The Nonlinear Relationship Between Urban Density and Per Capita Gasoline Consumption: Panel Evidence from 80 Iranian Counties Classified as Small, Medium, and Large

Original article

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Abstract

In oil-producing economies with fuel subsidies, the low cost of private vehicle use may weaken the conventional relationship between urban density and gasoline consumption. This study examines the relationship between urban population density and per capita gasoline consumption using a balanced panel of 80 Iranian counties, comprising 800 county-year observations over the 2013–2022 period. To this end, administrative data on recorded gasoline sales were combined with demographic, economic, and transportation data, and linear and nonlinear models were estimated using county and year fixed effects and county-clustered standard errors. Heterogeneity in this relationship across small, medium-sized, and large counties was also tested by interacting county-size categories with the linear and quadratic terms of population density. The linear model indicates that, after controlling for other factors, a 1% increase in population density is associated, on average, with an approximately 0.56% reduction in per capita gasoline consumption. However, the nonlinear model shows that the strength of this relationship is not constant and becomes more negative as density increases. Within the common density range, the estimated elasticities change from −0.832 to −0.949 for small counties, from −0.383 to −0.734 for medium-sized counties, and from −0.824 to −0.913 for large counties; all estimates are statistically significant. Overall, the findings suggest that compact development policies should be tailored to each county's initial density level and spatial structure and coordinated with access to employment, services, and public transportation.

Keywords: County Size, Fixed effects, Iran, Panel Data, Per Capita Gasoline Consumption, Urban Population Density

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1.Introduction

Rapid urbanization and the spatial expansion of cities, particularly in developing countries, have become major drivers of increasing energy demand in the transportation sector. In addition to demographic characteristics and travel demand, urban gasoline consumption may be influenced by urban spatial structure, population density, access to public transportation, and fuel prices (Bento et al., 2005; Ewing & Cervero, 2001). Urban sprawl is generally associated with increasing distances between residential areas, employment centers, and urban services, potentially increasing household dependence on private vehicles and, consequently, fuel consumption. From this perspective, examining the relationship between urban population density and transportation energy consumption is essential for designing sustainable urban policies and mitigating environmental impacts.

Iran represents an important case for examining this relationship due to its distinctive combination of rapid urbanization, physical urban expansion, and long-standing energy subsidy policies. According to the results of the Population and Housing Censuses, Iran's urban population increased from approximately 26.8 million in 1986 to 59.1 million in 2016 (Statistical Center of Iran, 1986, 2016). This trend has been accompanied by the expansion of many cities and an increasing need for daily travel. Under these circumstances, low gasoline prices and widespread access to fossil fuels may alter some of the conventional mechanisms through which urban population density affects energy consumption, as the low cost of private vehicle use may weaken household incentives to reduce car travel or adopt alternative transportation modes.

Much of the existing empirical evidence, discussed in greater detail in the following sections, indicates that urban sprawl increases household transportation fuel consumption by increasing dependence on private vehicles, reducing the efficiency of public transportation, and extending travel distances. However, findings from some recent studies in developing countries suggest that this relationship may vary depending on institutional structures, patterns of investment in public transportation, and the economic characteristics of individual countries. Therefore, the relationship among population density, urban sprawl, and transportation energy consumption cannot be expected to be uniform across countries. This highlights the need for context-specific studies, particularly in countries characterized by low energy prices and subsidy policies.

In Iran, the economy and the process of urban development have been influenced by oil revenues. At the same time, the persistence of energy subsidies and the maintenance of low gasoline prices have been accompanied by increased gasoline demand and consumption, affecting the volume of car travel and the use of public transportation by making private vehicle use more attractive (Houri Jafari & Baratimalayeri, 2008; Mirzamohammadi et al., 2012; Pilehvar, 2021). Although the primary objective of energy subsidies has been to improve social welfare and reduce household expenditures, keeping the marginal cost of vehicle use low may weaken incentives to reduce driving, choose fuel-efficient vehicles, or use alternative transportation modes (He & Kim, 2024). Furthermore, transportation policies generally differ across cities and countries because travel patterns vary according to their distinct social, political, economic, and cultural contexts (Heidarpour & Jaberi, 2021). Consequently, Iran provides a suitable setting for investigating whether increasing urban population density can still lead to reductions in per capita gasoline consumption under subsidized gasoline pricing.

Focusing on the relationship between urban population density and gasoline consumption in Iranian cities, this study seeks to determine the extent to which the conventional mechanism of reduced fuel consumption in densely populated cities operates within Iran's institutional and pricing context. To this end, the study employs observed administrative data on gasoline consumption at the county level, obtained from fuel stations affiliated with the National Iranian Oil Products Distribution Company, alongside demographic, economic, and infrastructure data. Using panel data covering 80 Iranian cities over a ten-year period makes it possible to control for time-invariant differences across cities and common time trends. Furthermore, classifying these cities into three broad population-based categories—large, medium-sized, and small—provides a more detailed understanding of the relationship between urban population density and gasoline consumption. The main contribution of this study lies in examining this relationship in an oil-

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dependent economy characterized by extensive fuel subsidies, employing panel data and directly observed gasoline consumption data rather than proxy or intermediate indicators, and providing evidence to support integrated policymaking in energy management and urban planning. The findings may offer valuable insights for Iran and other developing countries with low energy prices in designing policies aimed at reducing fuel consumption, controlling urban sprawl, and promoting sustainable urban transportation.

2.Literature Review

2.1.Urban Density and Transportation Energy Consumption

The relationship between urban form and transportation demand is a central topic in urban economics and transportation planning. The spatial distribution of population and activities, the location of employment and services, the structure of road networks, and accessibility to public transportation can influence trip length, travel mode choice, car ownership, and ultimately transportation energy consumption, as discussed in greater detail below. An empirical study has shown that built-environment characteristics affect trip length, travel mode choice, and vehicle miles traveled to a greater extent than they affect the number of trips (Ewing & Cervero, 2001). Another study examining 114 urban areas in the United States found that population concentration, jobs–housing balance, urban form, road network density, and public transportation provision are associated with travel mode choice and annual household vehicle miles traveled (Bento et al., 2005). These findings suggest that population density should be examined alongside other spatial, economic, and transportation-related characteristics.

One of the earliest studies to directly examine the relationship between urban density and transportation energy consumption reported a negative association between urban population density and per capita gasoline consumption using cross-sectional data from 32 cities worldwide. According to this finding, denser cities have lower per capita gasoline consumption due to shorter distances between activities and more favorable conditions for public transportation and non-car modes of travel (Newman & Kenworthy, 1989). However, another study reanalyzed the same dataset using a multivariate analytical technique known as Co-Plot and demonstrated that overall urban density alone cannot explain differences in energy consumption across cities. From their perspective, the relationship between density and energy consumption should be analyzed in conjunction with transportation systems, economic characteristics, and other dimensions of urban form (Mindali et al., 2004).

