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Is the High-Emission Vehicle Driving Area Restriction Policy an Effective Measure for Reducing Driving Distance? A Case Study of Busan, South Korea

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Abstract: Efforts to reduce air pollution by facilitating the transition to eco-friendly vehicles, particularly through driving restriction policies targeting high-emission vehicles (HEVs), play a crucial role in promoting environmental sustainability. Evaluating the effectiveness of the restriction in terms of reducing HEV driving mileage is essential for policy assessment and improvement. Moreover, given the overall decreasing trend in daily vehicle mileage, it remains uncertain whether the change in HEV driving distance can be directly attributed to the restriction policy. This study directly examines the effectiveness of the vehicle restriction policy using vehicle mileage data and a DID model. Data on daily mileage from 2019, 2021, and 2023 were collected for Busan, and the scenarios were divided into six groups based on the analysis group (treatment group is HEVs subject to vehicle restrictions, control A is HEVs not subject to vehicle restrictions and control B is non-HEVs) and the area of influence (catchment area, city area, and metropolitan area). The analysis revealed that while there was a reduction in daily mileage for HEVs when compared to each other, the decrease was modest, and no significant effect was observed when compared to non-HEVs. Consequently, it was confirmed that the impact of the vehicle restriction policy on reducing daily mileage is marginal. In light of the policy to expand the scope of vehicles subject to driving restrictions in South Korea, it is recommended that the number of enforcement cameras be increased, that enforcement hours be extended to an entire 24-h day, and more stringent enforcement measures be implemented.

Keywords: driving area restriction; high-emission vehicles; vehicle mileage; difference-in-difference

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1. Introduction

Various policies are being implemented to reduce vehicle mileage with the goal of alleviating environmental pollution and traffic congestion. Vehicle mileage reduction policies can be broadly categorized into two types: those that limit vehicle operations in specific areas or during certain times, or impose congestion charges to discourage vehicle use; and those that promote a modal shift from personal transportation to public transport through the expansion of public transport services and infrastructure.

As part of the vehicle operation restriction policy, South Korea has been limiting the operation of high-emission vehicles (HEVs) in specific areas. This policy is accompanied by various incentive programs aimed at encouraging the early scrapping of aging HEVs, resulting in a significant reduction in the number of HEVs on the road. For instance, the number of HEVs in South Korea decreased from 2,104,154 (December 2019) to 906,192 (December 2023), representing a 57% reduction [1]. In other words, the HEV operation restriction policy has effectively encouraged HEV owners to purchase non-HEVs, resulting in a shift from using HEVs to using eco-friendly vehicles.

Previous studies have primarily analyzed the effects of vehicle driving area restrictions through the use of air quality data. This approach may be viewed as mixing the impacts of vehicle transitions with the changes in driving distance resulting from the implementation of the vehicle driving area restriction. However, even after the implementation of driving area restriction policies, there are still HEVs that have not transitioned, and there is limited research on the changes in driving distance of these vehicles, which directly affect air pollutants and greenhouse gas emissions. In addition, it is difficult to directly assess the effect of vehicle driving area restriction policies on mileage reduction through air quality data, because air quality data carries the risk of varying results based on the environmental conditions at the time of measurement and the location of measurement. Moreover, it is challenging to ascertain whether the observed results are due to reduced mileage or the transition to different vehicles. Therefore, this study aims to focus on analyzing changes in the mileage of HEVs that have not transitioned to eco-friendly vehicles.

Many countries, including South Korea, are showing a trend of decreasing average daily mileage per vehicle due to an increase in short-distance travel and the number of vehicles owned per household. Therefore, there are questions regarding the daily mileage reduction due to the effects of vehicle driving area restrictions. To estimate the causal effect of the HEV operation restriction policy, it is essential to consider changes in mileage for both the treatment group (those subject to the restrictions) and the control group (those not subject to the restrictions). This study analyzed the causal effect of the HEV driving area restriction policy implemented in Busan in 2022 using a difference-in-difference (DID) model that reflects the changes in mileage for both restricted and non-restricted vehicles. Additionally, the regions affected by the operation restriction policy were classified into three areas based on the intensity of enforcement, allowing for an examination of whether the HEV operation restriction policy effectively reduced the mileage of HEVs in Busan in South Korea.

The structure of this paper is as follows. Chapter 2 presents a comprehensive review of the relevant literature, highlighting research gaps. Chapter 3 offers a detailed description of the HEV driving restriction policies in South Korea, the study site and the data collected. Chapter 4 indirectly examines the effect of the driving restrictions through a simple comparison of the daily mileage of the analysis group and assesses the need for applying a model. Subsequently, a DID model is introduced to verify whether the driving restriction policy has a significant impact on changes in daily mileage. At this stage, it is checked whether the parallel assumption holds for the average daily mileage between the analysis groups before the introduction of the driving restrictions. Chapter 5 discusses these findings within the broader context of the study's objectives and implications. Additionally, the study's limitations are addressed, and recommendations for future research are provided.

2. Literature Review

The effects of the vehicle driving area restriction policy are typically analyzed based on air quality data. Specifically, studies utilizing air quality monitoring station data have been conducted in Beijing, China [2]; eight streets, six urban background locations and four suburban background locations in Amsterdam, Netherlands [3,4]; London, England [5,6]; Barcelona and Madrid, Spain [7,8]; Germany [9]; as well as 32 major cities [10]. Panteliadis et al. analyzed the impact of restricting Euro 0, I, and II medium-sized vehicles in the Low Emission Zone of Amsterdam, Netherlands [3]. Ma et al. and Zhai quantified the impact of the Ultra-Low Emission Zone (ULEZ) in London, England [5,6]. Interestingly, Rossi et al. examined the relationship between traffic flow and air quality using data collected during the COVID-19 lockdown in Padua, Italy, to assess the effects of vehicle restrictions [11]. During the COVID-19 lockdown, similar studies to assess the impact of reduced traffic volumes on air quality were conducted in six cities in Italy [12], Santiago, Chile [13], and São Paulo, Brazil [14].

