Transport Energy Atlas of Sofia: Evaluating Present and Low Energy Scenarios Using Private Vehicle Traffic Data

Lidia Lazarova Vitanova [1]*, Tereza Trendafilova[1], Dessislava Petrova-Antonova [1]

[1] GATE Institute, Sofia University “St. Kliment Ohridski”, 1164 Sofia, Bulgaria
{lidia.vitanova, tereza.trendafilova, dessislava.petrova}@gate-ai.eu

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Abstract

Urbanisation has a significant impact on transport, energy consumption, and climate change, presenting several challenges for cities in terms of sustainable urban development. As cities grow, the demand for transport increases, resulting in more vehicles on the road, higher fuel consumption and increased energy use, causing air pollution and urban heat risks. To address these issues, this study proposes combining TomTom Traffic Stats data and Geographic Information Systems (GIS) methods to develop a comprehensive Transport Energy Atlas of Sofia. Two energy cases are considered: present and low energy. In the present case, fuel vehicles and electric vehicles (EVs) are 90% and 10%, respectively, while in the low-energy case, the proportions reversed to 10% fuel and 90% EVs. The traffic of private vehicles over a range of temporal and spatial scales is investigated. The results demonstrate considerable fluctuations in traffic, with the highest levels of congestion and energy consumption occurring during the morning and evening rush hours in central business districts and significant congestion in Sofia. In the low energy case, the energy consumption in areas with a high concentration of vehicles and heavy traffic decreases more than twice compared to the present case due to the shift of EVs from 10% to 90%. The results suggest that policies or incentives to promote the uptake of EVs could play a crucial role in reducing the energy consumption and environmental impact of urban transport systems.

1. Introduction

As urbanisation accelerates, the demand for transport energy increases, driving the need for more efficient energy sources and the implementation of energy-saving and environmentally friendly measures. It is, therefore, imperative to examine this relationship to reduce the environmental impact of transportation systems, improve energy efficiency, and facilitate the transition to low-carbon technologies, such as electric vehicles (EVs) and renewable energy-powered public transportation.

In recent years, research studies on energy consumption in the transport sector have increased significantly all over the world, e.g., in Greece (Mamarikas et al., 2022), UK (Banister and Banister, 1995), Ecuador (Puma-Benavides et al., 2024), Portugal (Faria et al., 2018), China (Song et al., 2014a; Sun et al., 2024), Russia (Mazurova and Galperova, 2018), Malaysia (Ong et al., 2012), Philippines (Rito et al., 2021)Middle East and North African countries (Saidi et al., 2018). A special focus is given to temporal and spatial trends in energy consumption (Stead, 2007), energy consumption levels (Rokicki et al., 2021), analysis of travel patterns and energy consumption (Banister and Banister, 1995), development of transport based on the amount of carbon dioxide (Song et al., 2014b), traffic and noise (Calejo Rodrigues, 2020), etc. For example, energy consumption levels within the transport sector are examined across EU countries (Rokicki et al., 2021). The results show an increase in energy consumption in transport from 2016 to 2018, attributed to favourable economic conditions prevailing at that time. The carbon dioxide impact of the development of transport was studied in Shanghai from 2000 to 2010 (Song et al., 2014b). The results demonstrate that transportation energy consumption increased significantly from 597.96 million tons of carbon in 2000 to 2070.22 million tons in 2010. The research also revealed that private cars are the most significant contributor to the energy consumption of transportation modes. Another study investigated the energy consumption of battery electric vehicles (BEVs) and internal combustion engine vehicles (ICEVs) in Greece (Mamarikas et al., 2022). It was found that BEVs have the lowest energy consumption in urban areas and at lower speeds (20–50 km/h), while ICEVs are most efficient at higher speeds (around 60 km/h), typical of suburban and rural settings.