Studies based on household-level data also generally support a negative relationship between population density and car use. One such study, using data from California households, found that lower residential density is associated with greater annual vehicle miles traveled and higher household fuel consumption (Brownstone & Golob, 2009). Another study examining households residing in urban areas of the United States found that households in higher-density areas consume less gasoline on average, even after controlling for income, gasoline prices, household characteristics, public transportation provision, freeway network density, and congestion. The findings of this study also indicated that greater freeway network density and congestion are associated with higher gasoline consumption, whereas public transportation accessibility and provision are associated with lower consumption (Su, 2011). Furthermore, another study showed that, although the magnitude and direction of these relationships may vary depending on the level of analysis and sample characteristics, population density has generally been associated with lower levels of transportation energy consumption and pollutant emissions in both urban- and national-level studies (Liddle, 2014).

An important framework for explaining this relationship was examined in a study that decomposed per capita fuel consumption into three components: car ownership, annual distance traveled per vehicle, and fuel consumption per kilometer. The results of the study, which covered 84 urban areas across different countries, showed that population density can reduce fuel consumption by lowering the need for car ownership, shortening travel distances, and increasing opportunities to use public transportation (Karathodorou et al., 2010). However, higher density may reduce fuel efficiency per kilometer through increased stop-and-go driving caused by traffic congestion. Therefore, the

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mechanisms associated with increasing density do not all operate in the same direction, and its overall effect depends on the combined changes in car ownership, travel distance, travel mode choice, and traffic conditions.

Evidence from developing countries also suggests that the relationship between urban form and energy consumption does not necessarily follow a universal pattern. One study in this field found that urban expansion in China did not necessarily lead to an increase in household transportation energy consumption. The authors attributed this finding to the simultaneous development of public transportation and its role in reducing dependence on private cars (Yang et al., 2024). This finding indicates that the energy implications of urban form depend on the institutional context, the level of public transportation development, and patterns of car ownership and use. Therefore, findings from cities in developed countries cannot be generalized to developing countries without accounting for these differences.

Empirical evidence from Iran in this field is more limited. However, one study examined the relationship between urban form indicators and travel behavior using data from households residing in the traffic analysis zones of Qazvin. The findings indicated that population density was negatively associated with distance traveled by private car, whereas greater distance from the city center was associated with longer household travel distances (Ghorbani & Salaripour, 2022). This study provides evidence on the relationship between population density and car use in an Iranian city; however, it does not directly measure gasoline consumption and is limited to a single city and a single point in time.

Overall, previous studies indicate that higher density is generally associated with lower gasoline consumption, shorter travel distances, and reduced automobile dependence. However, the magnitude and even the direction of this relationship may be influenced by urban spatial structure, transportation networks, congestion, vehicle ownership, and the economic and institutional context. Most existing studies are either cross-sectional or focus on household-level data and individual cities. In Iran, empirical evidence on the relationship between population density and actual gasoline consumption across multiple counties over time remains limited. Furthermore, the reviewed studies have not directly examined differences in this relationship among small, medium-sized, and large counties within a unified modeling framework.

2.2.The Role of Economic and Transportation Factors

Gasoline consumption is not solely determined by urban density or urban form; economic, demographic, and transportation-related variables also play important roles in explaining it. Fuel price is a conventional variable in gasoline demand models. The findings of Su (2011) support a negative price elasticity of gasoline demand, while Liddle (2014) also indicates that energy prices and income levels are commonly considered factors in studies of transportation energy consumption. In Iran, the maintenance of low gasoline prices and the large-scale production of vehicles using conventional technology have been identified as factors contributing to the growth in gasoline demand (Jafari & Baratimalayeri, 2008). However, because the official gasoline price is identical across all Iranian counties within each year, this variable primarily represents part of the institutional context and common annual shocks in the present study, and its independent effect cannot be identified in the main model that includes year fixed effects.

Household income can influence gasoline consumption through increased vehicle ownership, trip frequency, and travel distances. The findings of Brownstone and Golob (2009) and Su (2011) indicate that automobile use and consumption are associated with household income. Vehicle ownership is both a direct determinant of gasoline consumption capacity and a potential mechanism through which urban form influences fuel consumption. Studies by Bento et al. (2005) and Karathodorou et al. (2010) demonstrate that urban spatial characteristics can affect the number of vehicles available to households and the extent of their use.

Access to public transportation can also reduce dependence on private vehicles. Bento et al. (2005) showed that an increase in rail transit supply is associated with a lower probability of commuting by car. In Su (2011), public transportation accessibility and supply were associated with lower household gasoline consumption, while Karathodorou et al. (2010) also demonstrated that an extensive public transportation network can reduce the need for vehicle ownership and use. Therefore, differences across counties in income, vehicle ownership, employment, and

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access to urban rail transit should be considered when examining the relationship between density and gasoline consumption.

2.3.Theoretical Framework and Positioning of the Present Study

Urban expansion and urban sprawl are multidimensional concepts that cannot be measured using a single indicator alone. In a comprehensive study examining the concept of urban sprawl, Galster et al. (2001) defined it in terms of dimensions such as density, continuity, concentration, clustering, centrality, nuclearity (monocentricity or polycentricity), mixed uses, and proximity. Therefore, population density represents only one dimension of urban form and should not be considered a complete measure of horizontal urban expansion or urban sprawl. Nevertheless, because population density can be measured and compared across geographical units and over time, it remains one of the commonly used indicators in studies of urban form, travel behavior, and energy consumption (Brownstone & Golob, 2009).

Based on the reviewed literature, population density can influence per capita gasoline consumption through several mechanisms. Higher density generally reduces distances between residential areas, employment locations, and services; increases the feasibility of more efficient public transportation provision; and creates more favorable conditions for walking and other non-automobile transportation modes. These changes can reduce vehicle ownership, travel distances, and gasoline consumption. Conversely, higher density may increase fuel consumption per kilometer by intensifying traffic congestion and stop-and-go driving. Therefore, although higher density is initially expected to be associated with lower per capita gasoline consumption, the presence of competing mechanisms implies that the magnitude and direction of this relationship are not necessarily constant across all density levels. This argument justifies examining both linear and nonlinear specifications of the relationship.

Furthermore, the relationship between population density and gasoline consumption is not expected to be uniform across all counties. Small, medium-sized, and large counties may differ in terms of the concentration of employment and services, travel distances, congestion levels, car ownership, and access to public transportation. Evidence suggests that the effect of population density depends on economic, spatial, and transportation-related characteristics (Mindali et al., 2004; Karathodorou et al., 2010; Su, 2011; Yang et al., 2024). However, existing studies have not directly examined this heterogeneity by comparing the density–gasoline consumption curves across three population-size groups: small, medium-sized, and large cities. Therefore, the population-based classification employed in the present study serves as an analytical tool for testing heterogeneity in this relationship.

