-friendly vehicles and relatively slow technology advancement • The current level of travel demand management is maintained • Bio-diesel is blended at 5% in automotive diesel fuel by 2030 (3.5% in 2023)
CN	• By 2030, 4.5 million zero-emission vehicles, including electric and hydrogen vehicles, are to be deployed. By 2050, over 80% of total operational vehicles are expected to be BEVs, and over 17% to be FCEVs • Rapid expansion of electric and hydrogen charging infrastructure • Development of technology for medium and large-sized zero-emission vehicles and incentives for transition • Banning the sale of ICEVs - A 4.5% reduction in total passenger car travel by 2030 and a 15% reduction by 2050 compared to 2018 • Substitution of passenger car travel with alternatives such as bicycles, walking, public transport, digitalization, and the sharing economy • Implementation of vehicle miles traveled taxes, abolition of fossil fuel subsidies, etc. • By 2030, bio-diesel is to be blended at 8% in automotive diesel fuel, and this level is to be maintained until 2050

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[4] Refer to Yeo (2021) for a more detailed explanation of the METER transport sector.

Table 2. CN scenario's constraints on vehicle sales

Vehicle type	Year of ICEVs sales phase-out	Alternative vehicle technology	Constraints	Source
passenger car	2035	BEVs FCEVs	• Hybrid-car sales ban from 2035 • Rental cars will transition to 100% zero-emission vehicles starting from 2022 • Some domestic companies will stop selling diesel passenger cars by 2026	Hyundai Motor Company (2022b)
small bus	2035	BEVs FCEVs	• The sale of BEVs and FCEVs will commence in 2023	Industry expert advice
medium and large bus	2030	BEVs FCEVs	• Compressed natural gas (CNG) vehicle production will be discontinued in 2024 • The sale of FCEVs will commence in 2022	Industry expert advice
small truck	2030	BEVs	• Discontinuation of 1-ton diesel truck production in 2024 • Discontinuation of Liquefied Petroleum Gas (LPG) truck subsidies in 2024, aiming to achieve a 75% market share for 1-ton electric trucks	Kang and Byun (2021) Ministry of Environment (2021b)
medium truck	2035	BEVs	• Commencement of BEV sales in 2024 • Commencement of FCEV sales in 2026	Industry expert advice
large truck	2035	FCEVs	• Commencement of FCEV sales in 2023	Hyundai Motor Company (2022a)

industry, and the Korea Ministry of Environment's initiative for the conversion of business vehicles to zero-emission vehicles (K-EV100).

In this study, a separate scenario introducing carbon and VMT taxes was added to analyze the impact of external costs (Table 3). The carbon tax represents an external cost related to climate change, whereas the VMT tax represents the societal cost incurred by road traffic. The carbon tax is set at 200 USD/tCO2eq. in 2050 (approximately 260,000 KRW, assuming an exchange rate of KRW 1,250/USD) based on the IEA (2022)[5], and it is assumed to linearly increase from 2025 to 2050. The carbon tax for 2025 is set at 20,000 KRW/tCO2eq. considering recent prices in the Korean emissions trading system.[6]

VMT taxes refers to taxes levied proportionally to the distance traveled by vehicles. The purpose of implementing a mileage-based driving tax is twofold: to reduce traffic congestion in areas with severe congestion, and to secure funds for the construction and maintenance of road infrastructure. Presently in Korea, the driving tax imposed on gasoline and diesel (excluding LPG) is levied as part of the total fuel tax, with a total revenue in 2019 was 2.7 trillion KRW, which is approximately 8.2% of the total fuel tax revenue (Park et al., 2021). However, the driving tax on gasoline and diesel is not imposed on BEVs and FCEVs, which do not use fossil fuels. The carbon-neutral process of the road transport sector

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5) The IEA has analyzed that advanced countries require a carbon price of 250 USD/tCO2eq. by 2050, while major economies such as China and Brazil need a carbon price of 200 USD/tCO2eq. Other countries are suggested to require even lower levels of carbon pricing (IEA, 2022).

6) The carbon emission allowance prices in the Korean emissions trading system vary depending on the period and type of emission allowances. For the compliance year 2020, the average price of the main emission allowance, KAU20, was 18,510 KRW/tCO2eq. (period: September 2019 to August 2021) (Choi et al., 2022). In contrast, the most recently traded KAU22, during the period from July 2022 to March 2023, was traded at levels ranging from 12,000 KRW/tCO2eq. to 28,500 KRW/tCO$_2$eq. (KRX, 2023).

Table 3. Carbon tax and vehicle mile traveled tax

Policy	Tax Schedule
Carbon tax	• 2025: 20,000 KRW/tCO2eq. • 2050: 260,000 KRW/tCO2eq. • Linear increase from 2025 to 2050
Vehicle mile traveled tax	• 2025: 0.4 KRW/vehicle-km • 2050: 38.9 KRW/vehicle-km • Linear increase from 2025 to 2050

decreases the revenue from the driving tax on fossil fuels, leading to a reduction in addressing external effects such as traffic congestion by BEVs and FCEVs. Moreover, there is an increasing demand for investment in road infrastructure and electric/hydrogen vehicle infrastructure, leading to discussions on taxing based on the distance traveled (Ko et al., 2020; Park et al., 2021).