Despite the above studies, very few focus on investigating spatial and temporal energy transport patterns and presenting them through energy maps that cover large urban areas or at the city level. Such an investigation is crucial because, at the city level, transport systems form complex networks where traffic congestion and energy use are interlinked across neighbourhoods. Studying large-scale patterns helps to capture these interactions, identifying overarching inefficiencies and hotspots that may be missed by small-scale analyses, and could be the most crucial step for further exploration of emissions and urban heat island (UHI) effects at the city and neighbourhood level. Unfortunately, many studies lack data, including detailed specific fuel consumption rates, critical for accurate energy modelling (Rito et al., 2021). The spatial and temporal resolution of transport distribution is also challenging, as it may not capture short-term fluctuations in traffic or energy demand during peak hours or in specific zones (Chen et al., 2023).

Sofia, the largest city and capital of Bulgaria, also faces increasing traffic, which negatively impacts its citizens' environment and lifestyle. It is the most polluted capital in Europe, with alarmingly high concentrations of fine particulate matter (PM10) (EIT Climate-KIC, 2024; EU Urban Mobility

* Corresponding author

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Observatory, 2022). It is estimated that approximately 9,000 deaths annually in Bulgaria are attributable to diseases associated with poor air quality (EIT Climate-KIC, 2024). Addressing traffic congestion, climate change, and inadequate infrastructure is necessary to improve air quality and reduce the associated health risks.

In Bulgaria, particularly in Sofia, research on the transport network, traffic energy consumption, and their implications on the environment, climate change, and air pollution remain very limited. One such investigation focused on the traffic emissions inventory in Sofia and its effects on the urban environment (Burov and Brezov, 2023). The findings indicate that the unique configuration of urban road canyons and traffic loads create different levels of impact and risk from transport sources. However, the study explains the challenges of integrity and lack of access to comprehensive traffic and fleet data, which may reflect the neighbourhood level.

To address these issues, this research proposes an approach utilising TomTom's Traffic Stats data in combination with Geographic Information Systems (GIS) methods to develop a comprehensive Transport Energy Atlas in Sofia. It benefits researchers, society, and local governments by coordinating climate action and energy consumption reduction, setting zero-emission goals, and helping citizens and communities by providing helpful energy information.

Specific research questions have been defined to provide a comprehensive framework for analysing traffic patterns and energy consumption, addressing various dimensions, including spatial-temporal dynamics, infrastructure and prospects as follows:

• *What are the temporal and spatial patterns of traffic congestion and energy consumption of private vehicles in Sofia city?*

• *How does the traffic and energy consumption of private vehicles vary across different times of the day?*

• *Which areas in Sofia experience the highest traffic congestion and energy consumption levels caused by private vehicles?*

• *What traffic and energy consumption differences are observed between present energy use and low-energy scenarios in Sofia?*

2. Data and Methodology

This section introduces the study area and development of the Transport Energy Atlas, including data collection, preparation, and processing of pipeline energy and transport data in Sofia.

2.1 Study area

Figure 1 shows the location of Sofia with the associated urban area in red and the surrounding forest (dark green) and cropland (yellow). Sofia has a population of 1,221,172. It is situated in the western region of Bulgaria, within the confines of Sofia Valley, and its urbanised area is 255 km² (National Statistical Institute, 2022).

Figure 1. Study area: Sofia city. The urban, surrounding forest and cropland areas are shown in red, dark green and yellow.

The transport system in Sofia comprises a variety of mobility operators, including public transport authorities, providers of shared electric vehicles, e-scooters and bicycles, and taxi companies. Sofia has encountered several challenges recently, including traffic congestion, air pollution and rising temperatures. This is mainly attributable to the growing number of private vehicles in the city, with 663 cars per 1,000 inhabitants over the past three decades (EU Urban Mobility Observatory, 2023). The city is implementing various sustainable transport solutions, including expanding the metro network and introducing electric on-demand buses. (Bulgarian-Swiss Cooperation Program, 2019).

According to the Sofia Sustainable Urban Mobility Plan 2019 – 2035, passenger car use accounted for 30% of the total modal split in Sofia in 2017 (Bulgarian-Swiss Cooperation Program, 2019). Around 90% belong to the fuel type, and the other 10% to the electric vehicles (EV)-type. The fuel type is divided into gasoline (51% of the total) and diesel (49% of the total) according to the vehicle fleet data for road transport (number of vehicles) in 2019 (Ministry of Environment and Water Executive Environment Agency, 2021). The EV-type are divided into BEVs (69%) and plug-in hybrid electric vehicles (PHEVs) (38%) using the proportion between BEVs and PHEVs based on vehicle sales for 2022 (European Environment Agency, 2023a).