Accordingly, the present study examines two main expectations. First, the relationship between urban population density and per capita gasoline consumption may be nonlinear, such that the elasticity of gasoline consumption with respect to density is not constant across different density levels. Second, the shape and slope of this relationship may differ among small, medium-sized, and large counties. To investigate these expectations, panel data covering 80 Iranian counties over the period 2013–2022 are employed. The relationship between urban population density and per capita gasoline consumption is estimated after controlling for county fixed effects, common annual shocks, and economic and transportation-related variables that vary across counties and years. Subsequently, interactions between county size groups and the linear and quadratic terms of density are used to assess differences in the curves across the three groups and the marginal effects of density within their common range.

The contribution of the present study lies in three areas. First, unlike a substantial proportion of previous Iranian studies that have examined travel behavior or distances traveled, this study uses recorded gasoline consumption data. Second, the panel structure of the data allows for controlling time-invariant, unobserved county characteristics and common annual shocks. Third, by estimating a nonlinear model with group interaction terms, heterogeneity in the relationship between density and per capita gasoline consumption across small, medium-sized, and large counties is formally tested.

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3.Data and Methodology

3.1.Data and Variables

This study employs panel data covering 80 Iranian cities over the period 2013–2022. Gasoline consumption data were obtained from the official statistics of the National Iranian Oil Products Distribution Company (NIOPDC), while demographic, economic, and infrastructure data were collected from relevant official sources.

Within the geographical organization of the National Iranian Oil Products Distribution Company, Iran is divided into "distribution regions" and "distribution districts." The boundaries of distribution regions generally correspond to provincial administrative divisions, while those of distribution districts generally align with county boundaries. However, this correspondence is not exact or one-to-one in all cases. To harmonize the geographical levels of the variables, maps of distribution regions and districts were compared with official maps of Iran's provincial and county administrative divisions. Only distribution districts whose boundaries exactly matched those of a single county were selected for the sample. The second inclusion criterion was the availability of a complete and consistent set of data on gasoline consumption, population density, and the control variables introduced below throughout the period 2013–2022. Finally, due to subsidized gasoline prices and the potential for fuel smuggling in border areas, border counties were excluded from the study. Ultimately, of the 483 counties, 80 met all three criteria of geographical correspondence, data sufficiency, and exclusion of border counties and were included in the final sample. Accordingly, the unit of analysis is the county–year, and the final dataset constitutes a balanced panel of 80 counties observed over 10 years, yielding a total of 800 county–year observations.

The dependent variable is the natural logarithm of annual per capita gasoline consumption in each county. Raw gasoline consumption data were available at the fuel station level, disaggregated by distribution regions and districts. To convert these records into usable county-level data, the gasoline consumption recorded at all fuel stations located within each distribution district was first aggregated for each year. As explained in the sample selection section, only distribution districts whose geographical boundaries exactly corresponded to those of a single county were included in the study. Therefore, aggregating fuel station records at the distribution district level enabled the conversion of gasoline consumption data into county–year observations and their geographical alignment with population, density, and other study variables. Urban population data were obtained from the 2011 and 2016 Population and Housing Censuses conducted by the Statistical Center of Iran (SCI). Population values for the years between the two censuses were estimated using linear interpolation, while population values for the years after 2016 were estimated through linear extrapolation of the trend observed between the two censuses. Thus, the population used in this study represents the total population of all urban settlements within each county and excludes the county's rural population. This population measure was used consistently to calculate both per capita gasoline consumption and urban population density.

The main independent variable is the natural logarithm of urban population density. Since each county may contain several cities, the urban populations of all cities located within each county were first aggregated. Similarly, the areas of the physical urban footprints of all cities within the same county were summed. County-level urban population density was then calculated by dividing the total urban population by the combined area of the physical urban footprints of the cities within that county. Information on the cities located within each county was obtained from the statistical quarterly reports published by the Statistical Center of Iran. The boundaries of the physical urban footprints were delineated using historical satellite imagery, and their areas were calculated using the area measurement tool in Google Earth. A comparative examination of historical images indicated that the outer boundaries of the physical urban footprints of the sampled cities did not change appreciably during the study period, with most new construction occurring on vacant land and open spaces within existing urban boundaries. This growth pattern is referred to in the literature as *infill development*, which involves new construction on vacant sites within the previously developed urban area, without discontinuous development or substantial outward expansion of the urban boundary (Ugalde-Monzalvo, 2024). Accordingly, the area of each city's physical urban footprint was assumed to remain constant throughout the

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study period, and annual changes in density were primarily driven by changes in urban population. Ultimately, the main independent variable was constructed by dividing the total urban population of all cities within a county by their combined physical urban footprint area.

In addition to population density, a set of spatially and temporally varying control variables was included in the main model, comprising the natural logarithm of average real household income, the percentage of car ownership, the employment rate, and the presence of urban rail transit. Data on household income, car ownership, and employment rates were extracted from the Household Income and Expenditure Survey conducted by the Statistical Center of Iran and aggregated at the county level. The raw survey data were collected through random sampling, and the required indicators were calculated and employed based on the reported raw observations. The urban rail transit variable was defined as a dummy variable, taking a value of one for counties with an operational urban rail transit system in a given year and zero otherwise. The variables representing real gasoline prices and national real gross domestic product (GDP) vary only over time. Therefore, their independent coefficients cannot be identified in the main specification with year fixed effects, and these two variables were included only in sensitivity estimations that exclude year fixed effects.

Table 1- Variable Definitions and Data Sources

Variable	Definition	Data Source
log_GasCap	Natural logarithm of per capita gasoline consumption	National Iranian Oil Products Distribution Company (NIOPDC)
log_Density	Natural logarithm of urban population density	Statistical Center of Iran (SCI) and satellite imagery
GasCPI	Real gasoline price	Official gasoline prices and Consumer Price Index (CPI)
logIncCPI	Natural logarithm of average real household income	Household Income and Expenditure Survey (HIES) and CPI
Car	Percentage of households owning a private car	Household Income and Expenditure Survey (HIES)
Emp	Urban employment rate	Household Income and Expenditure Survey (HIES)
Age	Average household age	Household Income and Expenditure Survey (HIES)
Metro	Dummy variable indicating the presence of urban rail transit	Official municipal and public transportation data
agg_gdp	National real gross domestic product (GDP)	Central Bank of the Islamic Republic of Iran (CBI)

Since gasoline consumption data are reported based on recorded sales at fuel stations located within each distribution district, this variable is interpreted as an indicator of recorded gasoline consumption/sales at the city/county level. Therefore, to minimize geographical mismatches among variables, all demographic, economic, and infrastructure data were aggregated, to the extent possible, at the same geographical level.