However, examining changes in air quality presents several limitations. A study assessing the effects of highway speed limit policies in Amsterdam, Netherlands, found that it is nearly impossible to directly measure the impact of such policies on vehicle emissions and air pollution levels [15]. The study highlighted the limitations of vehicle restrictions, noting that changes in travel behavior due to these measures can dynamically affect emissions and may extend beyond the areas where restrictions are implemented. The study emphasized the importance of quantifying the impact of traffic restrictions on air quality [4]. Additionally, the study explored changes in road traffic to identify potential air quality variations, highlighting the significant role of weather conditions and atmospheric chemistry in shaping air quality levels [16]. During the COVID-19 outbreak in Beijing, China, while pollutant emissions from road traffic decreased, air quality worsened due to an increase in volatile organic compounds from external sources [17,18].

Additionally, the varying results regarding the effects of vehicle restrictions can also be problematic. While some studies confirm that driving restrictions are effective in improving air quality [3,5–9,11–18], others indicate that eliminating vehicles is more effective [2], that there is no significant effect [10], or that long-term and more restrictive measures are necessary [4]. There was also a study that simulated the effects of introducing a Low Emission Bus Zone in Jeju, South Korea, where vehicles were converted to environmentally friendly vehicles [19].

Several attempts have been made to overcome these limitations. One study measured the reduction in air pollutants resulting from the restriction of traffic in Guangzhou, China, by collecting air samples both roadside and on rooftops (approximately 50 m above ground) before and after the restriction [20]. Another study used the MOVES emission model to estimate vehicle pollutant emissions under a license plate restriction policy in Hangzhou, China [21]. Regarding the enhancement of the effects of vehicle restriction, Zhou et al. suggested that policies should be implemented earlier, applied in densely populated areas and regions with high GDP per capita, and that the expansion of restricted zones is necessary [22].

Significant research gaps remain. Directly collected air quality data makes it challenging to fully capture the effects of vehicle restrictions, and models used for emission estimates are still based on approximations. This study addresses these gaps by comparing empirical vehicle mileage data before and after the implementation of vehicle restrictions.

Research using the DID model to compare pre- and post-treatment effects has been applied in various fields. Dai et al. used the DID model to analyze the impact of the Carbon Emissions Trading (CET) policy on the reduction of carbon intensity [23]. Similarly, there is a study that used the DID model to evaluate the effect of China's Low-Carbon City Pilot (LCCP) on carbon emissions [24]. Miller et al. employed the DID method to examine the impact of the Panama Canal expansion on Latin American and Caribbean ports [25]. There is also research that used the DID model to examine the changes in road traffic mortality rates before and after the implementation of the alcohol sobriety checkpoint program in Mexico [26]. Caspi et al. used the DID method to analyze the health effects before and after the implementation of the minimum wage policy in Minnesota and North Carolina [27]. Additionally, there is a study in South Korea that used the DID method to investigate the impact of visual impairment on the likelihood of receiving medical aid [28]. This study aims to use a DID model to compare vehicle mileage before and after the implementation of vehicle restrictions.

3. Restriction Policy, Study Site, and Data

3.1. Restriction Policy

The HEV driving restriction area policies in South Korea can be broadly divided into three categories: the round-the-clock restriction on HEVs in the Seoul metropolitan area, the restriction in Seoul's Green Transportation Zone (GTZ), and the restriction in seasonal management areas [29]. First, the round-the-clock restriction on HEVs (commercial diesel vehicles only) in the Seoul metropolitan area targets old diesel vehicles and permanently restricts their operation in the metropolitan area. This policy has been in effect since July 2018 and applies to commercial diesel vehicles registered in the Seoul metropolitan area.

The GTZ restriction policy, implemented in December 2019, restricts the operation of HEVs in Seoul's Central Business District (CBD). Enforcement is year-round, with restriction hours from 6 AM to 9 PM. While these policies continuously limit the entry of HEVs into Seoul and its metropolitan areas, the entry and driving restrictions for HEVs in large cities outside of the capital began in 2022 with the implementation of the seasonal management area restriction policy. This policy restricts the operation of HEVs during the high air pollution season, from December to March. Violating vehicles are monitored through license plate recognition cameras installed in each city, and enforcement is conducted only on weekdays from 6 AM to 9 PM. Additionally, this policy applies not only to HEVs registered in seasonal management areas but also to all HEVs nationwide. Moreover, the implementation of these vehicle restriction policies is accompanied by incentives, such as encouraging early scrappage and supporting the installation of particulate matter reduction devices (DPF), which has significantly facilitated the transition of HEVs to zero-emission or low-emission vehicles. However, exemptions to enforcement for the seasonal restriction policy include vehicles equipped with emission reduction devices, and commercial vehicles.

3.2. Study Site

In this study, Busan, one of the first non-capital metropolitan areas to be designated as an HEV seasonal restriction zone in 2022, was selected as the study site. Busan is the country's second-largest city and a major hub for maritime trade and tourism. With a population of 3.8 million and 1.5 million registered vehicles in 2023, Busan faces significant air pollution challenges, particularly from vehicular emissions in its densely populated urban areas and its busy port. As of December 2023, the number of registered HEVs in Busan is 50,429, accounting for 8.8% of the total of 573,186 HEVs registered in non-capital areas of South Korea [1].

