

# Seasonal Variations in Travel Demand Elasticity in Response to Gasoline Price Changes

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**How to cite this paper:** Thompson, E. A., Lu, P., Zhao, G. C., Cirillo, C., Akoto, E. T., & Yang, X. Y. (2025). Seasonal Variations in Travel Demand Elasticity in Response to Gasoline Price Changes. *Open Journal of Business and Management*, 13, 1418-1434. <https://doi.org/10.4236/ojbm.2025.132074>

**Received:** February 4, 2025

**Accepted:** March 21, 2025

**Published:** March 24, 2025

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## Abstract

Seasonal variations in travel demand elasticity provide essential information for formulating efficient transportation regulations and ensuring sustainable urban growth. However, existing studies ignore the temporal dynamics of travel behavior, notably how fuel price sensitivity varies by season in metropolitan settings. This gap constrains policymakers' capacity to formulate solutions that effectively tackle variable travel patterns and their consequences for congestion and emissions. This study addresses the influence of gasoline prices and control variables such as population density, road counts, and seasonal variables on vehicle miles traveled (VMT) in Washington, D.C., metropolitan geographical area through an integrated econometric framework. The findings reveal that elevated gasoline prices considerably decrease VMT, illustrating the efficacy of fuel taxes in regulating travel demand. Snowy winters reduce VMT, whereas more population density lowers it, stressing the need for compact, multimodal urban strategies and designs. Incorporating temporal variability into elasticity modeling, this study addresses a substantial lacuna in the literature and offers policymakers and urban planners actionable strategies. The results underscore the worldwide significance of seasonally adaptable policies, like dynamic fuel taxes, improved public transportation, and strategic infrastructure development, to mitigate congestion, decrease emissions, and attain sustainable mobility throughout the year.

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## Keywords

Vehicle Miles Traveled, Gasoline, Seasonal Variations, Travel Demand Elasticity, And Sustainable Urban Transportation

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## 1. Introduction

The economic and environmental impacts of transportation demand in urban areas have drawn considerable attention from policymakers and researchers, especially as cities confront rising fuel prices and environmental challenges. Among the factors influencing sustainable development, reducing travel demand, particularly vehicle miles travel (VMT), is considered a key strategy for sustainability. (Wang & Chen, 2014). Hence, gasoline prices directly impact vehicle travel's frequency and distance. Studies on price elasticity within the transportation industry highlight that consumer responses to changes in fuel prices are complex and depend on numerous variables, including geographic location, income levels, and travel needs (Almansour, 2022; Fridstrøm & Østli, 2021). Seasonal effect particularly affects gasoline prices in countries with diverse seasonal changes (Donna, 2021; Goetzke & Vance, 2021; Wardman, 2022).

Therefore, understanding the seasonal variability in travel demand elasticity is crucial for transportation planners aiming to anticipate and manage changes in urban travel behavior. Seasonal factors such as temperature, school schedules, and holiday periods influence travel patterns, often fluctuating demand elasticity (Martínez et al., 2020; McKercher et al., 2024). For instance, summer months may see an increase in discretionary travel as more people undertake vacations. In contrast, winter months might yield lower elasticity due to adverse weather conditions and reduced leisure travel. These seasonal variations not only affect the volume of VMT but also influence the sensitivity of drivers to fuel price changes, which has implications for infrastructure planning and fuel tax policy (Afanasyev et al., 2021). Given the growing policy emphasis on sustainable urban mobility and reducing greenhouse gas emissions, the need for a nuanced understanding of these dynamics has become more urgent. However, a notable gap remains in understanding how seasonal variations affect travel demand elasticity in response to gasoline price changes, particularly within metropolitan settings.

Accordingly, this study addresses the research question: how does the elasticity of travel demand in response to gasoline price changes vary across different seasons? Thus, this study addresses this question by analyzing the seasonal variations in gasoline price elasticity within the Washington, D.C., metropolitan area. It aims to make both empirical and theoretical contributions to the field of transportation economics. Empirically, analyzing seasonal travel demand elasticity contributes to a detailed understanding of short-term versus long-term price responses in urban travel. At the same time, theoretically, it expands existing elasticity models to account for seasonal variables. This research ultimately seeks to inform urban transportation policies, particularly fuel taxes and public transportation invest-

ments, by providing evidence on the temporal aspects of gasoline price sensitivity in metropolitan areas, which has been underexplored in elasticity literature. The findings have implications for urban resilience strategies, especially as cities adapt to the dual pressures of fluctuating fuel costs and the need for sustainable transportation solutions.

The remainder of the study is organized as follows: Section 2 reviews the literature on the relations between gasoline prices and VMT while considering seasonal variations, and Section 3 explains the methodology. Section 4 presents results and discussions, and the research implications and Section 5 has the conclusions, study limitations, and future research directions.