2.2 Development of the Transport Energy Atlas

Development of the Transport Energy Atlas consists of a sequence of steps for data collection, preparation and processing of transport and energy data. The final step includes the integration processes of energy and transport data. The complete process is shown in Figure 2. The steps are implemented using the Python programming language and the geospatial analytical functionalities provided by QGIS software. Combining Python data processing with QGIS enables precise manipulation and visualisation of geospatial datasets. This combination allows for automating complex geospatial workflows, thereby promoting efficiency and accuracy in spatial data analysis.

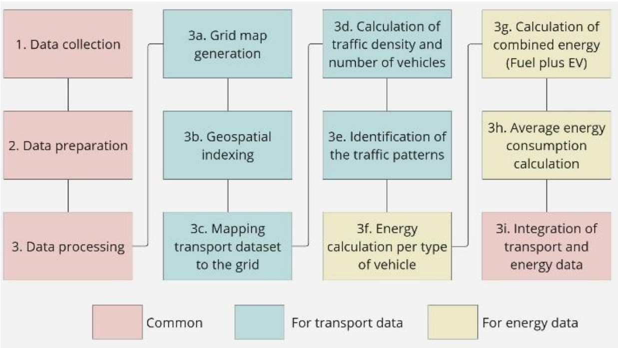

Figure 2. Data collection, preparation and processing pipeline.

2.2.1 Data collection, preparation and processing of transport data: This step is based on the methodology used in the research of private traffic patterns and urban mobility in Sofia (Vitanova et al., 2025). The traffic data is sourced from TomTom's Traffic Stats service, which provides access to an extensive traffic dataset (TomTom, 2024). The dataset comprises anonymised historical records of road speeds, travel durations, and traffic volume, collected via GPS devices installed in vehicles. It is divided into two primary components: (1) the Roads Dataset (RD), which provides details on the length of road segments and classifies them by their functional significance using Functional Road Classes (FRCs); and (2) the Traffic Dataset (TD), which includes multiple segments per road, each associated with a 'hits' value indicating traffic intensity and a 'median speed' reflecting the typical speed during the recorded time frame.

The traffic information is distributed across 24 individual .dbf files, with each road segment containing a 'hits' attribute that reflects hourly traffic volume and a 'median speed' attribute indicating the typical vehicle speed on that segment. These files are converted into .csv format to facilitate data processing. The 'hits' and 'median speed' values are extracted, and the average 'hits' per road segment are computed. Subsequently, the Roads Dataset (RD) is merged with the Traffic Dataset (TD) to create an Integrated Traffic Dataset (ITD), which links traffic flow and speed data to their respective road segments.

The data processing workflow comprises several key steps: generating the grid map, creating a spatial index, mapping the transport dataset onto the grid, calculating the traffic density and number of vehicles, and determining the energy consumption of cars within each grid cell (Figure 2).

The extensive urban road network is divided into 250 x 250 m grid cells (56169) to accommodate the traffic data. Each grid cell has a unique identifier, as well as its centroid's latitude and longitude. Then, to enhance the processing performance of the traffic data, a spatial index is generated for each grid, ITD, and RD using the *sindex* function from the GeoPandas Python library. The *split* function is applied to process and extend the ITD with grid cell information. This involves using the *sjoin*, overlay, and merge functions from the GeoPandas Python library. The *sjoin* function identifies road segments and intersections within grid cells. The *overlay* function retains the shared geometries between the merged road segments and grid cell boundaries. The length of each split road segment within the same grid cell is then calculated. Finally, the *merge* function combines data from the split roads and ITD, generating information for each unique grid cell, including longitude, latitude, and all 'hits' and 'median speed' attributes. The outcome of this function is a new dataset, called the Separated Roads Dataset (SRD), which provides details about road segments divided according to the grid cells they intersect.