To evaluate the impact of the HEV restriction on driving distance in Busan, the area of influence (AOI) associated with the HEV policy was delineated into three areas: catchment area, city area, metropolitan area. First, the catchment area was defined as traffic analysis zones within a 1 km radius from the locations of the vehicle restriction enforcement cameras installed in Busan. This is intended to analyze the reduction effect on driving distance for HEVs that occur at the traffic zones where these cameras are located. Second, the entire city area was selected as the AOI based on the assumption that the effects of the HEV restriction policy would influence the reduction of driving distance for all registered HEVs in the restricted city, regardless of the locations of the enforcement cameras. Finally, the AOI was expanded to the metropolitan area, which includes nearby cities exhibiting a relatively high degree of traffic dependency on Busan under the assumption that the effects of the HEV restriction policy would similarly influence the reduction of driving distance for registered HEVs in neighboring cities that regularly enter and exit the city areas.

Figure 1 depicts the aforementioned three AOIs for Busan, with the metropolitan area defined as cities for which the travel demand ODs destined for Busan accounts for more than 10% of the total travel demand. In addition, Figure 1 shows that the catchment area based on the locations of the enforcement cameras (with 30 cameras) covers approximately 49% of the total administrative areas in Busan.

3.3. Vehicle Driving Distance

Vehicle driving distance statistics in South Korea are released annually by the Ministry of Land, Infrastructure and Transport. The trends in vehicle registrations and average annual driving distance per vehicle over the past six years in South Korea indicate a decline in the average annual driving distance per vehicle, which decreased from 39.2 km in 2018 to 36.0 km in 2023. Concurrently, the total number of registered vehicles in South Korea rose from 22,882,032 vehicles in 2018 to 26,134,475 vehicles in 2023. Similarly, in the target area of this study, Busan, the number of registered vehicles is also on the rise, while the average annual driving distance per vehicle is decreasing, as shown in Figure 2.

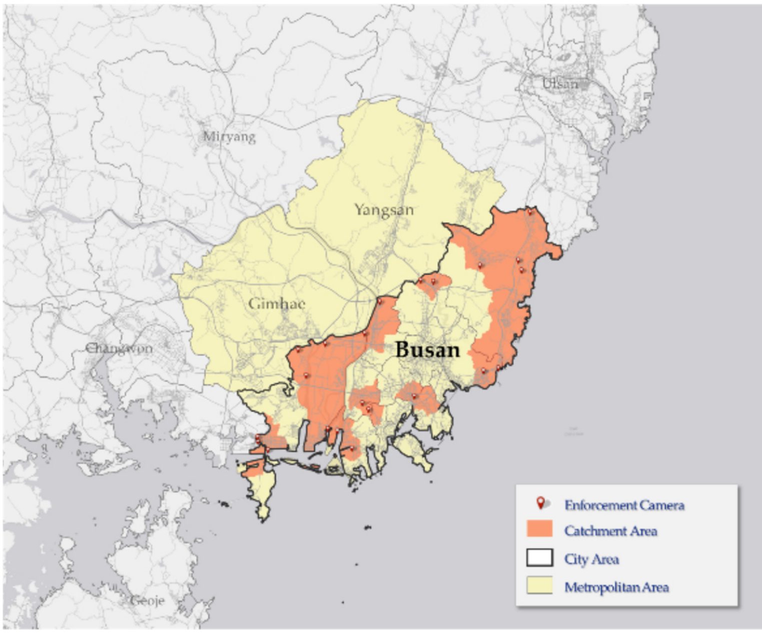


Figure 1. Area of Influence of the HEV driving restriction in Busan.

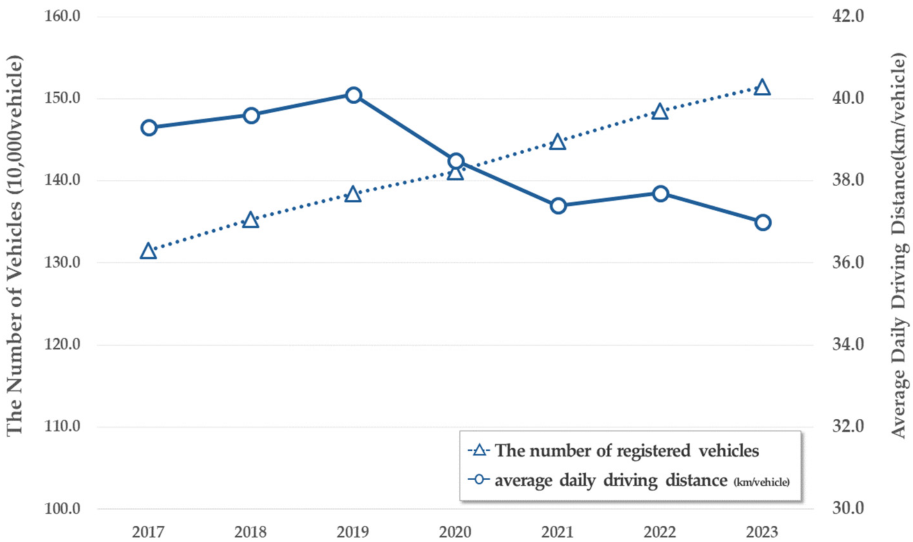


Figure 2. Trend of the Number of Vehicles and Average Driving Distance o Busan.

In Figure 2, the dashed line represents the number of registered vehicles, while the solid line represents the average annual driving distance. While the number of registered vehicles increases each year, the driving distance shows a declining trend.