## 2. Literature Review

The elasticity of travel demand regarding gasoline price changes is crucial in transportation economics, offering insights into consumer behavior and policy implications. Typically, gasoline price elasticity indicates the change in travel demand corresponding to changes in fuel prices, with studies observing low elasticity in the short term as travelers have limited alternatives (Donna, 2021; Goetzke & Vance, 2021; Wardman, 2022). However, as the temporal dimension extends, demand often becomes more elastic as individuals have time to adapt by shifting to alternative modes of transport, consolidating trips, or altering work arrangements (Hensher et al., 2024; Wu et al., 2023). Seasonal variabilities add further complexity as gasoline price responsiveness changes across different times of the year, influenced by environmental, seasonal travel demands, and fuel price volatility.

Studies on the seasonal variability of travel demand elasticity have revealed that seasonal climate changes significantly affect the elasticity of gasoline demand. Gourley (2021) observed that cold weather often yields lower price elasticity as consumers have limited alternatives for travel in adverse weather conditions. This is more apparent in areas where cycling or walking is impractical in winter. However, warmer seasons bring higher elasticity as consumers engage in more discretionary travel such as vacations, making gasoline demand more sensitive to price changes (Goyal et al., 2021; Vickerman, 2024). These seasonal variations stipulate the essence of context in assessing fuel price sensitivity, as regions with distinct seasonal changes may have different responsiveness to fuel price changes.

Moreover, the elasticity of gasoline demand also varies seasonally based on geographic and socioeconomic variabilities, shaping the types of travel alternatives available to different demographics. For instance, densely populated urban areas, such as Beijing and Texas, with public transit alternatives show high elasticity in warmer seasons when alternative modes like biking and transit are accessible (Chun et al., 2024; Wu & Liao, 2020). However, suburban and rural areas, where car dependence is high, demonstrate more consistent demand regardless of season (Molamphy, 2024). Additionally, to an asymmetrical response, consumers adjust more to fuel price increases than decreases, particularly in peak travel seasons like summer (Kamyabi & Chidmi, 2022; Kumar et al., 2020). This asymmetry indicates that the budgetary impact of gasoline prices on consumers is intensified during

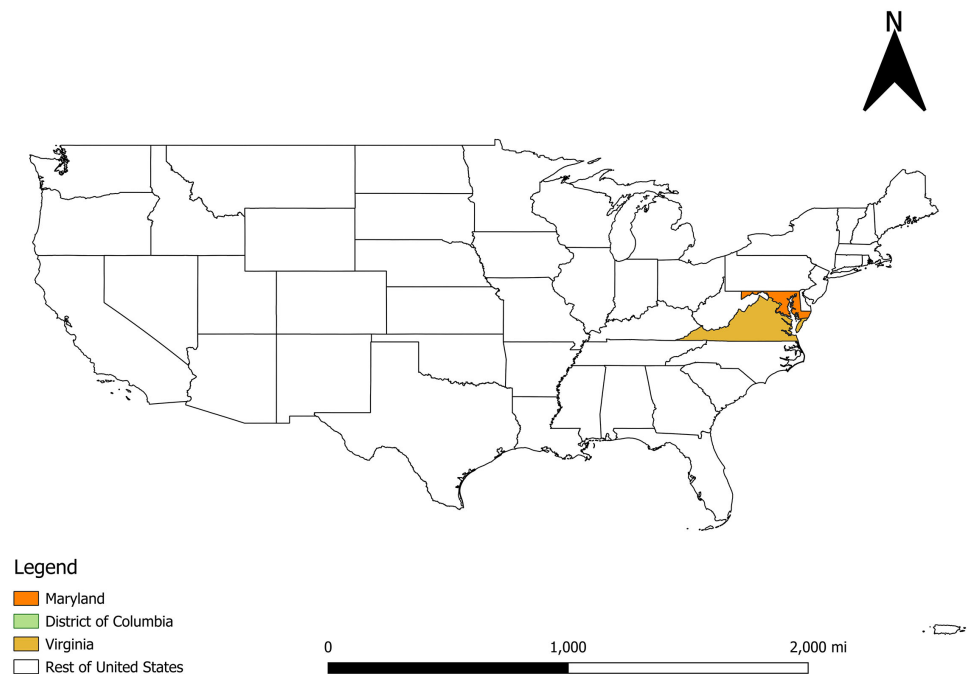
high-travel seasons, with direct effects on their travel demand elasticity.

Despite significant findings on the relationship between gasoline prices and travel demand, there are no studies on how this elasticity shifts across seasons in urban settings with granular geographic and socioeconomic data. This study aims to fill that gap by analyzing seasonal variations in travel demand elasticity in the Washington, D.C., metropolitan area, focusing on how fuel price responsiveness differs across census tracts and seasons. By integrating a seasonal framework into elasticity modeling, this study contributes to a refined understanding of travel demand patterns, enabling transportation policymakers to craft more effective, seasonally adjusted interventions for congestion and environmental impact mitigation.