While there is not much research on the level of the VMT tax, Park et al. (2021) assumed the total mileage-based driving tax needed to compensate for the shortfall in taxes due to reduced fuel consumption in the carbon-neutral process and proposed a scenario that targets a maximum VMT rate of 38.9 KRW/vehicle·km by 2050, increasing linearly at 10-year intervals[7]. In this study, we adopt Park et al.'s (2021) scenario, setting the VMT tax at a maximum of 38.9 KRW/vehicle·km by 2050 and starting at 0.4 KRW/vehicle·km in 2025, with a linear increase.

However, one limitation of this study is that the scenarios for carbon and VMT taxes do not consider the uncertainty of future policy conditions. Carbon prices may decrease or increase compared with the levels proposed in this study's scenarios, depending on the intensity of GHG reduction policies, both domestically and internationally. The levels of VMT taxes may also vary depending on conditions such as traffic congestion and demand for transport infrastructure investment. Considering these limitations, there is a need for additional scenario studies that set a more diverse range of carbon and VMT taxes, considering the uncertainties in future policy introductions.

4. Results

4.1. Vehicle stock by scenario

The analysis of changes in vehicle stock can be categorized into passenger and freight road transport. Variations between the BAU and CN scenarios are identified and summarized. Considering the differences in the size and purpose of vehicles, passenger road transport can be categorized into non-business passenger cars, business passenger cars, non-business buses, and business buses. Similarly, freight road transport can be categorized into non-business and business trucks.

4.1.1. Passenger road transport

For passenger transport, the projected total number of vehicles in the CN scenario is estimated to be approximately 23,705 thousand by 2030, 24,620 thousand by 2040, and 23,903 thousand by 2050. These numbers are expected to steadily increase until 2040, after which a gradual decrease is anticipated. In the BAU scenario, the total number of vehicles is forecasted to be 23,705

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[7] Based on the condition of an average annual driving distance of 14,308 km per car in 2018 (39.2 km per car per day), Park et al. (2021) applied the following scenarios for the vehicle mileage-based driving tax: 0.4–6.7 KRW/vehicle-km (average of 3.0 KRW/vehicle-km) for the years 2026 ~ 2030; 7.4–17.4 KRW/vehicle-km (average of 10.7 KRW/vehicle-km) for the years 2031 ~ 2040; 19.9 to 38.9 KRW/vehicle-km (average of 28.9 KRW/vehicle-km) for the years 2041 ~ 2050.

thousand in 2030, 24,618 thousand in 2040, and 23,916 thousand in 2050, showing minimal differences compared with the CN scenario. The rate of increase in the total number of vehicles is projected to be 19.3% (0.9% per year) from 20,636 thousand in 2020 to a peak of 24,620 thousand in 2040, which is significantly lower than the experience of the past 20 years (2000–2020) with a growth rate of 120.7% (6.0% per year). The BAU and CN scenarios exhibited similar growth rates.

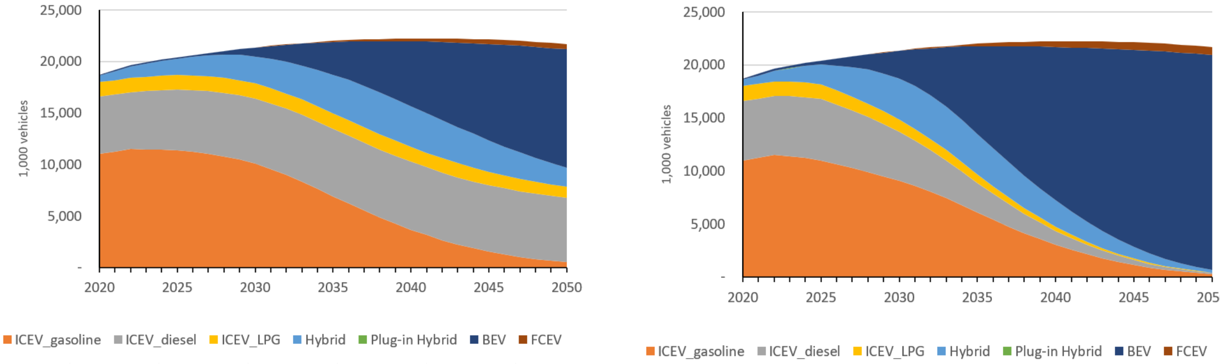
For passenger cars, which constituted 96.2% of the total passenger transport vehicle stock in 2020 (non-business passenger cars: 90.7%; business passenger cars: 5.5%), achieving carbon neutrality is crucial. The analysis indicates that the proportion of passenger cars will remain at a similar level (approximately 97.5%) until 2050. Currently, non-business passenger cars use a hierarchy of fuel types: gasoline, diesel, hybrids, and LPG. However, BEVs are expected to occupy the highest market share by 2050. Nevertheless, there is a significant difference in the market shares of BEVs and fossil fuel ICEVs between the BAU and CN scenarios. In the BAU scenario, gasoline vehicles will almost disappear by 2050; however, when combined with diesel, gasoline, and LPG vehicles, they will still account for approximately 41% of all vehicles (Fig. 2[a]). Despite the improvement in the energy efficiency of ICEVs and reduction in GHG emissions, the replacement of vehicles falls short of achieving carbon neutrality. In contrast, the CN scenario predicts a rapid shift from fossil fuel ICEVs (including HEVs and PHEVs) to BEVs, with BEVs accounting for over 50% of the total vehicle stock from 2040 and reaching near-complete replacement by 2050 (Fig. 2[b]).