The individual driving distance data for HEVs and non-HEVs include various vehicle-related information, such as the year of inspection, place of registration, latest inspection date, odometer reading at the time of inspection, vehicle usage (commercial or non-commercial), vehicle category (passenger vehicle, van, freight vehicle, or special-purpose vehicle), vehicle size (subcompact, compact, midsize, full-size), and vehicle fuel type. The driving distance data obtained through the data cleansing process consists of a total of 95,213 vehicles registered in the three AOIs. Table 1 presents the number of vehicles by AOI, treatment group, and control group for the analysis. In Table 1, the treatment group refers to non-commercial HEVs subject to enforcement and registered in each AOI, as commercial HEVs are exempt from enforcement. For the purpose of analyzing the effects of driving restrictions, this study classified the control group into two categories. Control group A consists of non-commercial HEVs not subject to enforcement and registered in each AOI, while control group B consists of non-commercial, non-HEVs registered in each AOI. Specifically, control group A is selected to compare the changes in vehicle mileage between non-commercial HEVs subject to enforcement and those not subject to enforcement, while control group B is selected to compare the changes in vehicle mileage between non-commercial HEVs subject to enforcement and non-HEVs (non-commercial vehicles).

Table 1. The number of vehicles used in the study.

Area of Influence			Treatment Group	Control Group		Total
				A	B	
Metropolitan area			4454	8037	82,722	95,213
	City area		2857	6200	60,320	69,377
		Catchment area	1227	2289	24,073	27,489

The driving distance data of these vehicles were collected for the years 2023 (after restriction), 2021, and 2019 (before restriction). The reason for collecting the data on a biennial basis is that non-commercial vehicles are inspected once every two years.

The average daily mileage for each vehicle was calculated using the latest inspection date and odometer readings. Table 2 presents the descriptive statistics of daily mileage by analysis group, AOI, and year. Cases where the daily mileage exceeded 500 km/day were considered outliers and excluded from the analysis. This threshold was determined considering that a trip from Busan to Seoul covers approximately 430 km, and a trip from Busan to Gangwon spans about 300 km, with additional allowances made for detours; 500 km corresponds to the 99.8th percentile of the overall daily average mileage distribution. There was a gradual decline in daily mileage from 2019 to 2023, which corresponds to the reduction in average annual driving distance in both cities, as illustrated as in Figure 2. Figure 3 shows the distribution of daily mileage by AOI and analysis group for the years 2019, 2021, and 2023.

Table 2. The descriptive statistics of the daily mileage by treatment and AOI (km/vehicle).

Treatment Group	Area of Influence	Year	Median	Mean
Treatment	Catchment area	2019	21	25
		2021	18	23
		2023	14	19
	City area	2019	20	25
		2021	17	23
		2023	14	20
	Metropolitan area	2019	21	26
		2021	18	24
		2023	15	20
Control A	Catchment area	2019	21	27
		2021	19	25
		2023	17	22
	City area	2019	24	26
		2021	19	24
		2023	17	22
	Metropolitan area	2019	21	27
		2021	19	25
		2023	17	22

Table 2. *Cont.*

Treatment Group	Area of Influence	Year	Median	Mean
Control B	Catchment area	2019	36	41
		2021	33	38
		2023	29	34
	City area	2019	35	40
		2021	32	37
		2023	29	34
	Metropolitan area	2019	36	41
		2021	33	38
		2023	29	34