### 3. Methodology

#### 3.1. Spatial Context and Data Description

This study investigates the seasonal variations in travel demand elasticity in response to gasoline price fluctuations in the Washington, D.C., metropolitan area. As displayed in **Figure 1**, this area is also known as DMV for the District of Columbia, Maryland, and Virginia. These areas provide a particularly interesting case for studying seasonal elasticity patterns due to their distinct seasonal weather and diverse socioeconomic demographics. The regions experience marked seasonal weather variations, with hot, humid summers and cold winters, which can significantly affect travel behaviors. Additionally, these areas comprise a wide range of census tracts with varying income levels, population densities, and access to public transportation options, each of which can affect the degree of dependence on personal vehicles and the responsiveness to gasoline price changes (Mattson, 2020).



**Figure 1.** Geographical area of the study.

The dataset utilized in this study is mobile device location data (MDLD), which includes weekly gasoline prices and average VMT at the census tract level, providing a detailed and high-resolution view of travel demand patterns across the region. The analysis spans a time frame from May 2021 to October 2022, capturing sufficient seasonal cycles to explore potential differences in elasticity across seasons. The dataset has many elements; for this study's purpose, only the necessary elements are presented in **Table 1**. Also, avg\_drivemileage is described as VMT. The data types for the data are not applicable (N/A) because they are used to group the other data into seasons. Leveraging a high-resolution dataset comprising weekly gasoline prices and VMT at the census tract level, this study can capture a more granular view of how travel demand elasticity varies across different community types and seasonal periods in these areas.

**Table 1.** Data labels of the study's dataset.

Label	Label Description	Data Type
Data	The date of observation in YYYY-MM-DD format	N/A
avg_drivemileage	Average mileage for driving trips in the region.	Dependent variable
avg_gasprice	Average gasoline price in the region (measured in currency per gallon).	Independent variable
median_HHincome	Median household income in the region (measured in USD).	Control Variable
STFIPS	State FIPS code uniquely identifies the state.	Control Variable
RoadCount	Number of roads in the region.	Control Variable
pop_dens	Population density (number of people per square unit area).	Control Variable

### 3.2. Gasoline Price Data

**Figure 2** depicts the trends in average gasoline prices in the dataset where STFIPS 11 represents the District of Columbia, STFIPS 24 as Maryland, and STFIPS 51 as Virginia, based on data from 115,091 gas stations. The prices stipulate a steady increase during 2021, followed by a sharp surge in early 2022, peaking mid-year and then declining. The District of Columbia consistently recorded the highest prices, while Virginia maintained the lowest. This may reflect the differences in taxation, supply chain logistics, and regional policies. The initial price increase aligns with post-pandemic economic recovery and rising demand, while the mid-2022 spike corresponds to geopolitical disruptions and crude oil market volatility. The subsequent decline after mid-2022 reflects stabilizing global markets and reduced seasonal demand, with Virginia experiencing the most significant recovery. These trends depict the interconnected yet regionally distinct dynamics of gasoline pricing, providing critical information into transportation costs and regional policy implications.

### 3.3. Vehicle Miles Traveled Data

The dataset illustrates the trends in average VMT for the three regions, as illustrated in **Figure 3**. Maryland consistently recorded the highest VMT, followed by

Virginia and the District of Columbia, reflecting differences in urban density, transportation infrastructure, and commuting patterns. VMT peaked during the summer of 2021, coinciding with post-pandemic travel recovery, and decreased in late 2021, which may be due to seasonal factors. In 2022, VMT increased again, peaking in spring before sharply declining by October, particularly in Maryland, likely influenced by rising fuel costs (Figure 2) and changing travel behaviors. These trends reveal the relationship between travel demand, fuel prices, and regional characteristics.