Finally, to examine heterogeneity in the relationship between population density and per capita gasoline consumption according to city size, the sampled cities were classified into three groups based on their urban population in 2016, as reported in the Population and Housing Census. Using population data from a fixed reference year ensures that cities' membership in population-based groups remains unchanged throughout the panel period. Accordingly, cities with populations below 100,000 were classified as small cities, those with populations between 100,000 and 500,000 as medium-sized cities, and those with populations exceeding 500,000 as large cities. This classification was based on observed gaps in the population distribution of the sampled cities, resulting in 38, 35, and 7 cities in the respective categories. The 80 sampled counties comprise Abadan, Abadeh, Abarkuh, Ardestan, Ardakan, Azna, Estahban, Asadabad, Isfahan, Eqlid, Aligudarz, Omidiyeh, Andimeshk, Ahvaz, Izeh, Bafq, Borazjan, Bardaskan, Borujen,

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Bostanabad, Bahar, Behbahan, Bushehr, Bukan, Buin, Bijar, Pol-e Dokhtar, Takestan, Tabriz, Taft, Takab, Tehran, Tuyserkan, Khorrambid, Khorramshahr, Khaf, Darab, Damghan, Dorud, Dez, Dehdasht, Dehgolan, Divandarreh, Ramhormoz, Sarab, Saqqez, Semirom, Sonqor, Sanandaj, Sirjan, Shabestar, Shahr-e Babak, Shahreza, Shahrekord, Shush, Shushtar, Shiraz, Fariman, Fasa, Firuzabad, Qorveh, Karaj, Kangavar, Gachsaran, Lord, Langan, Mobarak, Maragheh, Marand, Masjed Soleyman, Mashhad, Malayer, Malekan, Mahabad, Miandoab, Mianeh, Naqadeh, Nahavand, Nehbandan, and Yasuj.

It should be noted that this grouping constitutes an operational classification specific to the sample of the present study, intended to facilitate a more disaggregated examination of the results, and does not necessarily correspond to the official classification of Iranian cities.

Table 2- Classification of Counties in the Study Sample

Number of Observations	Number of Counties	Population Criterion	Group
380	38	Fewer than 100,000 inhabitants	Small
350	35	100,000–500,000 inhabitants	Medium-sized
70	7	More than 500,000 inhabitants	Large

3.2.Descriptive Statistics

Before estimating the model, descriptive statistics for the main variables were calculated. The results presented in Table 3 indicate that the sampled cities differ considerably in terms of per capita gasoline consumption, population density, household income, and vehicle ownership. The descriptive statistics for the full sample show that the mean values of the natural logarithm of per capita gasoline consumption and the natural logarithm of population density are 6.168 and 8.570, respectively. The relatively wide ranges of these two variables, along with the variation in income, vehicle ownership, and employment, indicate substantial descriptive differences across the sampled cities. These differences justify the use of panel data and city fixed effects to account for time-invariant, unobserved characteristics of each city. Furthermore, temporal variations in real gasoline prices and macroeconomic conditions highlight the need to control for common annual shocks and trends.

Table 3- Descriptive Statistics for the Full Sample

Variable	Number of Observations	Mean	Std. Dev.	Minimum	Maximum
log_GasCap	800	6.168086	0.353285	5.226908	7.803906
log_Density	800	8.569884	0.454222	7.185387	10.08372
sqlogDensity	800	73.64898	7.740345	51.62979	101.6815
GasCPI	800	9.542526	2.731216	4.686036	14.77105
logIncCPI	800	14.0276	0.312041	13.00825	16.27094
Car	800	45.05195	15.22746	0	91.66666
Emp	800	37.20443	5.410966	23.52941	70
Metro	800	0.06	0.237635	0	1
agg_gdp	800	13.6568	0.795067	12.611	15.154

The disaggregated descriptive statistics presented in Table 4 show that the mean logarithm of population density increases from 8.405 in small cities to 8.642 in medium-sized cities and 9.102 in large cities. In contrast, the mean logarithm of per capita gasoline consumption is 6.312 in small cities, decreasing to 6.045 and 6.005 in medium-sized and large cities, respectively. Thus, at the descriptive level, groups with higher average population density exhibit lower average per capita gasoline consumption. However, this simple comparison does not control for other urban characteristics, time-invariant differences across cities, or temporal changes and should not be interpreted as evidence of a causal relationship.

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Table 4- Descriptive Statistics by City Size Group

متغیر	City Size Group	Observations	Mean	Std. Dev.	Min.	Max.
log_GasCap	Small	380	6.3115	0.387	5.551	7.804
log_Density		380	8.4052	0.468	7.185	9.245
logIncCPI		380	13.975	0.334	13.01	16.27
Car		380	45.312	16.57	0	91.66
Emp		380	38.299	6.072	23.94	70
Metro		380	0	0	0	0
log_GasCap	Medium-sized	350	6.045	0.268	5.226	6.749
log_Density		350	8.642	0.309	7.296	9.442
logIncCPI		350	14.05	0.292	13.24	15.23
Car		350	43.51	14.44	5	81.818
Emp		350	35.78	4.625	23.53	50
Metro		350	0	0	0	0
log_GasCap	Large	70	6.005	0.205	5.514	6.431
log_Density		70	9.102	0.484	8.313	10.083
logIncCPI		70	14.200	0.177	13.891	14.624
Car		70	51.313	8.327	10.970	65.994
Emp		70	38.365	3.175	30.991	46.235
Metro		70	0.6857	0.467	0	1

The other variables also exhibit differences across groups. The mean logarithm of real household income and the average level of car ownership are higher in large cities. Furthermore, the urban rail transit variable has a mean of zero in the small- and medium-sized city groups, whereas its mean is 0.686 in the large-city group. This difference reflects the concentration of urban rail transit systems in the large cities included in the sample. However, descriptive statistics alone cannot determine whether the relationship between density and gasoline consumption differs across the three groups after controlling for other factors. This issue is examined in the following sections using fixed-effects models, interactions between city size and density, and joint tests of coefficients.

3.3.Econometric Model

The empirical strategy of this study is structured in three stages. In the first stage, the average relationship between population density and per capita gasoline consumption is estimated for the full sample using a linear two-way fixed-effects model. In the second stage, a quadratic term of the natural logarithm of population density is added to the model to examine whether the slope of the relationship varies across different density levels. In the third stage, to test whether the shape and slope of this relationship differ across small, medium-sized, and large cities, the linear and quadratic density terms are interacted with city-size group indicators. Differences among the three groups' curves are evaluated using joint Wald tests, while differences in their slopes are assessed by calculating and comparing marginal effects over the common range of population density. Thus, each of the following models directly addresses one of the study's research objectives.