The GHG emissions directly emitted from non-business passenger cars are expected to decrease to almost zero. The pace of this transition is determined by the types of new vehicles introduced to the market over the next 30 years. The BAU scenario allows for unrestricted sales of new ICEVs. Therefore, the number of new diesel vehicles remained constant, except for the replacement of gasoline vehicles with gasoline HEVs. Even with an increase in the adoption of BEVs and FCEVs, the large-scale replacement of ICEVs and HEVs has not been achieved, indicating that the direct costs of BEVs and FCEVs are still relatively high compared with those of diesel and HEVs. In contrast, the CN scenario introduced a policy to ban the sale of new ICEVs from 2035. After implementing the policy, it is anticipated that new vehicles will predominantly be BEVs, which will account for more than 50% of the total vehicle stock after the mid-2030s. Therefore, it is evident that the introduction and timing of a policy prohibiting the sale of new ICEVs are crucial for achieving carbon neutrality in the passenger road transport sector.

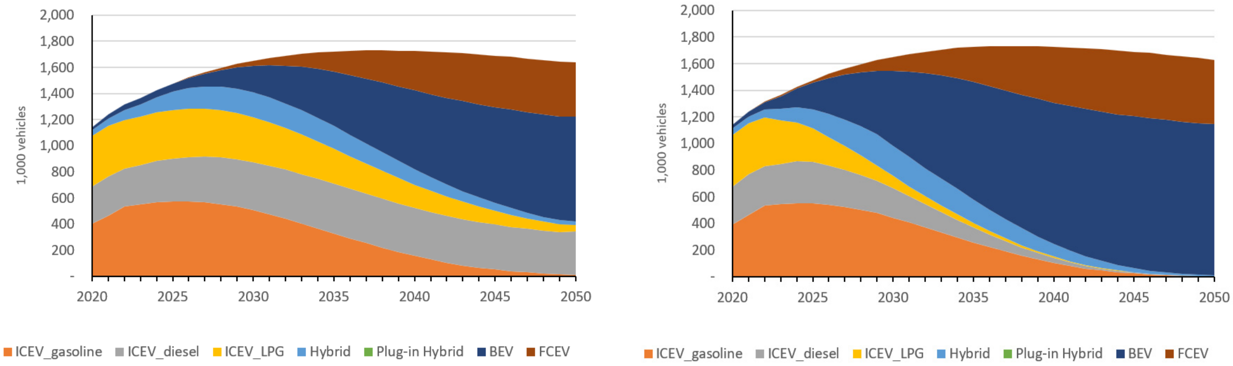
In the case of business passenger cars, although their share of the total vehicle stock is not high, government policies aimed at rapidly transitioning to BEVs and FCEVs are applied more actively than for non-business passenger cars. Examples include corporate carbon neutrality declarations and the Korea Ministry of Environment's initiative to transition to non-polluting business vehicles (K-EV100). Therefore, in the CN scenario for business passenger cars, a policy prohibiting the sale of new ICEVs (including HEVs and PHEVs) has already been applied in the latter half of the 2020s. It is anticipated that the proportion of ICEVs will decrease to less than 50% by 2030 (Figure 2[d]). By contrast, ICEVs continue to be prevalent in the BAU scenario. Consequently, it is projected that approximately 20% of ICEVs will still be operational by 2050, and the adoption of FCEVs will significantly expand (Fig. 2[c]). The prominent presence of FCEVs in the business passenger car sector is attributed to the METER scenario incorporating government plans to expand the adoption of FCEVs as a limiting condition. This leads to a significantly higher proportion of FCEVs in the business passenger car sector compared to the non-business passenger car sector, persisting until 2050.

In 2020, buses accounted for approximately 3.8% of the total passenger vehicle stock (private buses, 3.1%; business buses, 0.7%), which is considerably lower than that of light-duty vehicles (LDVs). This share is expected to decrease slightly to approximately 2.5% by 2050 (private buses, 1.9%; business buses, 0.6%).