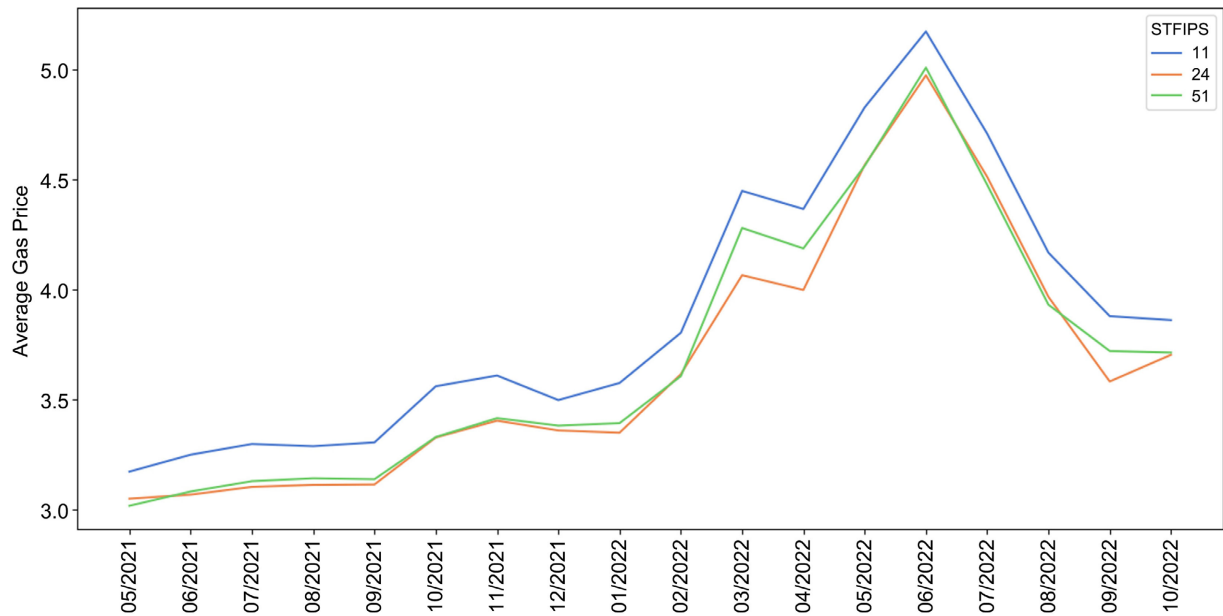


Figure 2. Trend of gasoline prices in the dataset.

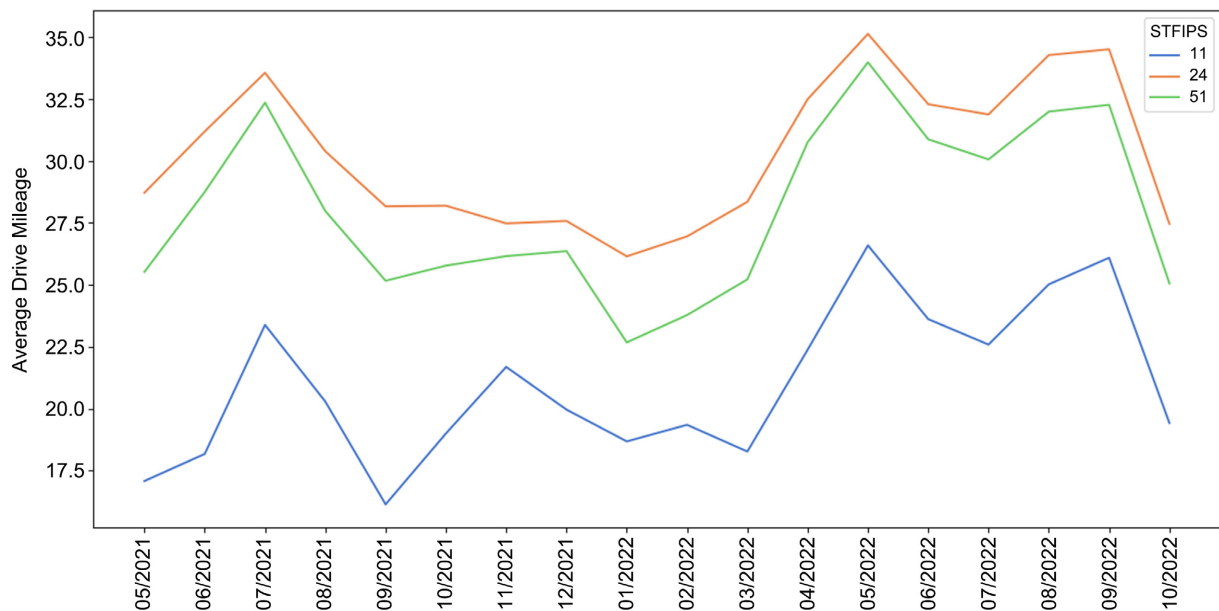


Figure 3. Trends in Vehicle Miles Traveled (VMT) dataset.

### 3.4. Data Collection and Preprocessing

Raw MDLD utilized in this paper are collected from a consistent national mobility data panel produced by the University of Maryland's NextGen National Household Travel Survey (NHTS) team in collaboration with multiple data vendors. The data are averaged for each census tract within the Washington, D.C., metropolitan area, allowing us to examine variations in fuel prices over time and across different locations within the metropolitan area. **Table 2** summarizes the original MDLD in log form for further analysis. Before summarizing the data, rigorous data cleaning was performed to address inconsistencies or gaps, including interpolating missing weekly data points to maintain continuity. The dataset was then divided into seasonal categories (spring, summer, fall, and winter) to facilitate comparative analysis across different times of the year. Python software was used to perform the logarithm of the data to estimate the econometric elasticity model. Simultaneously, VMT data were aggregated weekly, measuring travel demand at the same census tract level.