In the final phase of data processing, traffic density is calculated by dividing the number of 'hits' by the 'median speed' for each road segment. To estimate the total number of vehicles per segment, this density value is multiplied by the segment's length in kilometres. These computations are carried out across all 24-hourly datasets, and the results are averaged over the entire time span. The processed data is then spatially aggregated by grid cells, summing the total number of vehicles from all road segments contained within each cell.

2.2.2 Data collection, preparation and processing of energy data: The data collection includes gathering the fuel and EV consumption data, vehicle fleet proportions data, calorific values, and densities.
Due to the lack of separate consumption data for the fuel type, the average specific consumption of the fuel cars of around 5.9 l/100km for 2017 and new cars for 2021 is considered for both gasoline and diesel types (International Energy Agency (IEA), 2019; Odyssee-Mure, 2021). Then, the calorific values and densities of gasoline (43.774 MJ/kg, 750 kg/m³) and diesel (42.695 MJ/kg, 840 kg/m³) are collected. (European Environment Agency, 2023b). According to the provisional 2022 data for the EV type, the average energy consumption of BEVs and PHEVs is roughly 0.166 kW/km and 0.177 kW/km. (European Environment Agency, 2023a).

The data preparation step includes fuel consumption conversion, where the fuel consumption from l/100 km is converted to l/km, conversion of the fuel volume consumed per km (l/km) into mass per km (kg/km) by multiplying by the respective fuel density, and calculation of the energy consumption in MJ/km by multiplying the mass per km by the calorific value of the fuel. Subsequently, the energy consumption of fuels is converted from MJ/km to kW/km. The resulting values for gasoline and diesel are 0.538 kW/km and 0.588 kW/km, respectively.

Once the energy consumption of the fuels and EVs had been estimated, the subsequent step calculated the total energy consumption for each fuel and EV type. This is achieved by multiplying the energy consumption per km by the total number of each representative fuel and EV vehicle. Subsequently, the total energy consumption is calculated by aggregating the energy values for fuels, represented by gasoline and diesel vehicles, and EVs, represented by BEVs and PHEVs. Finally, the average energy consumption per vehicle is calculated by dividing the combined total energy consumption by the total number of cars. The resulting values for fuels and EVs are 0.563kW/km and 0.169kW/km, respectively.

In the final step, two energy cases are defined: one representing the current situation and one representing a low-energy scenario. To determine these cases, the proportions of fuel-powered vehicles and EVs and their respective energy consumption are calculated from the total number of private cars in Bulgaria in 2022 (2,896,777 vehicles) (CEIC, 2022; Eurostat, 2024). The proportion of fuel-powered vehicles and EVs is defined for the present case as 90% and 10%, respectively, based on the current fuel-type share analysis (Scopes Data, 2024; Statista, 2023). In contrast, for the low-energy case, the proportion is defined as 10% fuel and 90% EVs, in alignment with the analysis of the fleet transition from the current state to a sustainable future (Table 1) (Scopes Data, 2024).

This study calculated the proportion of fuels and EVs in three steps. First, the total energy consumption for each vehicle type is calculated. Second, the individual vehicle types are added to determine total energy consumption. Finally, the average energy consumption is calculated. The methodology employed is analogous to that utilised for the fuel cars previously described. The calculation results are presented in Table 1.

Cases	Present	Low energy
Energy consumption	0.524kW/km	0.208kW/km
Proportions	Fuel 90%, EV 10%	Fuel 10%, EV 90%

Table 1. Configuration of energy cases.

2.2.3 Data integration of transport and energy data: The subsequent stage of this study involves calculating the energy consumption of vehicles within each grid cell. The lengths of the road segments, measured in meters, must first be converted to km by dividing by 1000, as the average energy consumption per vehicle is expressed in kW/km. The energy consumed for each road segment is determined by multiplying the segment length, the average energy consumption per vehicle, and the number of cars passing through that segment. Given two distinct cases for average vehicle energy consumption (Table 1), this calculation is repeated for both cases.