An examination of the composition of private buses by



(a) Private LDV in BAU scenario (b) Private LDV in CN scenario

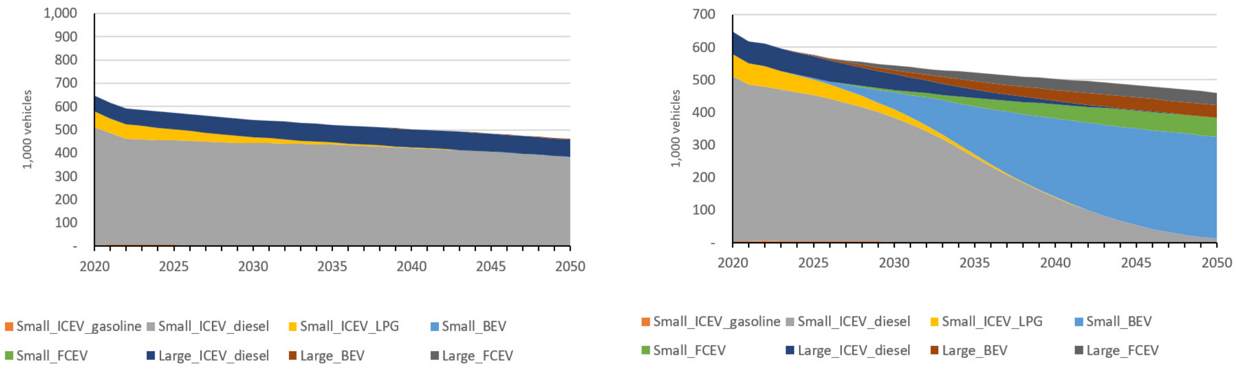


(c) Business LDV in BAU scenario (d) Business LDV in CN scenario

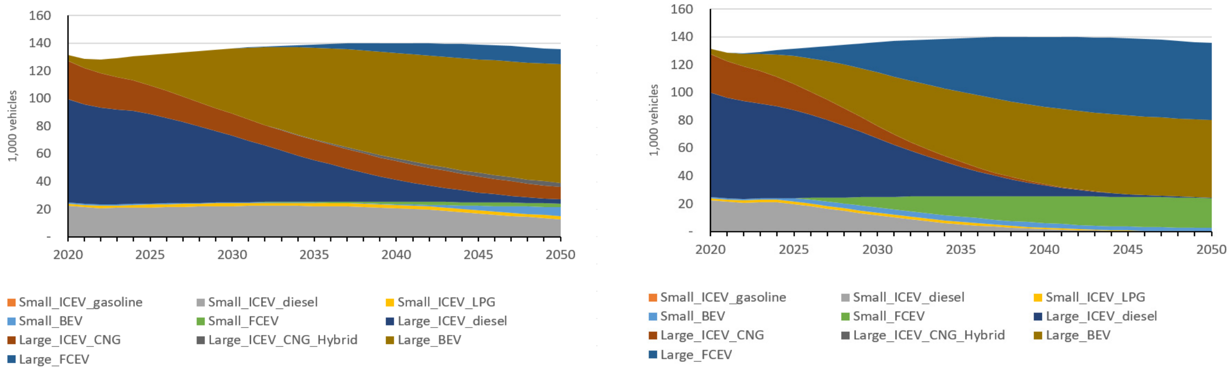
Fig. 2. Number of vehicles by LDV

type in the 2020s revealed that diesel vehicles were dominant. However, in subsequent years, different trends emerged based on vehicle size. In the BAU scenario, for small private buses, the adoption of new BEVs and FCEVs was limited. In contrast, in the CN scenario, BEVs and FCEVs constitute the majority of new vehicle sales from the latter half of the 2020s onward (Fig. 3[a], [b]). This outcome reflects the conditions in the CN scenario in which new electric and hydrogen buses will be introduced in 2023 for small private buses. For large private buses, in the BAU scenario, there was a slight increase in the adoption of BEVs, whereas in the CN scenario, BEVs and FCEVs saw a similar proportionate increase owing to the decline in diesel vehicles (Fig. 3[a], [b]). The two scenarios exhibited different trends, with the BAU scenario maintaining a high proportion of diesel vehicles throughout the period, whereas the CN scenario saw a substantial shift to BEVs and FCEVs from the mid-2030s onward. The CN scenario, which prohibits the sale of new buses with internal combustion engines (ICE) buses from 2030, leads to the rapid replacement of vehicles with electric and hydrogen alternatives. In summary, the results indicated that the replacement of small private buses with BEVs and FCEVs occurred relatively smoothly, particularly in the CN scenario. However, for large private buses, the transition to BEVs and FCEVs is challenging without implementing policies that prohibit the sale of new ICE buses.

Business buses refer to vehicles primarily used as urban buses, intercity buses, charter buses, and other similar purposes. Small business buses exhibit distinct differences between the two scenarios. In the BAU scenario, the widespread adoption of BEVs is anticipated to occur only from the mid-2040s onward. However, in the CN scenario, a rapid shift to hydrogen-based replacements begins in the latter half of the 2020s, with hydrogen buses dominating by 2050 (Fig. 3[c], [d]). For large business buses, differences are observed in both



(a) Private bus in BAU scenario (b) Private bus in CN scenario



(c) Business bus in BAU scenario (d) Business bus in CN scenario

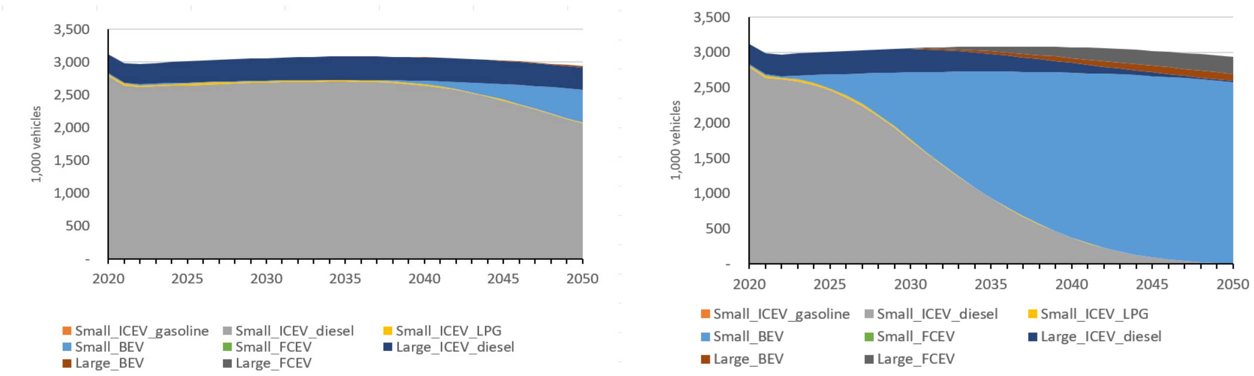
Fig. 3. Number of vehicles by bus

scenarios. In the CN scenario, which includes the phasing out of ICE bus sales by 2030 and the cessation of CNG bus production from 2024, electric and hydrogen van adoption will exceed 50% by the mid-2030s, with virtually no ICE buses remaining until 2050 (Fig. 3[d]). In contrast, the BAU scenario shows a higher absolute share of electric buses; however, small-scale CNG buses will persist until 2050 (Fig. 3[c]). However, for large business buses, both scenarios predicted a predominant transition from diesel buses to electric and hydrogen alternatives, highlighting the government's stronger policies promoting the adoption of electric and hydrogen buses in business vehicle fleets.