Empirical studies of gasoline consumption and transportation energy use generally model fuel consumption as a function of urban spatial characteristics, economic and demographic variables, vehicle ownership, and transportation infrastructure. Building on this framework, the present study examines the relationship between urban population density and per capita gasoline consumption using panel data from Iranian cities. Given that the dataset consists of repeated observations for 80 cities over the period 2013–2022, the baseline model is estimated using two-way fixed effects to control for time-invariant differences across cities and common annual shocks. The baseline model is specified as follows:

$$\log_GasCap_{it} = \alpha_0 + \alpha_1 \log_Density_{it} + \alpha_2 z_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (1)$$

where (i) denotes the city and (t) denotes the year. The variable $\log_GasCap_{it}$ represents the natural logarithm of per capita gasoline consumption, $\log_Density_{it}$ denotes the natural logarithm of urban population density, and z_{it} is a vector of economic, demographic, and infrastructure-related control variables that vary across cities and years. Furthermore, μ_i represents city fixed effects, and γ_t represents year fixed effects, while ε_{it} denotes the random error term of the model.

City fixed effects control for unobserved, time-invariant characteristics, such as geographical location, historical patterns of urban development, the persistent structure of the urban network, and automobile-use culture. Year fixed effects account for common annual shocks and trends, including policy changes, general inflation, macroeconomic conditions, and developments in the fuel market affecting all cities. The main coefficient of interest is α_1, which represents the elasticity of per capita gasoline consumption with respect to urban population density after controlling for these factors. To examine the potential nonlinearity in the relationship between population density and gasoline consumption, the following extended model is also estimated:

$$\log_GasCap_{it} = \alpha_0 + \alpha_1 \log_Density_{it} + \alpha_2 (\log_Density_{it})^2 + \alpha_3 z_{it} + \mu_i + \gamma_t + \varepsilon_{it} \quad (2)$$

In this model, the statistical significance and signs of the coefficients α_1 and α_2 indicate whether the relationship between population density and gasoline consumption is linear or exhibits a nonlinear pattern. If α_1 is positive and α_2 is negative, the relationship takes an inverted U-shaped form. The validity of this pattern is evaluated in the results section by examining the turning point, determining whether it falls within the observed range of population density, and calculating marginal slopes at different density levels.

In the main model, variables that vary only over time and exhibit no spatial variation across cities, such as real gasoline prices and national real gross domestic product (GDP), cannot be separately identified in the presence of year fixed effects, as their effects are absorbed by the year fixed effects. Therefore, these variables are examined in alternative specifications or robustness checks that exclude year fixed effects. All models are estimated using heteroskedasticity-robust standard errors clustered at the city level to account for within-city correlation and potential heteroskedasticity.

Furthermore, to examine heterogeneity in the relationship between population density and per capita gasoline consumption according to city size, the baseline nonlinear model was extended by interacting city-size group indicators with the linear and quadratic terms of the natural logarithm of population density. Small cities were designated as the reference group. Since city-size group membership remains constant throughout the study period, the main effects of the group indicators are absorbed by the city fixed effects. However, interactions between group indicators and population density can be identified because population density varies over time. It should be noted that using a pooled model with interaction terms, while retaining all sample observations, allows for formal statistical testing of differences among the group-specific curves.

$$\log_GasCap_{it} = \beta_i + \lambda_t + \alpha_1 \log_Density_{it} + \alpha_2 (\log_Density_{it})^2 + \delta_1(Medium_i \times \log_Density_{it}) + \delta_2(Large_i \times \log_Density_{it}) + \theta_1(Medium_i \times \log_Density^2_{it}) + \theta_2(Large_i \times \log_Density^2_{it}) + \gamma z_{it} + \varepsilon_{it} \quad (3)$$

where $\log_Density_{it}$ denotes the natural logarithm of population density in city (i) in year (t), $Medium_i$ is a dummy variable for medium-sized cities, and $Large_i$ is a dummy variable for large cities. Small cities serve as the reference group; therefore, both $Medium_i$ and $Large_i$ take a value of zero for small cities. Furthermore, Z_{it} is a vector of control variables comprising the natural logarithm of real household income, car ownership, the employment rate, and the presence of urban rail transit. The terms β_i and λ_t represent city fixed effects and year fixed effects, respectively. Due to the inclusion of the quadratic term and interaction terms for different city-size groups, the estimated coefficients cannot be directly interpreted as the effects of population density. Therefore, the marginal effect of density for each group is obtained by differentiating the model equation with respect to the natural logarithm of population density, as follows:

$$ME_S(D) = \alpha_1 + 2\alpha_2 D \quad (4)$$

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$$ME_M(D) = (\alpha_1 + \delta_1) + 2(\alpha_2 + \theta_1)\, D \quad (5)$$

$$ME_L(D) = (\alpha_1 + \delta_2) + 2(\alpha_2 + \theta_2)\, D \quad (6)$$

Since both the dependent variable and population density enter the model in natural logarithmic form, the marginal effects derived above are interpreted as elasticities. In other words, each marginal effect represents the estimated percentage change in per capita gasoline consumption associated with a 1% change in population density at a given density level.

The range of the natural logarithm of population density is not identical across the three groups. The common observed range for all three groups extends approximately from 8.314 to 9.245. To avoid comparisons based on extrapolation, marginal effects were calculated at log-density values of 8.4, 8.6, 8.8, and 9.0. These values fall within the observed range of all three groups and allow for comparisons of group-specific elasticities at identical density levels.

4.Analysis and Results

4.1.Baseline Regression Results

Table 5 presents the estimation results for the baseline linear and nonlinear models examining the relationship between urban population density and per capita gasoline consumption. Columns (1) and (2) examine the linear relationship between the natural logarithm of population density and the natural logarithm of per capita gasoline consumption. In columns (3) and (4), the squared term of the natural logarithm of population density is added to investigate potential nonlinearity in this relationship. All specifications include city fixed effects. Columns (2) and (4) additionally control for year fixed effects and are therefore considered the main specifications of the study. In columns (1) and (3), year fixed effects are excluded, and national-level variables, including the real gasoline price, its one-year lag, and national real gross domestic product (GDP), are incorporated into the models.