Additionally, to assess energy consumption during periods of varying traffic density in Sofia, the analysis considers hours with the lowest (3:00-4:00 am) and highest (5:00-6:00 pm) traffic for both energy consumption cases. Consequently, for each road segment, energy consumption values are calculated based on average traffic and traffic levels in the periods 3:00-4:00 am and 5:00-6:00 pm. The total energy consumption for each grid cell is obtained by summing the energy values of all road segments within the cell. The result is a dataset that, for each grid cell, provides information on the energy consumed by vehicles on all road segments within the cell, both on an average daily basis and during the specified peak and off-peak hours.

3. Results and Discussion

This section examines the traffic patterns of private vehicles in Sofia. It focuses on the results related to the Transport Energy Atlas, emphasising a spatial comparison between the lowest and highest energy consumption and examining the differences in energy consumption between present and low energy cases.

3.1 Traffic patterns of private vehicles in Sofia city

The temporal and spatial patterns of private vehicles and their energy consumption in Sofia are investigated for October 2022. The results related to the temporal and spatial patterns are based on those from the research on private traffic patterns and urban mobility in Sofia (Vitanova et al., 2025). October was selected as the study period because it reflects a time when Sofia's residents have generally resumed their everyday routines following the summer break, and the academic year has recently commenced in mid-September. This period provides stable and representative traffic behaviour, making it well-suited for accurate analysis. The findings are detailed in the sections that follow.

3.1.1 Traffic temporal patterns: The analysis of average monthly traffic patterns reveals pronounced peaks between 8:00–9:00 a.m. and 5:00–6:00 p.m. (Figure 3). These peak hours align with the beginning and end of the standard workday during weekdays and with increased movement related to leisure, shopping, and dining on weekends. In contrast, traffic volume is at its lowest between 3:00 and 4:00 a.m., a period that corresponds to the typical hours of rest for the majority of Sofia's residents, leading to minimal road activity.

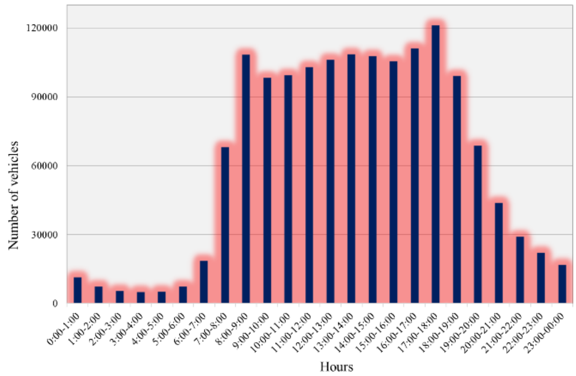

Figure 3. Monthly mean diurnal traffic variation in October 2022.

3.1.2 Traffic spatial patterns: The areas with the highest traffic volumes in Sofia are primarily located at major intersections, along key boulevards, and on the Sofia Ring Road, as well as in proximity to shopping malls and administrative centres (Figure 4). The analysis indicates that traffic intensity is greater in the southern districts of the city, likely reflecting the region's more substantial economic and commercial activity, including a higher concentration of retail complexes and office spaces that draw both commuters and visitors.

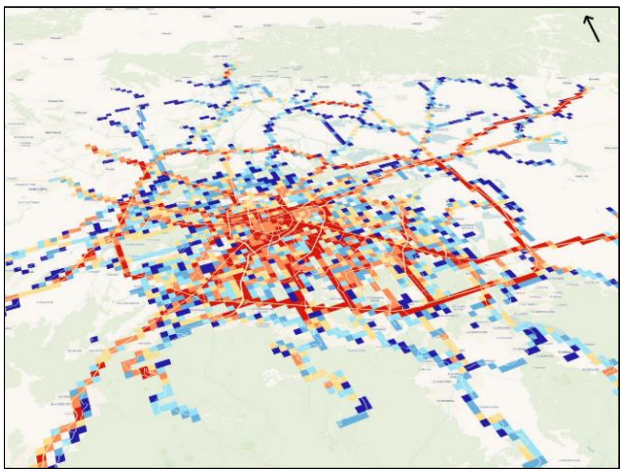

Figure 4. Mean spatial distribution of traffic in October 2022.