**Table 2.** Summary of the mobile device location data in log.

Year	STFIPS	avg_gasprice	median_HHincome	pop_dens	RoadCount	avg_drivemileage	Season
2021	DC	3.17354	101475.327	2592498.048	17470	17.07828	Spring
2021	DC	3.28024	101415.9478	6751443.133	45558	20.58583	Summer
2021	DC	3.49812	101266.5568	6767558.706	45644	18.94397	Fall
2021	DC	3.49883	101096.8797	2040299.948	13922	19.96226	Winter
2021	Maryland	3.05047	106446.6081	2865892.395	302848	28.72115	Spring
2021	Maryland	3.09681	106623.2042	7396692.107	781464	31.61737	Summer
2021	Maryland	3.28654	106675.7447	7364979.931	787092	27.96775	Fall
2021	Maryland	3.36066	106960.338	2248391.653	242450	27.57908	Winter
2021	Virginia	3.01821	130090.0051	3152977.008	154548	25.52393	Spring
2021	Virginia	3.12064	130230.971	8227343.86	403936	29.56148	Summer
2021	Virginia	3.29835	130582.693	8237981.927	404479	25.70627	Fall
2021	Virginia	3.38259	130547.0506	2537691.255	124660	26.36218	Winter
2022	DC	4.57142	100947.2226	6667440.309	45194	22.75792	Spring
2022	DC	4.68856	100227.571	6742311.837	45138	23.64754	Summer
2022	DC	3.87052	101621.5015	4617161.283	30950	22.42039	Fall
2022	DC	3.67758	100965.2939	4558073.71	31175	18.97476	Winter
2022	Maryland	4.23832	106689.4115	7351443.275	788806	32.23537	Spring
2022	Maryland	4.48775	106516.5467	7361366.106	788373	32.74579	Summer
2022	Maryland	3.64911	106329.1963	5003433.87	495787	30.68843	Fall
2022	Maryland	3.46837	106774.8917	5076949.524	546256	26.50792	Winter
2022	Virginia	4.32669	127359.1081	7368790.066	345380	29.66892	Spring
2022	Virginia	4.45068	119898.4347	6138658.941	263014	30.956	Summer
2022	Virginia	3.71784	130591.8303	5680159.492	278569	28.26512	Fall
2022	Virginia	3.48866	130609.0038	5703092.067	279985	23.16594	Winter

### 3.5. Econometric Model for Elasticity Estimation

To estimate the elasticity of travel demand in response to gasoline price changes, we employed a log-linear regression model where weekly VMT serves as the dependent variable, and gasoline prices are the primary independent variable. Specifically, we used the following model:

$$\ln(\text{VMT}_{it}) = \alpha + \beta \ln(\text{Gas Price}_{it}) + \gamma Z_{it} + \epsilon_{it}$$

where  $i$  represents each census tract,  $t$  represents each week,  $\beta$  captures the gasoline price elasticity of travel demand, and  $Z_{it}$  denotes a vector of control variables, including seasonal indicators and socio-demographic factors (e.g., average income, population density). The error term  $\epsilon_{it}$  captures unobserved factors that may influence VMT. By applying this model, we estimated the short-term elasticity of travel demand concerning gasoline price changes for each season, allowing us to capture any seasonal variation in elasticity.

To ensure the robustness of our findings, we conducted several checks. A test of the model was conducted, and the results were analyzed using ANOVA. This helps to understand how well the model fits the data. Second, four tests for the normal distribution of residuum were performed to assess whether the data followed a normal distribution. These tests include Kolmogorov-Smirnov, Kolmogorov-Smirnov (Lilliefors Corr.), Shapiro-Wilk, and Anderson-Darling. The results of these tests are presented in **Figure 4**. This robust methodological approach provides confidence in the reliability and generalizability of our findings.

## 4. Results and Discussion

The econometric analysis of travel demand elasticity highlights key relationships between the dependent variable, VMT, and various predictors, including gasoline prices, population density, and road infrastructure. In **Table 3**, the constant term 2.02, representing the baseline VMT when all predictors are set to zero, was not statistically significant ( $p = .193$ ), suggesting that the model's intercept does not provide a meaningful standalone interpretation. This result does not undermine the model's utility; instead, it highlights real-world travel behaviors, where VMTs are driven by dynamic predictors like gas prices, population density, and road infrastructure. Thus, the significance of these predictors validates the model's accuracy and capacity to inform practical, data-driven transportation policies and planning strategies. Hence, the coefficient for gasoline price (Gasoline Price) was statistically significant ( $p < .001$ ), indicating that a 1% increase in gas price corresponds to a .44-unit increase in VMT. This result underscores the influence of fuel costs on travel behavior, aligning with prior studies in transportation economics (Garcia-Sierra et al., 2015; Yang & Timmermans, 2013) (**Table 3**).