Table 5- Baseline Regression Results for Equations (1) and (2)

Variables	(1) log_GasCap	(2) log_GasCap	(3) log_GasCap	(4) log_GasCap
log_Density	-0.262*	-0.557***	2.965***	2.742***
	(0.140)	*(0.203)*	*(0.652)*	*(0.806)*
GasCPI	-0.00332***		-0.00341***	
	(0.00120)		*(0.00117)*	
L.GasCPI	-0.0306***		-0.0304***	
	(0.00114)		*(0.00112)*	
logIncCPI	-0.0704***	-0.0220	-0.0708***	-0.0214
	(0.0244)	*(0.0186)*	*(0.0238)*	*(0.0184)*
Car	0.000661*	-0.000257	0.000702**	-0.000221
	(0.000377)	*(0.000322)*	*(0.000339)*	*(0.000314)*
Emp	-0.000518	-0.00117	-0.000267	-0.000975
	(0.000942)	*(0.000847)*	*(0.000903)*	*(0.000825)*
Metro	-0.124*	-0.131***	-0.0373	-0.0480*
	(0.0677)	*(0.0458)*	*(0.0345)*	*(0.0258)*
agg_gdp	0.0564***		0.0581***	
	(0.00940)		*(0.00799)*	
sqlogDensity			-0.191***	-0.193***
			(0.0405)	*(0.0445)*
City FE	Yes	Yes	Yes	Yes
Year FE	*No*	*Yes*	*No*	*Yes*
Observations	720	800	720	800
Within R-squared	0.598	0.675	0.616	0.697

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Notes: The dependent variable in all columns is the natural logarithm of per capita gasoline consumption (log_GasCap). Standard errors clustered at the city level are reported in parentheses. *p<0.10, **p<0.05, ***p<0.01

The results of the linear model in column (2) show that the coefficient on the natural logarithm of population density is −0.557 and is statistically significant at the 1% level. Since both the dependent variable and population density enter the model in logarithmic form, this coefficient is interpreted as an elasticity. Therefore, after controlling for time-invariant differences across cities, common annual shocks, and other variables included in the model, a 1% increase in urban population density is associated, on average, with an approximately 0.56% decrease in per capita gasoline consumption.

However, the results of the main nonlinear model in column (4) indicate that the relationship between population density and gasoline consumption cannot be adequately explained by a constant elasticity across all density levels. The coefficient on the linear density term is positive, while the coefficient on its quadratic term is negative, and both are statistically significant. The negative sign of the quadratic term indicates that the slope of the relationship becomes more negative as density increases. Due to the inclusion of the quadratic term, the coefficients of 2.742 and −0.193 should not be interpreted individually as the effect of density. Instead, the economic interpretation of the model should be based on the derivative of the estimated equation and the corresponding marginal effects.

In columns (1) and (3), the coefficients on the real gasoline price and its one-year lag are negative and statistically significant at the 1% level. These signs are consistent with the economic logic of fuel demand. However, these variables vary only over time and exhibit no variation across cities. Therefore, they cannot be separately identified in models that include year fixed effects, as their effects are absorbed by the year dummy variables. For this reason, columns (2) and (4) serve as the main specifications for analyzing the relationship between population density and per capita gasoline consumption, while columns (1) and (3) are interpreted as alternative specifications.

4.2.Heterogeneity in the Relationship Between Population Density and Gasoline Consumption by City Size

To examine whether the relationship between population density and per capita gasoline consumption is uniform across small, medium-sized, and large cities, the cities were classified according to their population in the 2016 Population and Housing Census. Cities with populations below 100,000 were classified as small, those with populations between 100,000 and 500,000 as medium-sized, and those with populations exceeding 500,000 as large. Accordingly, the sample comprises 38 small cities, 35 medium-sized cities, and 7 large cities, corresponding to 380, 350, and 70 city–year observations, respectively.

Each city's membership in these groups was held constant throughout the 2013–2022 study period. Small cities constitute the reference group. Therefore, in the linear model, the main coefficient on the natural logarithm of population density represents the slope for small cities, while the interaction coefficients for medium-sized and large cities capture the differences in their slopes relative to small cities. In the nonlinear model, the interaction coefficients represent differences in the linear and quadratic components of the density–gasoline consumption curves for medium-sized and large cities relative to the reference group.

Since group membership remains constant over time, the main effects of the medium-sized and large-city dummy variables are absorbed by the city fixed effects. The omission of these coefficients results from perfect collinearity with the city fixed effects and therefore does not prevent the estimation of interactions between city-size groups and population density.

Table 6- Heterogeneity in the Relationship Between Population Density and Per Capita Gasoline Consumption by City Size

Variables	(1) Group-Specific Linear Model	(2) Group-Specific Nonlinear Model
log_Density (Small cities)	−0.735***	0.811
	(0.143)	*(0.969)*
	0.350*	3.715***

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log_Density × Medium-sized cities	*(0.183)*	*(1.238)*
log_Density × Large cities	−0.212*	−0.390
	(0.124)	*(2.021)*
log_Density² (Small cities)	-	−0.0978
		(0.0602)
log_Density² × Medium-sized cities	-	−0.1944**
		(0.0762)
log_Density² × Large cities	-	0.0237
		(0.1131)
logIncCPI	−0.0225	−0.0213
	(0.0187)	*(0.0187)*
Car	−0.000451	−0.000318
	(0.000313)	*(0.000298)*
Emp	−0.00165**	−0.00139*
	(0.000819)	*(0.000788)*
Metro	−0.0545***	−0.0535***
	(0.0181)	*(0.0191)*
City Fixed Effects	Yes	Yes
Year Fixed Effects	Yes	Yes
Observations	800	800
Number of Cities	80	80
Within R-squared	0.692	0.714
Joint Test of Heterogeneity (F-statistic)	4.18	6.55
Joint Test of Heterogeneity (p-value)	0.0187	0.0001

Notes: Small cities constitute the reference group. The main effects of the medium-sized and large-city dummy variables are omitted because of perfect collinearity with city fixed effects. Standard errors clustered at the city level are reported in parentheses. *p < 0.10, **p < 0.05, ***p < 0.01.

In the group-specific linear model, the coefficient on the natural logarithm of population density for small cities is −0.735. Therefore, in this group, a 1% increase in population density is associated with an approximately 0.74% decrease in per capita gasoline consumption. The interaction coefficient between the medium-sized city indicator and population density is 0.350; thus, the implied slope for medium-sized cities is obtained by summing the coefficient for the reference group and the interaction coefficient. Accordingly, the implied linear elasticity for medium-sized cities is approximately −0.39, indicating that the negative relationship is weaker in this group than in small cities. Similarly, the implied slope, or equivalently the implied linear elasticity, for large cities is −0.947.

To formally assess heterogeneity, the four interaction coefficients in the nonlinear model were tested jointly. The results of the Wald test indicate that the null hypothesis of identical density–gasoline consumption curves across the three groups is rejected.

$$F(4,79) = 6.55 \quad \text{Prob} > F = 0.001 \qquad (7)$$

Pairwise tests of the group-specific curves indicate that the curve for medium-sized cities differs significantly from that for small cities. In contrast, the null hypothesis of equality between the curves for large and small cities cannot be rejected. The comparison between medium-sized and large cities is also not statistically significant at the 5% level, although there is weak evidence of a difference between them at the 10% level. Taken together, these results suggest that the overall heterogeneity is primarily driven by differences between medium-sized and small cities. The findings do not establish that all three groups differ significantly from one another in every respect. Furthermore, failure to reject the null hypothesis of equality between the curves for large and small cities does not constitute proof that they

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are identical, particularly given that the large-city group includes only seven cities and the limited number of clusters in this group reduces the statistical power of the test.