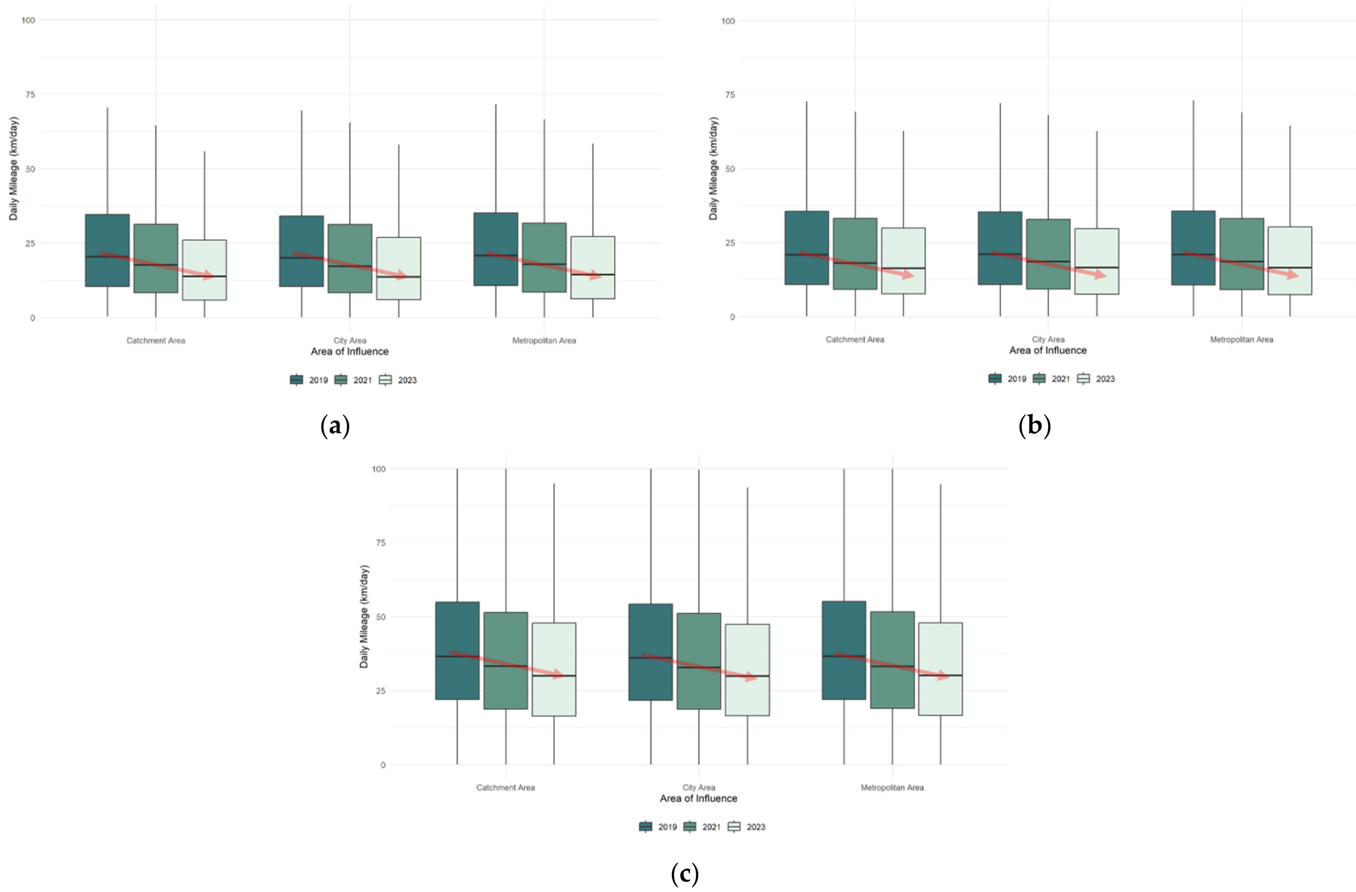


Figure 3. Annual daily mileage distribution by year, the analysis group and AOI. The red line represents the decreasing trend of the median value by AOI. (**a**) Treatment group; (**b**) control group A; (**c**) control group B.

The number of employees, oil price, gross regional product per capita, and gross regional product for Busan, Gimhae, and Yangsan by year were collected in order to be used as covariates in the subsequent model (Table 3). The values for Busan, Gimhae, and Yangsan, excluding the oil price, are the sum of the values for each region, while the oil price is the average of the oil prices for the three regions. Each variable is an indicator that represents the economic level of the region.

Table 3. The average of number of employees, oil price, GRDP per capita, and GRDP.

Area	Year	Number of Employees (Persons)	Oil Price (Won)	GRDP per Capita (1000 Won)	GRDP (100 Million Won)
Catchment and City Area	2017	1,155,514	1273	27,210	93,178
	2018	1,169,661	1374	28,355	96,495
	2019	1,196,973	1322	29,436	99,531
	2020	1,066,592	1170	29,272	98,225
	2021	1,115,608	1377	31,950	106,510
	2022	1,150,981	1820	34,465	113,844
	2023	1,173,977	1535	34,951	106,688
Metropolitan Area	2017	1,457,658	1282	88,926	119,178
	2018	1,477,797	1371	89,664	123,050
	2019	1,516,226	1316	90,942	126,542
	2020	1,354,496	1165	88,738	124,625
	2021	1,427,577	1376	91,790	133,145
	2022	1,468,441	1819	94,305	140,479
	2023	1,492,334	1531	92,623	133,511

4. Effects of HEV Driving Area Restriction on the Reduction of Driving Distance

4.1. Simple Comparison

The effect on driving distance resulting from the HEV vehicle restriction can be assessed through a straightforward comparison of driving distances before and after the policy's implementation for the targeted HEVs. Table 4 presents the results of the simple comparison. After the implementation of the HEV restriction policy, the average daily mileage of the targeted HEVs (treatment group) decreased by 4 to 5 km by AOI, while the average daily mileage of the non-targeted HEVs (control group A) decreased by 3 to 4 km. The average daily mileage of non-HEVs (control group B) decreased by 5 to 6 km.

Table 4. The mean of the daily mileage by analysis group and AOI (km/vehicle).

Area of Influence	Treatment Group				Control Group A				Control Group B			
	Before	After	Reduction		Before	After	Reduction		Before	After	Reduction	
			km/day	% *			km/day	% *			km/day	% *
Catchment area	24	19	−5	−21	26	22	−4	−15	41	35	−6	−15
City area	24	20	−4	−17	25	22	−3	−12	40	35	−5	−12
Metropolitan area	25	20	−5	−20	26	22	−4	−15	41	35	−6	−15

* ((After − Before)/Before) × 100.

While it may appear that the daily mileage of the targeted HEVs has decreased, the fact that the mileage of the control groups, which was not subject to the driving restrictions, also declined suggests that counterfactual inference is necessary to accurately assess the impact of the driving restriction. Therefore, the effect of the driving restrictions on vehicle mileage should be evaluated by considering the mileage changes of the targeted HEVs in comparison with the corresponding changes in the control groups.

On the other hand, the driving distance of HEVs is relatively lower than that of non-HEVs. This may be due to a higher prevalence of aging vehicles among HEVs, which could have resulted in less usage. However, as this study analyzes whether there is a significant difference in the reduction of daily driving distance between the two groups, the magnitude of the driving distance is unlikely to affect the analysis results.

4.2. Comparison Using Difference-in-Difference Model

The Difference-in-Differences (DID) model can be used to analyze the average difference between groups exposed to treatment and those not exposed at a specific point in time.

Specifically, analyzing the treatment effect between the control group and the treatment group (two groups) before and after exposure (two periods) is referred to as a 2 × 2 DID design. This difference is called the Average Treatment Effect on the Treated (ATET) and can be expressed as follows:

$$ATET = E[Y_{i2} - Y_{i1}|D = 1] - E[Y_{i2} - Y_{i1}|D = 0] \quad (1)$$

Y_{it} is the dependent variable value for the i-th observation at time t (where $t = 1$ for pre-treatment and $t = 2$ for post-treatment), and $D = 1$ indicates the treatment group, while $D = 0$ represents the control group.

This can be expressed in a regression model as follows [23–28]:

$$Y_{it} = \beta_0 + \beta_1 Group + \beta_2 Treatment + \beta_3 Group \times Treatment + \epsilon_{it} \quad (2)$$

Here, $Group$ is 0 for the control group and 1 for the treatment group, and $Treatment$ is 0 for pre-treatment and 1 for post-treatment. ϵ_{it} is the error term.

The DID model assumes parallel trends. Parallel trends mean that the trends of the variable of interest in the treatment group and the control group are identical before the treatment. To use the DID model, it is necessary to first verify that the parallel trends assumption is satisfied, which is known as the parallel trends test.