Among the control variables, population density demonstrated a significant negative effect on VMT, with a coefficient of  $-.18$  ( $p < .001$ ). This suggests that higher population density is associated with reduced vehicular travel, likely due to greater access to alternative transportation modes or reduced need for personal vehicle use in denser areas like Shanghai and New York (Boulangue et al., 2017; Saghapour et

al., 2016). Road infrastructure, measured by the road count, exhibited a positive and highly significant relationship with VMT, with a coefficient of .14 ( $p < .001$ ), indicating that increased road availability encourages more significant vehicle usage (Yu & Zhao, 2021). However, household income did not exhibit a statistically significant effect ( $p = .218$ ), suggesting that income variations within the study region do not meaningfully influence travel demand. This challenges the traditional assumption that income levels heavily dictate travel demand (Magriço et al., 2023). This could result from the narrow income range in the study region, widespread access to alternative transportation options, and fixed travel needs.

Seasonal variations further revealed significant patterns in travel demand elasticity. Compared with the reference season (summer), average VMT decreased by .1 units in spring ( $p = .018$ ), .07 units in fall ( $p = .043$ ), and .17 units in winter ( $p = .001$ ). These findings align with a study that stipulates there is reduced travel activity during colder months, particularly in winter, when adverse weather conditions likely discourage driving (Gössling et al., 2023). Seasonal impacts may also reflect shifts in discretionary travel, as summer often coincides with vacations and leisure trips, while colder seasons see fewer opportunities for outdoor activities. Additionally, winter's pronounced reduction in VMT could be attributed to an ice-shedding risk, reduced daylight hours, and a general decline in non-essential travel (Hudde, 2023; Matejicka & Georgakis, 2022). In contrast, spring and fall show more moderate decreases, likely due to transitional weather conditions that permit limited discretionary travel. These seasonal patterns have practical implications for transportation planning as they suggest that policy interventions, such as promoting public transit or implementing congestion pricing, should account for the temporal variability in travel demand to maximize year-round efficiency and effectiveness.

To ensure the robustness of the models, several tests were conducted. The ANOVA test for the regression model in Table 3 yielded an F-statistic of 34.14 ( $p < .001$ ), confirming the model's statistical significance and ability to explain travel demand variations. Additionally, Table 4 shows the results of four statistical tests to assess whether the data follows a normal distribution. A high p-value (greater than .05) suggests that the data do not significantly deviate from normality. All four tests indicate that the data do not deviate significantly from the normal distribution. This means that different statistical methods that assume the normality of the data could be used. Therefore, a closer look at the quantile-quantile (Q-Q) plot is always a good idea. The Q-Q plot in Figure 4 evaluates the normality of the residuals by comparing their quantiles to those of a theoretical normal distribution. Most points closely align with the diagonal reference line, indicating that the residuals are approximately normally distributed. While slight deviations appear at the tails, these are minor and fall within the confidence bands, suggesting the normality assumption holds sufficiently for valid model inference. Hence, these results are accurate and emphasize the critical influence of gasoline prices, road count, and seasonal factors on vehicular travel in the Washington, D.C., metropolitan area.

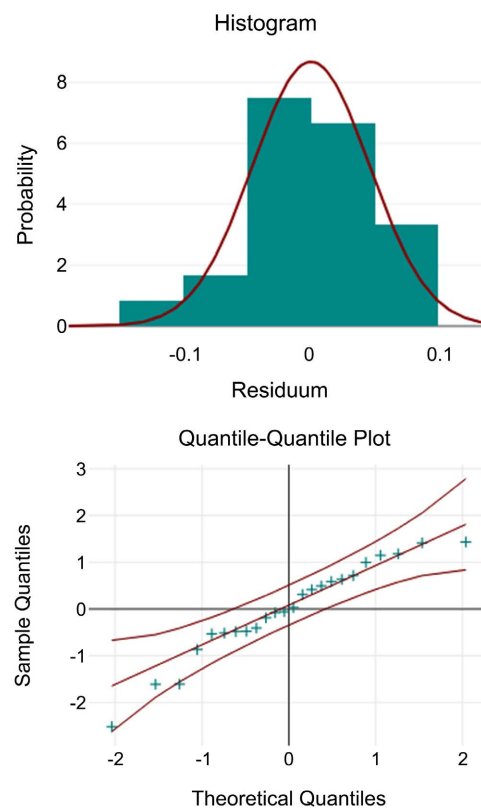
**Table 3.** Econometric elasticity estimation.