To assess the necessity of retaining the nonlinear specification, the coefficients on all quadratic terms were jointly tested. The test results reject the null hypothesis that these terms can be excluded from the model. Therefore, omitting the quadratic components and imposing a single linear relationship on the data is not justified, and the interpretation of the findings should be based on the nonlinear model and its corresponding marginal effects.

$$F(3,79) = 11.21 \quad Prob > F = 0.001 \qquad (8)$$

Among the control variables, the coefficients on real household income and car ownership are not statistically significant in either of the two group-specific models. The coefficient on the employment rate is negative and statistically significant at the 5% level in the linear model and at the 10% level in the nonlinear model. The coefficient on the Metro variable is also negative and statistically significant at the 1% level in both specifications. However, these coefficients represent conditional associations and should not be interpreted as causal effects, particularly in the case of urban rail transit, given the limited number of cities with operational rail transit systems and the limited temporal variation in this variable.

4.3.Marginal Effects of Population Density by City Size

The range of the natural logarithm of population density is not identical across the three groups. The common observed range for all three groups extends approximately from 8.314 to 9.246. To avoid extrapolation and ensure comparisons across groups at identical density levels, marginal effects were calculated at log-density values of 8.4, 8.6, 8.8, and 9.0, all of which fall within the observed range of the three groups.

Table 7- Marginal Effects of Population Density on Per Capita Gasoline Consumption by City Size

Log Population Density	Small Cities	Medium-sized Cities	Large Cities
8.4	−0.832***	−0.383***	−0.824***
	(0.129)	*(0.117)*	*(0.220)*
8.6	−0.871***	−0.500***	−0.853***
	(0.140)	(0.131)	(0.189)
8.8	−0.910***	−0.617***	−0.883***
	(0.154)	*(0.147)*	*(0.159)*
9.0	−0.949***	−0.734***	−0.913***
	(0.171)	*(0.166)*	*(0.130)*

Notes: The reported estimates represent the elasticities of per capita gasoline consumption with respect to population density. Delta-method standard errors clustered at the city level are reported in parentheses. The marginal effect for medium-sized cities at a log-density level of 8.4 has a p-value of 0.001, while all other marginal effects have p-values below 0.001. *** $p < 0.01$.

The results presented in Table 7 indicate that the marginal effects of population density are negative and statistically significant at all examined density levels across all three city-size groups. These findings highlight three key points. First, within the common range of population density, higher density is associated with lower per capita gasoline consumption in all three groups. Second, the magnitude of this negative relationship increases as population density rises. Third, the observed pattern does not support a simple, monotonic ranking across small, medium-sized, and large cities. Small and large cities exhibit relatively similar elasticities, whereas the elasticities for medium-sized cities are less negative, particularly at lower density levels. As log-density increases from 8.4 to 9.0, the gap between the elasticities of medium-sized cities and those of the other two groups narrows.

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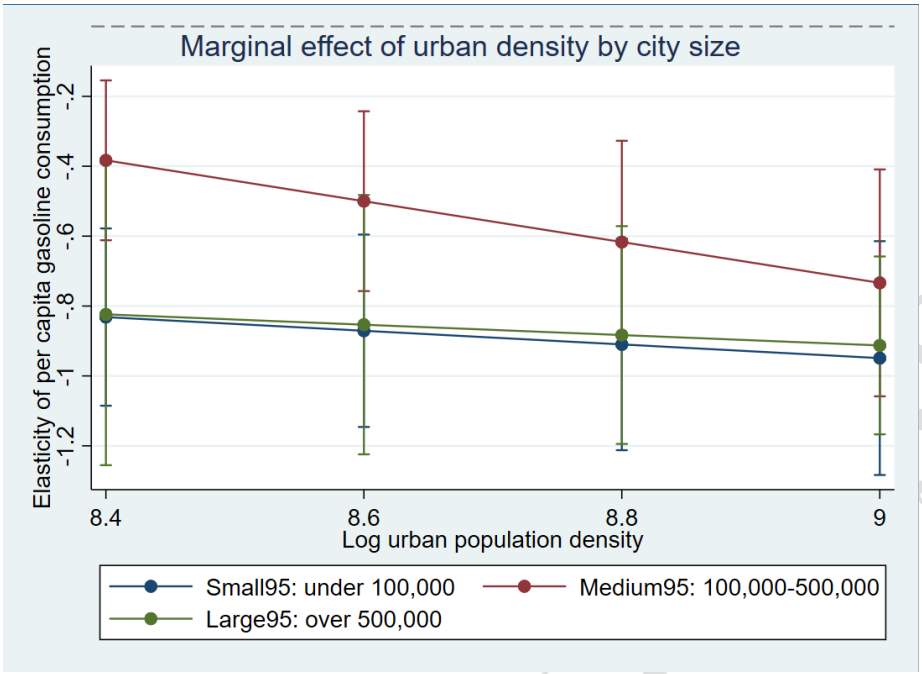


Figure 1- Marginal Effects of Population Density on Per Capita Gasoline Consumption by City Size, with 95% Confidence Intervals

The points represent the estimated elasticities of per capita gasoline consumption with respect to population density, while the vertical lines indicate 95% confidence intervals. The horizontal zero line is included to assess the direction and statistical significance of the estimated effects.

4.4.Robustness Checks

To examine the sensitivity of the main findings to alternative approaches for controlling for temporal developments and changes in sample composition, the nonlinear model was estimated under several alternative specifications. Column (1) presents the baseline model with city and year fixed effects. In column (2), the year fixed effects are replaced with the real gasoline price, its one-year lag, and national real gross domestic product (GDP). In column (3), a linear time trend is additionally included alongside these macroeconomic variables. In column (4), Tehran is excluded from the sample.

Table 8- Robustness Checks of the Nonlinear Model

	(1) Baseline	(2) Fuel Price & GDP	(3) Linear Trend	(4) Excl. Tehran
log_Density	2.742***	2.965***	3.035***	2.661***
	(0.806)	*(0.652)*	*(0.781)*	*(0.839)*
sqlogDensity	-0.193***	-0.191***	-0.210***	-0.188***
	(0.0445)	*(0.0405)*	*(0.0448)*	*(0.0462)*
logIncCPI	-0.0214	-0.0708***	-0.0257	-0.0206
	(0.0184)	*(0.0238)*	*(0.0197)*	*(0.0183)*
Car	-0.000221	0.000702**	-0.0000813	-0.000249
	(0.000314)	*(0.000339)*	*(0.000280)*	*(0.000316)*
Emp	-0.000975	-0.000267	-0.00112	-0.000944

	(0.000825)	*(0.000903)*	*(0.0008)*	*(0.000826)*
Metro	-0.0480*	-0.0373	-0.0364	-0.0505*
	(0.0258)	*(0.0345)*	*(0.0286)*	*(0.0259)*
year			0.0286***	
			(0.00291)	
GasCPI		-0.00341***	-0.00696***	
		(0.00117)	*(0.00105)*	
L.GasCPI		-0.0304***	-0.0316***	
		(0.00112)	*(0.00114)*	
agg_gdp		0.0581***	-0.0141***	
		(0.00799)	*(0.00420)*	
Observations	800	720	720	790
Within R-squared	0.697	0.616	0.678	0.699
City FE	Yes	Yes	Yes	Yes
Year FE	Yes	No	No	Yes
Fuel Price & GDP	No	Yes	Yes	No
Linear Trend	No	No	Yes	No
Sample	Full	Full	Full	Excluding Tehran

Notes: Standard errors clustered at the city level are reported in parentheses. * p < 0.10, ** p < 0.05, *** p < 0.01.