This study uses DID model to examine whether there are differences in daily mileage before and after the vehicle operation restriction for the targeted HEVs and vehicles in the control groups. The analysis scenarios are divided into six categories based on two control groups and three AOIs (catchment areas, city areas, and metropolitan areas). Table 5 shows the control groups and AOIs for each analysis scenario. The categories marked with an 'o' in the table indicate that they are included in the respective scenario.

Table 5. Analysis scenarios.

Scenario	Comparison Group		Area of Influence		
	A	B	Catchment Area	City Area	Metropolitan Area
S1	○		○		
S2	○		○	○	
S3	○		○	○	○
S4		○	○		
S5		○	○	○	
S6		○	○	○	○

The equation of the DID model commonly applied to each scenario is as follows:

$$Daily\ Milage_{it} = \beta_0 + \beta_1 Restriction\ Status + \beta_2 Treatment + \beta_3 Restriction\ Status \times Treatment + X_{it} + \epsilon_{it} \quad (3)$$

where a $Restriction\ Status$ value of 0 indicates before restriction, while a value of 1 indicates after restriction. $Treatment$ of 0 indicates control A or control B group, while a value of 1 indicates treatment group. i represents the vehicle number, and t represents the year (2019, 2021, 2023). X_{it} is a covariate.

The parallel trends assumption can be tested using a regression model by examining whether the changes in average daily mileage from 2019 to 2021 are the same between the treatment group and the control group prior to the implementation of the vehicle policy. In this approach, a dummy variable is applied, where 2019 is coded as 0 and 2021 as 1, and another dummy variable is used to differentiate between the control group (coded as 0) and the treatment group (coded as 1). If the confidence interval for the coefficient of the interaction term in the regression model includes 0, the parallel assumption is considered to be satisfied. This indicates that there is no statistically significant difference in the trends between the treatment and control groups prior to the intervention [30,31]. Additionally, the slopes of average daily mileage for the treatment and control groups during the pre-policy period can be visually assessed using line graphs to determine whether any differences exist. In this study, both the parallel trend test and line graphs were utilized to assess the validity of the parallel assumption.

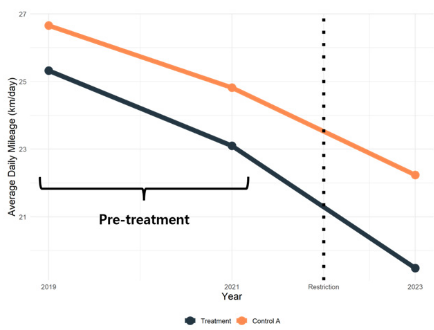
Table 6 presents the results of the parallel trend test. Except for scenario S3, the confidence intervals in all scenarios include 0, indicating that the parallel assumption is satisfied. In the case of S3, although the confidence interval does not include 0, the estimate of −0.827 is quite small, making it challenging to definitively conclude that the parallel trends assumption is violated. Therefore, we further reviewed the trend graphs to gain additional insights.

Table 6. Results of parallel trend test by scenario.

Scenario	Estimate	S.E.	99% Confident Interval	
			Lower Bound	Upper Bound
S1	−0.386	0.560	−1.80	1.10
S2	−0.576	0.348	−1.50	0.32
S3	−0.827	0.294	−1.60	−0.07
S4	1.256	0.575	−0.23	2.70
S5	0.856	0.372	−0.10	1.80
S6	0.720	0.304	−0.063	1.50

Figure 4 illustrates the trends in average daily mileage by year for each scenario. In each graph, the slopes of average daily mileage prior to the implementation of the vehicle restriction policy (2019 and 2021) do not show significant differences between the treatment group and the control group. This is consistent with the results shown in Table 6. In the case of scenario 3, there is a slight difference in the slope, but it is not substantial enough to significantly impact the analysis results. Therefore, we suggest that the parallel trends assumption is satisfied in all scenarios.

In this study, the number of employees, oil price, GRDP per capita, and GRDP were considered as covariates. For scenarios 1, 2, 4, and 5, which target Busan, the values of the number of employees, oil price, GRDP per capita, and GRDP in Busan were considered. For scenarios 3 and 6, which focus on the metropolitan area, the values for Busan, Gimhae, and Yangsan were considered. Before using them as covariates, the correlation between the number of employees, oil price, GRDP per capita, and GRDP was examined within the scope of each scenario, and high correlations between the variables were observed (Table 7). Therefore, due to concerns about multicollinearity, GRDP, which can represent regional economic indicators, was used as a covariate.



(S1)

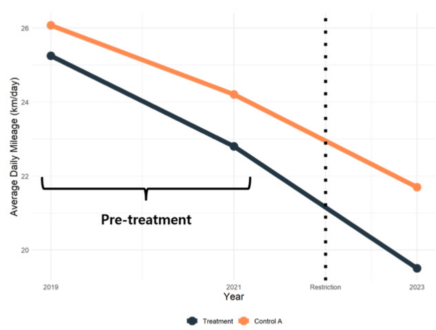


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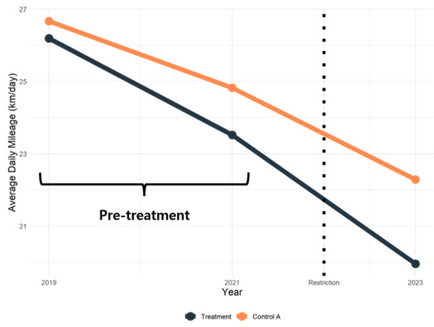
Figure 4. *Cont.*



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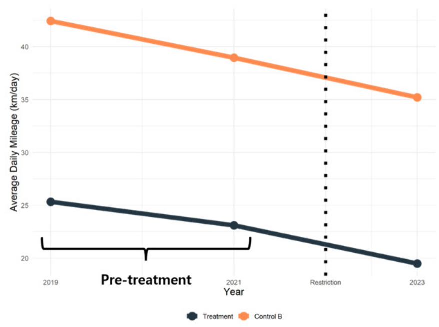