Model	Coefficients	Standard error	t	<i>p</i>	Lower bound	Upper bound
Summer						
Constant	2.02	1.49	1.36	.193	-1.13	5.18
Gasoline Price	.44	.1	4.48	<.001	.23	.65
Household Income	.16	.13	1.28	.218	-.1	.43
Population Density	-.18	.04	-4.34	<.001	-.27	-.09
Road Count	.14	.01	12.66	<.001	.12	.17
Season Spring	-.1	.04	-2.63	.018	-.17	-.02
Season Fall	-.07	.03	-2.2	.043	-.14	0
Season Winter	-.17	.04	-3.96	.001	-.26	-.08
Spring						
Constant	1.92	1.49	1.3	.214	-1.23	5.08
Gasoline Price	.44	.1	4.48	<.001	.23	.65
Household Income	.16	.13	1.28	.218	-.1	.43
Population Density	-.18	.04	-4.34	<.001	-.27	-.09
Road Count	.14	.01	12.66	<.001	.12	.17
Season Spring	.1	.04	2.63	.018	.02	.17
Season Fall	.02	.04	.66	.519	-.05	.1
Season Winter	-.07	.03	-2.07	.055	-.14	0
Fall						
Constant	1.95	1.49	1.31	.209	-1.21	5.1
Gasoline Price	.44	.1	4.48	<.001	.23	.65
Household Income	.16	.13	1.28	.218	-.1	.43
Population Density	-.18	.04	-4.34	<.001	-.27	-.09
Road Count	.14	.01	12.66	<.001	.12	.17
Season Spring	-.02	.04	-.66	.519	-.1	.05
Season Fall	.07	.03	2.2	.043	0	.14
Season Winter	-.09	.04	-2.37	.031	-.18	-.01
Winter						
Constant	1.85	1.48	1.25	.23	-1.29	5
Gasoline Price	.44	.1	4.48	<.001	.23	.65
Household Income	.16	.13	1.28	.218	-.1	.43
Population Density	-.18	.04	-4.34	<.001	-.27	-.09
Road Count	.14	.01	12.66	<.001	.12	.17
Season Spring	.07	.03	2.07	.055	0	.14
Season Fall	.17	.04	3.96	.001	.08	.26
Season Winter	.09	.04	2.37	.031	.01	.18

95% confidence interval for coefficients and ANOVA test of F-statistic of 34.14 ( $p < .001$ ).

**Table 4.** Tests for normal distribution of residuum.

Statistics	Value	<i>p</i> -values
Kolmogorov-Smirnov	.13	.765
Kolmogorov-Smirnov (Lilliefors Corr.)	.13	.364
Shapiro-Wilk	.95	.292
Anderson-Darling	.35	.463

**Figure 4.** Normal distribution of residuum.

## 5. Research Implications

### 5.1. Practical Implications

The results of this study provide crucial insights for urban transportation policy-makers and managers seeking to enhance the efficiency and sustainability of travel demand management strategies. First, the strong, statistically significant relationship between gasoline prices and the VMT highlights the potential of fuel pricing as a policy lever. A 1% increase in gas price reduced VMT by .44 units, underlining its efficacy in curbing vehicle use and encouraging shifts to alternative transportation modes (Thompson et al., 2022). This directly impacts implementing or adjusting fuel tax policies such as increasing carbon taxes, especially in metropolitan areas like Washington, D.C., where reducing congestion and greenhouse gas emissions is a priority. Additionally, strategies for fuel pricing can include subsi-

dizing alternative fuels and providing tax rebates for households that reduce their annual fuel consumption. Hence, policymakers can discourage excessive vehicle use and support more urban sustainability goals.

Second, the negative association between population density and VMT further underscores the importance of investing in dense, multimodal urban environments. In denser areas, the availability of alternative transportation options such as public transit, biking, and walking reduces dependency on personal vehicles. Urban planners can use this insight to prioritize transit-oriented development and expand high-density zones to lower VMT levels. Simultaneously, the positive relationship between road count and VMT implies that expanding road infrastructure can inadvertently incentivize higher vehicle usage, reinforcing the need for integrated transportation planning. Policies promoting public transit systems or disincentivizing vehicle use, such as congestion pricing or dedicated bus rapid transit lanes, could mitigate the unintended effects of road expansion on vehicular travel. Third, the seasonal variations in VMT, particularly the significant decline during winter, point to the necessity of adapting policies to temporal travel patterns. For instance, enhancing winter-specific public transit options, such as seasonal fare discounts, heated bus shelters, real-time transit tracking applications, snow-resistant transit vehicles, or road safety measures, such as enhancement of roads and timely snow and ice removal, could maintain mobility while discouraging private vehicle use during adverse weather conditions.