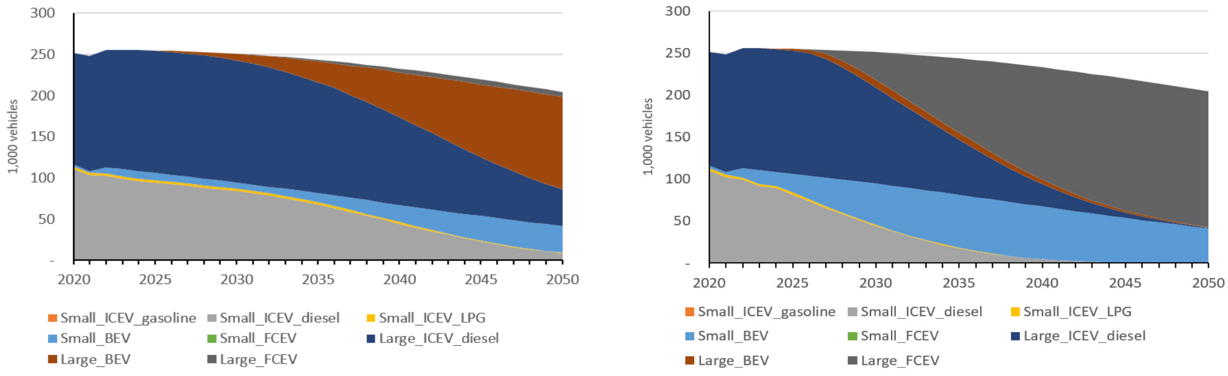
4.1.2. Freight road transport

The total number of trucks showed a trend similar to that of passenger cars. In the CN scenario, the total number of trucks is projected to reach approximately 3,648 thousand by 2030, 3,639 thousand in 2035, 3,619 thousand in 2040, and 3,444 thousand in 2050. The BAU scenario forecasts a level similar to that of the CN scenario. The increase in the total number of trucks shows a decrease from 3,647 thousand in 2020 to 3,639 thousand in 2035, indicating a decrease rate of -0.2% (-0.03% per year) over the 15-year period. This represents a noteworthy change compared to the significant increase of 46.0 % (2.3% per year) observed over the past 20 years (2000 ~ 2020).

Private trucks will account for 87.3% of all trucks by 2020, with business vehicles accounting for the remaining 12.7%. Most (80.8%) of these private trucks are small vehicles. The proportion of small private trucks is expected to remain at a similar level until 2050. Currently, both small and medium-sized trucks in private freight vehicles are mostly fueled by diesel. In the BAU scenario, the trend for small-sized private trucks is expected to continue, with diesel vehicles dominating until approximately 2040, after which electric vehicles are



(a) Private truck in BAU scenario (b) Private truck in CN scenario



(c) Business truck in BAU scenario (d) Business truck in CN scenario

Fig. 4. Number of vehicles by truck

projected to replace them. For medium-sized private trucks, the share of diesel fuel is anticipated to remain nearly constant until 2050 (Fig. 4[a]). In the CN scenario, small private trucks are expected to experience a significant shift toward BEVs supplied comprehensively from the late 2020s, with the majority replaced by BEVs by 2050. Medium-sized private trucks are expected to be predominantly replaced by FCEVs, with some being replaced by BEVs (Fig. 4[b]).

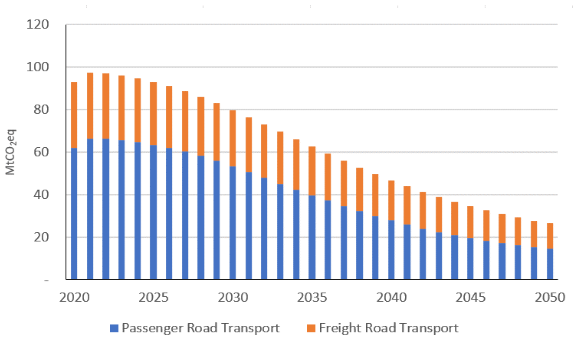
As observed in the passenger vehicle analysis, the substantial difference between the BAU and CN scenarios is affected by the introduction of policies prohibiting the sale of ICEVs between 2030 and 2035. In the private freight vehicle sector, without policies prohibiting the sale of ICEVs, there are limitations to the cost-effectiveness of replacing ICEVs with BEVs and FCEVs, as evident from the BAU scenario. Unlike private passenger vehicles, where, even without the introduction of policies prohibiting ICEV sales, the BAU scenario projects BEVs and FCEVs to occupy more than half of the total number of vehicles by 2050, the private freight vehicle sector, considering the predominance of diesel vehicles, emphasizes the importance of policies prohibiting the sale of ICEVs for carbon neutrality.