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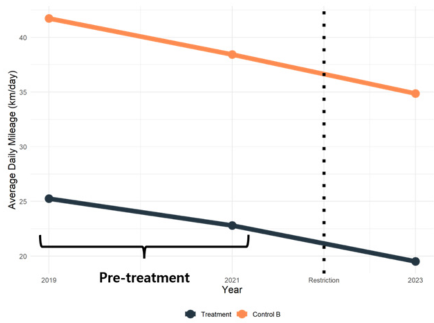

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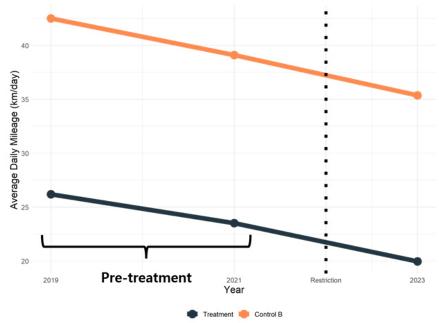

(S6)

Figure 4. The changes in average daily mileage before and after the implementation of vehicle restrictions are shown by scenario treatment group (represented by the green solid line) and control group A or B (represented by the orange solid line). The black dotted line indicates the year 2022 when the vehicle restrictions were implemented. (S1) Scenario 1; (S2) Scenario 2; (S3) Scenario 3; (S4) Scenario 4; (S5) Scenario 5; (S6) Scenario 6.

Table 7. The correlation analysis results for the number of employees, oil price, GRDP, and GRDP.

Area	Variable	Number of Employees	Oil Price	GRDP per Capita	GRDP
Catchment and City Area	Number of Employees	1	0.34	0.075	0.007
	Oil Price		1	0.791	0.85
	GRDP per capita			1	0.93
	GRDP				1
Metropolitan Area	Number of Employees	1	0.43	0.42	0.15
	Oil Price		1	0.92	0.84
	GRDP per capita			1	0.96
	GRDP				1

The results of applying the DID model across various scenarios are presented in Table 8. In this study, HAC (Heteroskedasticity and Autocorrelation Consistent) standard errors were used to eliminate the bias in the results caused by heteroscedasticity and autocorrelation. The analysis results showed that the estimated values of the average treatment effect (ATE, β_1) ranged from -2.81 to -3.69 and were statistically significant at the 5% level. This indicates that the daily mileage of both the treatment group and the control group decreased after the implementation of the vehicle restriction policy.

Table 8. The comparison results of the DID model estimation.

Scenario	ATE (β_1)				ATET (β_3)			
	Estimate	S.E.	t	*p*-Value	Estimate	S.E.	t	*p*-Value
S1	−3.69	0.79	−4.69	<0.000	−1.23	0.93	−1.33	0.19
S2	−3.44	0.46	−7.45	<0.000	−1.08	0.53	−2.05	0.04
S3	−3.71	0.039	−9.48	<0.000	−1.44	0.46	−3.12	0.001
S4	−2.93	0.74	−3.95	<0.000	0.76	0.76	−1.00	0.32
S5	−2.81	0.45	−6.18	<0.000	0.69	0.47	1.49	0.14
S6	−3.04	0.38	−8.06	<0.000	0.54	0.38	1.40	0.16

However, the estimated values of the average treatment effect on the treated group (ATET, β_3) were negative in scenarios 1 to 3, which compare restricted HEVs with unrestricted HEVs, and positive in scenarios 4 to 6, which compare restricted HEVs with non-HEVs. The significant negative ATETs suggest that, after the implementation of the vehicle driving restriction, the reduction in the mileage of the HEVs subject to enforcement was greater than that of the HEVs not subject to enforcement at the 5% level. Conversely, the positive ATETs indicate that the reduction in the mileage of the HEVs subject to enforcement was less than that of the non-HEVs following the implementation of the vehicle driving restriction.

Most importantly, it is worth highlighting that the significant ATET values of −1.08 and −1.44 in scenarios 1 and 2 suggest that the impact of the vehicle driving restriction is quite modest. The results indicate that the daily mileage of restricted HEVs declined by only 1.08 to 1.44 km subsequent to the implementation of the vehicle driving restriction. Moreover, the reduction in daily mileage for restricted HEVs does not exceed that of non-HEVs, suggesting that the favorable effectiveness of the vehicle restriction policy is uncertain.

This is further confirmed in Figure 5. The treatment group is represented by the purple solid line, while the control group is represented by the gray solid line. The red dotted line represents the counterfactual daily mileage for the treatment group if driving restrictions had not been implemented. When the reduction in daily mileage for the treatment group exceeds that of the counterfactual condition, the purple solid line appears below the red dotted line. This trend is especially evident in the comparisons with control group A, as shown in scenarios (S1), (S2), and (S3) in Figure 5.