## 5.2. Theoretical Implications

This study makes three notable theoretical contributions to the field of transportation economics by advancing the understanding of seasonal travel demand elasticity and its determinants. First, compared with prior studies focusing on static or aggregate elasticity models (Comi et al., 2021; Hensher et al., 2023), this research integrates seasonal variations into the elasticity framework, offering a nuanced perspective on temporal dynamics in travel behavior. The statistically significant reductions in VMT during spring, fall, and winter relative to summer in **Table 3** stipulate the relationship between discretionary travel and external factors such as weather and daylight availability. These findings contribute to the ongoing studies on incorporating seasonal and contextual variables into elasticity models, enhancing their predictive power and relevance to real-world scenarios (Hasnine et al., 2021; Shantz et al., 2022).

Moreover, this study challenges traditional assumptions about the influence of household income on travel demand. Contrary to established theories that posit income as a significant determinant of VMT, this study found no statistically significant effect of household income on travel behavior within the Washington, D.C., metropolitan area. This suggests that income may play a secondary role in regions with robust public transit infrastructure and relatively homogenous socioeconomic conditions, prompting researchers to revisit and refine existing elasticity models. Additionally, the significant impact of road count on VMT rein-

forces the theoretical argument that infrastructure supply shapes travel behavior, a critical insight for future work on the induced demand trend in urban environments (Thompson et al., 2024).

Third, the robust methodological framework employed in this study, including econometric modeling and normality testing, demonstrates the importance of incorporating rigorous statistical validation in elasticity research. The results, validated through ANOVA testing and Q-Q plot analysis, provide a strong empirical foundation for future studies exploring the intersection of fuel pricing, seasonal variability, and travel demand. Thus, this study establishes a precedent for exploring how temporal and contextual elements influence travel behavior, contributing to the global conversation on sustainable transportation planning and policy design.

## 6. Conclusion and Future Directions

This study comprehensively analyzes the seasonal variations in travel demand elasticity in response to gasoline price changes, focusing on the Washington, D.C., metropolitan area. Integrating seasonal, socioeconomic, and infrastructure-related variables into an econometric framework offers a nuanced understanding of the dynamic factors influencing VMT. The results illustrate the critical roles of gasoline prices, population density, road infrastructure, and seasonal effects in shaping travel demand patterns. Specifically, the significant impact of gasoline prices highlights the potential of fuel pricing policies as an effective lever to manage vehicular travel and promote sustainable urban mobility. Incorporating seasonal variations, such as the notable reduction in VMT during winter months, adds an essential temporal dimension to existing elasticity models, allowing policymakers to tailor interventions to specific times of the year.

The results possess significant practical and theoretical ramifications. The study emphasizes the effectiveness of gasoline taxes, road infrastructure design, and transit-oriented development to alleviate congestion and minimize environmental effects. The study indicates that elevated gasoline prices significantly decrease VMT, underscoring the efficacy of dynamic or targeted fuel taxation in urban settings. Likewise, the inverse correlation between population density and VMT underscores the necessity of creating compact, multimodal urban environments. This study theoretically enhances transportation research by elucidating seasonal impacts on travel demand, addressing a notable deficiency in the elasticity literature. The study illustrates that travel habits are influenced not only by fuel prices and infrastructure availability but also by temporal factors, including weather and discretionary travel options, which were frequently neglected in earlier models.

## 7. Limitations and Future Directions

This study possesses certain limitations that provide opportunities for future directions. First, the study is confined to the Washington, D.C., metropolitan area,

perhaps limiting the applicability of the findings to other places with distinct socioeconomic or geographic attributes. Second, the study depends on aggregate data, which may obscure individual-level variances in travel behavior and fuel price sensitivity influenced by demographic or lifestyle factors. Third, although the study encompasses seasonal variations in travel demand, it fails to consider extreme weather phenomena, such as intense storms or heat waves, which may also impact travel patterns.

Therefore, future research should address these limitations by expanding the geographic scope to include metropolitan areas with differing climates, levels of urbanization, and socioeconomic contexts. Comparative analyses across regions can provide deeper insights into the generalizability of seasonal travel demand elasticity. Additionally, incorporating disaggregated data at the household or individual level could offer a more granular understanding of how demographic factors, such as age, gender, or occupation, interact with fuel price sensitivity and seasonal effects.

Future studies could examine the impact of alternative fuel adoption and electric vehicle penetration on seasonal travel demand elasticity. This would provide critical insights into how transitioning to sustainable transportation modes affects traditional elasticity models. Moreover, integrating extreme weather conditions into the analysis would enhance the robustness of the findings, particularly as climate change increases the frequency and intensity of such events. Also, exploring dynamic models that account for lagged responses to fuel price changes could yield a more accurate understanding of long-term travel demand adjustments, complementing the short-term elasticity insights provided by this study.

## Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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