The results presented in Table 8 indicate that the coefficients of the main variables remain stable across all specifications. The coefficient on log_Density is positive in all columns, ranging from 2.661 to 3.035, and is statistically significant at the 1% level. Similarly, the coefficient on sqlogDensity remains negative across all models, ranging from −0.188 to −0.210, and is statistically significant at the 1% level. Excluding Tehran from the sample does not substantially alter the magnitude of the main coefficients or the within R-squared. Therefore, the nonlinear and concave relationship between population density and per capita gasoline consumption is robust to alternative controls for temporal variation and the exclusion of Tehran.

In the specifications without year fixed effects, the coefficients on the real gasoline price and its one-year lag are negative and statistically significant, consistent with the economic logic of fuel demand. However, the coefficients of some control variables are more sensitive to model specification. Accordingly, the primary purpose of Table 8 is to assess the robustness of the coefficients on population density and its squared term.

5.Conclusion

5.1.Discussion

The main finding of this study is that the relationship between urban population density and per capita gasoline consumption in Iranian counties is negative but nonlinear. The linear model indicates that a 1% increase in population density is associated, on average, with an approximately 0.56% decrease in per capita gasoline consumption. However, the magnitude of this relationship increases as density rises. The robustness of this pattern across alternative specifications for controlling temporal changes and after excluding Tehran further indicates that the main finding does not depend on the inclusion of the capital or on any particular approach to controlling for temporal variation.

The direction of this relationship is consistent with the findings of Newman and Kenworthy (1989), Brownstone and Golob (2009), Karathodorou et al. (2010), and Su (2011), who associate higher population density with lower car ownership, shorter travel distances, and reduced fuel consumption. The methodological distinction of the present study lies in its use of recorded gasoline consumption and panel data. Consequently, rather than primarily reflecting cross-sectional differences between high- and low-density counties, the estimated coefficients capture the association between changes in population density within each county and changes in its gasoline consumption over time.

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Another contribution of this study is the examination of this relationship across small, medium-sized, and large counties. The null hypothesis of identical curves across the three groups is rejected; however, the differences are primarily observed between medium-sized and small counties, and the results do not support a monotonic ranking based on county size. The weaker relationship between density and gasoline consumption in medium-sized counties, particularly at lower density levels, may reflect increases in density that are not accompanied by a corresponding concentration of employment and services, land-use mix, or public transportation provision. This finding is consistent with the perspective of Mindali et al. (2004), who emphasize that density alone is insufficient to explain energy consumption.

The coefficients on urban rail transit and gasoline prices have the expected signs. However, the limited temporal variation in urban rail transit and the absorption of nationally uniform gasoline prices by year fixed effects prevent causal interpretations of these coefficients. The main findings also represent conditional associations, as reverse causality, other dimensions of urban form, fuel sales to nonresidents, and the small number of large counties may affect the estimates.

5.2.Policy Implications

The findings support differences in the relationship between population density and gasoline consumption across county-size groups but do not establish a simple ranking from small to large counties. Therefore, population-based classification should be used to identify the principal challenges facing each group.

Small counties have the lowest average population density and the highest average per capita gasoline consumption. Nevertheless, within the common density range, their marginal effects of density are relatively strong and close to those estimated for large counties. Thus, the main policy implication for this group is to prevent population growth and construction from being directed toward disconnected peripheral developments and instead channel them toward vacant or underutilized areas within existing urban boundaries. Assuming the presence of a basic public transportation network comprising buses, minibuses, and taxis, transportation priorities could focus on adjusting the routes and schedules of these existing services to connect neighborhoods with major employment and service centers.

Medium-sized counties exhibit a different pattern. At a log-density level of 8.4, the elasticity for this group is −0.383, which is weaker than those of small and large counties, but it reaches −0.734 at a log-density level of 9.0. Therefore, increasing scattered building density or simply adding residential units does not, by itself, constitute an effective policy for this group. The central priority should be to concentrate new development along continuous corridors that provide simultaneous access to employment, services, and existing public transportation networks. In these counties, permits for large peripheral developments should be conditional on accessibility assessments and plans to strengthen the capacity and frequency of existing public transportation services.

Large counties have the highest average population density and the lowest average per capita gasoline consumption, while the marginal effect of density remains negative and substantial. Nevertheless, average car ownership in this group is higher than in the other two groups, and urban rail transit systems are also predominantly concentrated in these counties. Accordingly, the main priority is to direct development toward the catchment areas of operational transit stations and improve the efficiency of existing networks through better coordination of feeder services, reduced waiting times, integrated ticketing, and parking management in high-traffic centers.

At the national level, the negative coefficients on the real gasoline price and its one-year lag suggest that spatial policies should be complemented by gradual and predictable fuel price reforms. Such reforms should be accompanied by targeted support for vulnerable households and funding for public transportation operations to maintain accessibility to different parts of the city.

5.3.Limitations and Directions for Future Research

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This study has several limitations. First, gasoline consumption data are based on recorded sales at fuel stations within each fuel distribution district and may include fuel purchased by passing vehicles, intercity travelers, or vehicles engaged in activities outside urban boundaries. Therefore, this variable does not precisely represent gasoline consumption by households residing in the county.

Second, some economic and social variables were derived from the Household Income and Expenditure Survey and aggregated at the city level, potentially introducing sampling errors, particularly in smaller cities.

Furthermore, although the city and year fixed-effects model controls for time-invariant heterogeneity across cities and common temporal shocks, it does not fully address potential endogeneity arising from time-varying factors and the bidirectional relationship between population density and gasoline consumption.

Future research could employ more detailed travel data and information on different fuel types, instrumental-variable methods or quasi-experimental designs, and spatial models. Separately examining cities with different public transportation structures could also provide a more precise understanding of the conditions under which urban density contributes to reduced gasoline consumption.

Author Contributions

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Conflict of Interest

The authors declare no conflicts of interest related to this research.

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