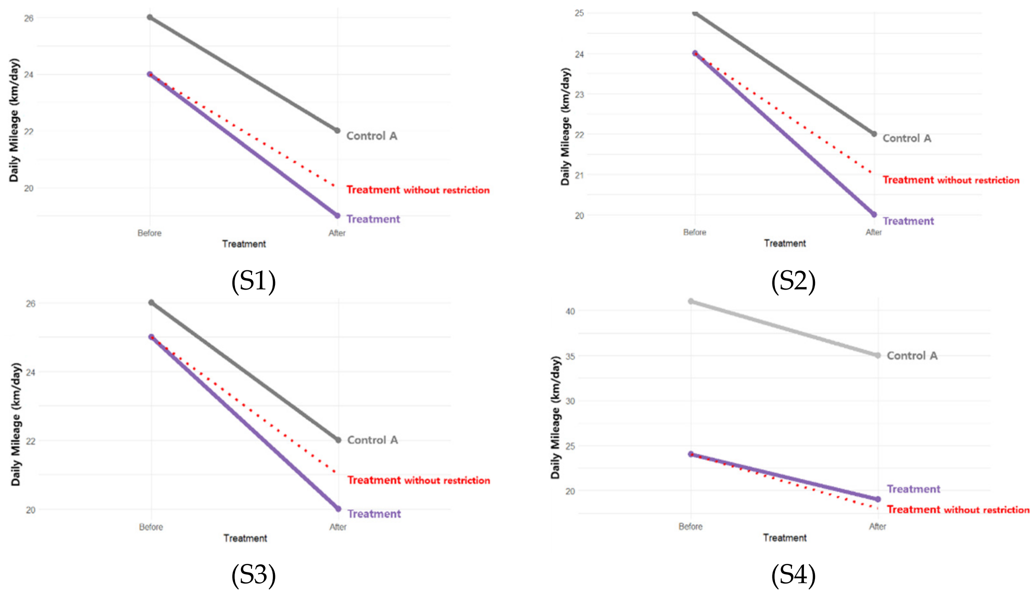

Figure 5. *Cont.*

Figure 5. The changes in average daily mileage before and after the implementation of vehicle restrictions for the treatment group (represented by the purple solid line) and the control group (represented by the gray solid line) are shown by scenario. If the vehicle restrictions were not implemented, the daily mileage of the treatment group would adjust to match the change in daily mileage of the control group, represented by the dotted red line. (S1) Scenario 1; (S2) Scenario 2; (S3) Scenario 3; (S4) Scenario 4; (S5) Scenario 5; (S6) Scenario 6.

5. Conclusions and Discussion

A range of policies is currently being implemented to reduce vehicle mileage with the objective of mitigating environmental pollution and traffic congestion. As part of this effort, vehicle restriction policies have been introduced, including a specific policy targeting HEVs in South Korea. Nonetheless, the effectiveness of these vehicle restriction policies has been called into question, as daily mileage is showing a downward trend in South Korea. While many studies have reviewed the effects of vehicle restriction policies, most have derived their results indirectly by using air quality data, which can be influenced not only by the implementation of the restriction policies but also by factors such as temperature and wind. This study investigated the direct impact of the vehicle driving restrictions by comparing vehicle mileage before and after the policy's implementation.

This study examined the effect of HEV driving restrictions on vehicle mileage, with a focus on Busan, the first region in South Korea outside the capital area to implement these restrictions. We divided the areas associated with the HEVs policy into three categories, referred to as the areas of influence (AOIs), for the purpose of regional control of the policy's effects. The treatment group was designated as HEVs subject to vehicle restrictions, while the control group consisted of non-restricted HEVs (control group A) and non-restricted non-HEVs (control group B). The models were constructed by categorizing the scope of analysis based on two control groups and three AOIs, resulting in a total of six analysis scenarios. The results indicate that the average daily mileage of the treatment group decreased more than that of control group A (non-restricted HEVs) following the implementation of the restriction. However, the decrease in the average daily mileage of the treatment group was not greater than that of the non-HEVs. This implies that the effectiveness of vehicle restrictions in reducing mileage is minimal, contrary to common expectations.

Although this study was unable to explicitly analyze each HEV's trajectory due to a lack of data, the effectiveness of the vehicle restriction policy is considered minimal for the following reasons: 1. The enforcement cameras can only monitor specific parts of the cities, leaving gaps in coverage on roads both within the city and on routes leading out of the city. 2. The HEVs may avoid enforcement by choosing to drive during non-enforcement hours (9 PM to 6 AM) or on weekends. As a result, there are potential loopholes for HEVs to avoid restrictions by taking alternative routes and/or driving during non-enforcement times, which may contribute to only a minimal decrease in their mileage.

Since South Korea is planning to expand the scope of HEVs subject to driving restrictions, policymakers should consider not only the transition to eco-friendly vehicles but also the reduction of driving mileage through the restriction policy. To enhance the effectiveness of vehicle restriction policies in reducing mileage, the following are suggested: first, addition or modification of enforcement camera locations; second, implementation of stronger enforcement measures by extending enforcement hours; third, development of supplementary policies that facilitate the transition from HEVs to zero-emission vehicles; and fourth, establishment of comprehensive surveillance systems to ensure compliance with the expansion of vehicle restriction areas. The selection of enforcement locations can utilize GPS data, such as Digital Tacho Graph (DTG) data, which is proposed for future research. Given that South Korea intends to expand the categories of vehicles subject to operation restrictions, it is imperative that the enhancement of trajectory-based monitoring for these restricted vehicles be thoroughly evaluated in advance.

Although this study represents the first analysis of the impact of HEV driving restrictions on mileage in South Korea, it has several research limitations. Since the HEVs restriction was implemented in 2022–2023, and only a single comparison between the periods before and after implementation was performed, assessing the cumulative effects is therefore challenging. Future research should compare additional years as vehicle restrictions are implemented multiple times, allowing for a more thorough examination of cumulative effects. Additionally, COVID-19 may have influenced vehicle mileage. However, since the vehicle number and year were designated as panel indices, the impact is expected to be negligible. Another limitation is that the analysis was conducted in only one region. More metropolitan areas where high-emission vehicle restrictions are applied should be examined. Future research will explore trends in regions where the vehicle restriction has not been implemented. In addition, future studies need to analyze the mileage of new vehicles acquired to replace HEVs following the implementation of the vehicle driving restriction policy.

Nevertheless, this study is significant as it directly examined the effectiveness of vehicle restriction policies through mileage data, confirmed that the effects are minimal, and suggested ways to enhance the effectiveness of the policies.

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