For business trucks, the vehicle number of medium- and large-sized trucks are approximately 1.5–2 times more than that of small-sized trucks. Achieving carbon neutrality in business trucks depends on whether the technologies for replacing medium-sized ICEVs are technically and economically feasible. In the BAU scenario, small business trucks gradually transition to BEVs, replacing a significant proportion after 2040 as diesel vehicles decrease. A similar trend was observed for medium- and large-sized business vehicles; however, diesel vehicles were still present (Fig. 4[c]). In contrast, in the CN scenario, small business trucks are expected to be largely replaced by BEVs before 2030, with a substantial transition expected by approximately 2040. In medium-sized trucks, FCEVs will begin replacing diesel ICEVs after the prohibition of diesel ICEV sales by around 2035; by 2050, FCEVs are expected to dominate (Fig. 4[d]). As observed in the analysis of private trucks, both small and medium-sized business vehicles face challenges in achieving carbon neutrality because of the technical and economic costs of BEVs and FCEVs, which lag behind ICEVs for an extended period. However, in private trucks, without measures prohibiting ICEV sales, the widespread adoption of BEVs and FCEVs is almost impossible. In contrast, in business trucks, the continued proliferation of BEVs and FCEVs is expected even without measures prohibiting ICEV sales.

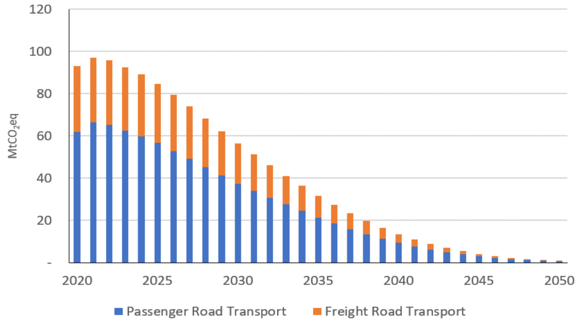
4.2. GHG emissions in road transport

In this study, we calculated GHG emission pathways for the passenger and the freight road transports separately. In the passenger transport sector, under the BAU scenario, GHG emissions are expected to decrease from 62.0 million tCO2eq. in 2020 to 14.6 million tCO2eq. in 2050 (23.7% of 2020 emissions). On the other hand, in the CN scenario, emissions are projected to decrease to 0.6 million tons of CO2eq. in 2050 (1.0% of the 2020 emissions) and almost reaches carbon neutrality (Fig. 5). In the freight transport sector, the GHG emissions under the BAU scenario are expected to decrease from 31.2 million tCO2eq. in 2020 to 11.9 million tCO2eq. in 2050 (38.2% of 2020 emissions). The CN scenario indicated a further reduction, with emissions reaching 0.2 million tCO2eq. in 2050, which is approximately 0.6% of 2020 emissions, approaching carbon neutrality (Fig. 5).

It is evident that achieving nearly “zero” energy consumption is impossible if there is a demand for vehicle usage. Therefore, the key strategy is to replace ICEVs with BEVs and FCEVs, moving in a direction where fossil fuels are not used. However, it is crucial to consider strategies that reduce the overall energy consumption and continuously improve the energy efficiency of vehicles to facilitate the process of achieving carbon neutrality.



(a) BAU scenario



(b) CN scenario

Fig. 5. GHG emissions in road transport

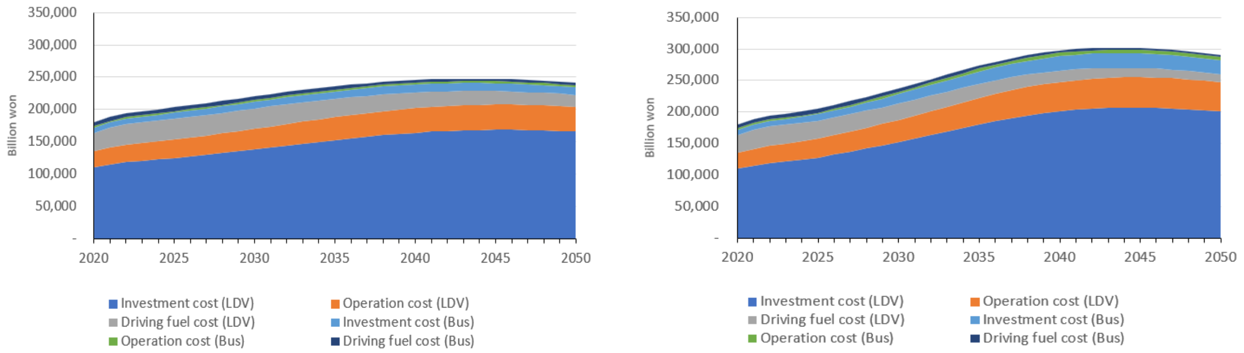
4.3. Economic costs for net zero

In the METER used in this study, the criteria determining the adoption levels of BEVs and FCEVs are direct costs, which include investment costs, fixed operating costs, fuel costs, and external costs, calculated using carbon and VMT taxes. In the following sections, direct costs are analyzed separately for the passenger and freight road transport sectors, whereas external costs are analyzed for the entire road transport sector.

4.3.1. Direct costs

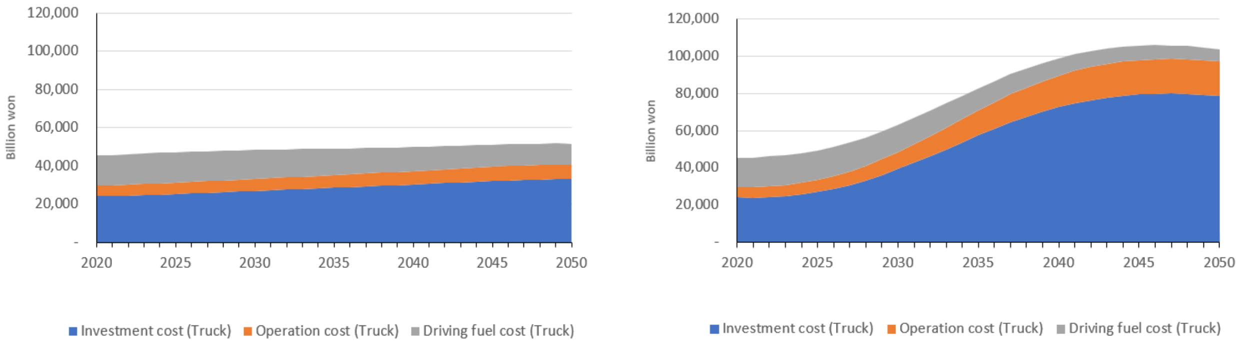
Fig. 6(a). and Fig. 6(b). shows the carbon-neutral costs in the passenger road transport sector. In the BAU scenario, the direct costs in the passenger transport sector exhibit a distribution of 225.9–298.6 trillion KRW per year, gradually decreasing after reaching the highest point in the mid-2040s. The estimated direct costs for the period 2020 ~ 2050 amount to 7,050 trillion KRW. In contrast, in the CN scenario, the annual direct costs show a distribution of 226.0–407.0 trillion KRW, peaking in the mid-2040s and then declining. For the period of 2020～2050, it is projected to be 8,012 trillion KRW, which is 13.6% higher than that of the BAU scenario. The largest cost component is the investment cost for passenger cars, accounting for 61–69% of the annual direct costs, followed by the fixed operating cost of passenger cars, fuel cost of passenger cars, and investment cost of buses. The combined investment cost for passenger cars and buses is forecast to be 5,840 trillion KRW in the CN scenario, which is 18.7% higher than the 4,921 trillion KRW in the BAU scenario. Both investment and fixed operating costs increase gradually in both scenarios until the mid-2040s, followed by a gradual decline. Fuel costs showed a continuous decrease over time.

Fig. 6(c). and Fig. 6(d). illustrates carbon-neutral costs in the freight road transport sector. In the BAU scenario, the direct costs in the freight transport sector show a distribution of 45.3–51.7 trillion KRW per year and gradually increase until 2050. The estimated direct costs for the period 2020～2050 amount to 1,520 trillion KRW. The CN scenario exhibited annual direct costs with a distribution of 45.5–105.8 trillion KRW, with a sharp increase expected from the mid-2030s. The projected direct costs for the period 2020～2050 are 2,447 trillion KRW, which is 61.0% higher than the BAU scenario. Although the direct costs in the freight transport sector are relatively small compared to passenger transport, the temporal trends are distinctly different. Investment costs for freight vehicles represent the largest cost component, constituting 52.9–64.1% of the annual total costs in the BAU scenario, and 53.0–75.9% in the CN scenario. Therefore, it can be concluded that investment costs play a crucial economic role in the CN scenario for freight road transport. Reflecting this trend, fixed operating costs will also experience an increase from the mid-2030s under the CN scenario. Fuel costs are expected to decrease gradually in both scenarios owing to improved



(a) Passenger transport costs in BAU scenario

(b) Passenger transport costs in CN scenario



(c) Freight transport costs in BAU scenario

(d) Freight transport costs in CN scenario

Fig. 6. Direct costs in road transport

vehicle energy efficiency.

The above analysis indicates that freight transport is more challenging than passenger transport in terms of achieving carbon neutrality, both technically and economically. Therefore, it is necessary not only for the South Korean government, but also on a global scale, to expand investments in the technological development of electric and hydrogen-powered freight vehicles. Efforts should be made to surpass the current predictions by enhancing technological advancements and reducing investment costs.

4.3.2. External costs

In both passenger and freight road transport sectors, the CN scenario incurs significantly higher direct costs than the BAU scenario. Higher direct costs imply that the transition to BEVs and FCEVs is relatively challenging. However, it is important to note that the direct cost analysis conducted earlier has limitations as it does not account for the costs associated with external effects. Considering that the goal of this study is to achieve carbon neutrality, it is essential to analyze these external costs. Therefore, indirect external costs, represented by carbon taxes and vehicle-mile-based driving charges, should be considered when comparing the magnitudes of these costs. This holistic approach provides a comprehensive understanding of the economic implications of carbon neutrality in the transport sector.

As shown in Fig. 7, the total direct and external costs for the BAU scenario amount to KRW 12,178 trillion from 2020 to 2050. This includes direct costs of 8,570 trillion won in both the passenger and freight transport sectors, supplemented by external costs such as carbon (1,665 trillion won) and VMT (1,943 trillion won) taxes. In the CN scenario, the sum over the same period is 12,662 trillion. This comprises the direct costs in the passenger and freight transport sectors, totaling 10,459 trillion won, with additional external costs, including carbon (60 trillion won) and VMT (1,601 trillion won) taxes. Therefore, from a direct cost perspective, the CN scenario incurs an additional 1,888 trillion won compared with the BAU scenario. However, when considering additional external costs, the CN scenario requires more than KRW 484 trillion. Consequently, considering external costs enhances the economic viability of the CN scenario. Nevertheless, the design and levels of carbon and VMT taxes can vary based on the tax rates, necessitating diverse scenario analyses. Further research is needed to scientifically investigate the societal impact of external effects.

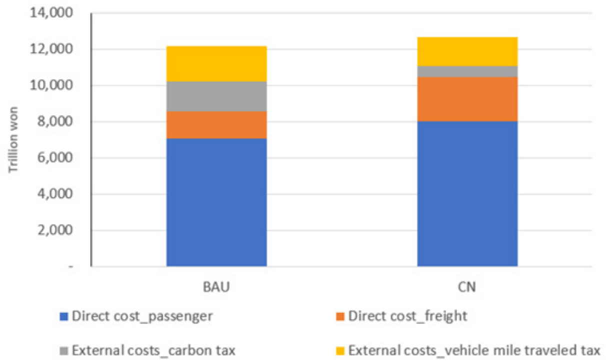


Fig. 7. Comparison of direct and external costs

5. Policy implications

By comparing the CN scenario proposed by the Korean government with the BAU scenario, which maintains the current policies, key considerations for achieving carbon neutrality in the road transport sector can be identified. The policy implications of this study are as follows:

First, the scenario analysis for road passenger transport showed that the large-scale expansion of electric and hydrogen vehicles is a crucial strategy for carbon neutrality. However, achieving carbon neutrality requires more direct costs (investment, fixed operational, and fuel costs) than those in the BAU scenario, making it challenging without strong policy interventions. The most critical policy for carbon neutrality was the introduction of a ban on ICEV sales by the mid-2030s. Existing policies, such as subsidies for BEV and FCEV purchases and corporate average fuel efficiency standards, should be continually strengthened until the implementation of the ban on ICEVs to increase the feasibility of enforcing the ban.

Second, non-business passenger cars and buses face greater challenges in adopting BEVs and FCEVs than business vehicles do. Therefore, a more detailed approach is required for non-business vehicles. In the non-business sector, BEVs have emerged as the most crucial technology. However, in the business sector, the increasing importance of FCEVs underscores the need to formulate policies for charging infrastructure installations and vehicle technology development considering these differences.

Third, similar to passenger transport, the freight transport sector should rapidly transition from all vehicle types to BEVs and FCEVs, with a ban on ICEV sales proving to be the most effective. Owing to technical constraints and other factors, the direct costs are 67.2% higher than those in the BAU scenario, making carbon neutrality more challenging than in the passenger sector. Therefore, robust policy interventions are crucial. For instance, corporate average fuel economy (CAFE) standards have been in place since 2012 to reduce GHG emissions from automobiles. This system has been in use in small-freight vehicles since 2012. It has been implemented since 2023 in medium- and large-freight vehicles. Specifically, for medium and large freight vehicles, the relevant standards should be gradually strengthened until the introduction of a ban on the sale of ICEVs in the mid-2030s.

Fourth, achieving carbon neutrality in freight transport involves a crucial technological aspect in which small vehicles transition to electric vehicles and large vehicles shift to hydrogen. This implies that in non-business use, where the proportion of small trucks is high, there will be a greater emphasis on electric vehicles. In contrast, in business, where large trucks dominate, the focus is on hydrogen vehicles. Therefore, differentiated approaches that consider factors such as vehicle size are essential for the development of charging infrastructures and technologies tailored to freight vehicles.

Fifth, the CN scenario incurs direct costs of more than 14.3% compared with the BAU scenario. However, when external costs based on carbon and VMT taxes are included, the total cost difference can be reduced or even become less. Therefore, when formulating carbon-neutral strategies, simultaneously considering the external effect costs enhances economic viability. In addition, carbon and VMT taxes should be thoroughly evaluated as a means to secure the government funds necessary for maintaining and managing transport infrastructure, especially in anticipation of a decrease in income from existing environmental taxes on fossil fuel transport energy.

6. Conclusion

Since the South Korean government declared its plan to achieve carbon neutrality by 2050 in October 2020, various studies have been conducted on methods to achieve carbon neutrality in each sector, including transport. This study utilizes the METER to analyze the feasible and scientific aspects of the CN scenario proposed by the South Korean government and BAU scenario. The analysis included annual pathways of the technological vehicle fleet structure, GHG emissions, and associated economic costs until 2050.

Additionally, considering whether vehicles are in the non-business or business sector is crucial because core technologies for eco-friendly vehicle vary depending on the main vehicle size in both sectors. Policies for charging station penetration and technological development should be tailored accordingly. From an economic cost perspective, simultaneously considering both direct and external costs enhances economic viability. Particularly, the introduction of carbon and VMT taxes can address the issue of reduced income from existing environmental taxes on the transport fossil fuels during the process of achieving carbon neutrality.

However, this study has limitations as it does not incorporate the GHG emissions generated during the supply of energy sources for electric and hydrogen vehicles or the costs associated with charging station installation and hydrogen supply networks required for the widespread adoption of electric and hydrogen vehicles. Future studies should address these limitations to provide a more comprehensive analysis. Additionally, analyzing various scenarios for carbon and VMT taxes will contribute to deriving more realistic policy implications.

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