3.1.3 Spatial comparison between lowest and highest traffic: The average spatial distribution of traffic between 3:00 and 4:00 a.m. reveals localised activity around Sofia Airport, as well as along central boulevards and the Sofia Ring Road (Figure 5). Early morning traffic may be attributed to airport departures, shift workers, or individuals commuting during off-peak hours.

In contrast, the highest average traffic levels are recorded between 5:00 and 6:00 p.m. (Figure 5), with congestion most pronounced at key intersections and along major boulevards, aligning with the evening rush hour as residents return from work and school. A notable volume of traffic is also observed on the Sofia Ring Road, which serves as a vital bypass and connector to highways, industrial areas, residential neighbourhoods, and commercial districts, helping vehicles avoid the densely populated city centre.

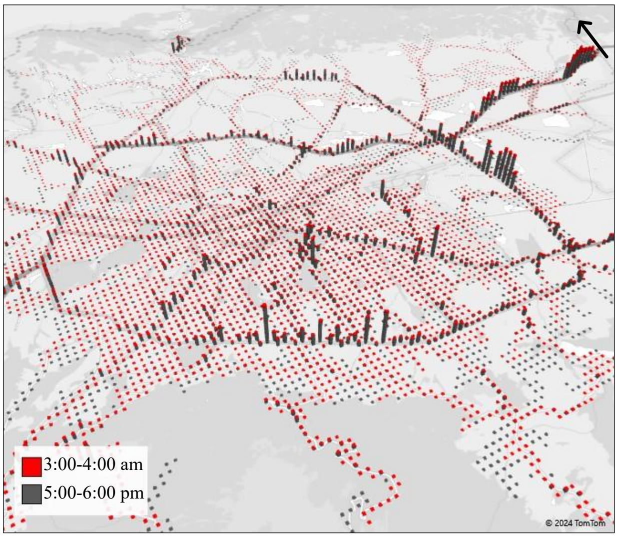

Figure 5. Spatial comparison of number of vehicles between 3:00-4:00 am and 5:00-6:00 pm.

3.2 Transport Energy Atlas

This section introduces two energy cases, the present and the low energy, along with a visual representation of energy consumption distribution across the city, highlighting the lowest, mean and highest levels.

3.2.1 Present Transport Energy Atlas: TomTom's Traffic Stats data and GIS are employed to estimate the energy consumption of private vehicles citywide in this study. Normalised values represent the energy consumption distribution for October within a specified range (Figure 6). As with the findings regarding the number of cars, the data indicates that energy consumption is higher in the southern part of the city, particularly along major boulevards and Sofia Ring Road, as well as at the junctions with highways. The sparse and dense categories represent the minimum and maximum number of vehicles, respectively, with 1 and 56 cars per grid measuring 250 x 250 m. Note that the number of vehicles used in this study represents only around 8% of the total number of private cars in Sofia. Despite this limitation, the findings still reflect a meaningful temporal and spatial distribution of traffic in Sofia, offering valuable insights into broader traffic dynamics and helping to identify trends in the entire vehicle fleet. The elevated energy consumption observed in the southern part of Sofia, particularly along central boulevards, the Sofia Ring Road, and highway junctions, can be attributed to several factors as follows:
Traffic Density: These areas function as principal transit routes for local and long-distance traffic, resulting in elevated vehicle concentrations, particularly during peak hours. The Ring Road and highways attract a considerable volume of vehicles, which consume more fuel and contribute to a higher overall energy use.
Urban Expansion: The southern regions of Sofia have undergone a period of rapid urbanisation and economic development, which has increased both residential and commercial activities. This growth results in an increased demand for transportation, leading to greater energy consumption.
Infrastructure: Major boulevards and highways are designed to accommodate high traffic volumes, but their infrastructure can lead to congestion, especially at junctions and intersections. This further increases fuel consumption as vehicles idle or move slowly during peak hours.
Spatial Patterns: These roads connect key commercial and business districts with residential areas, meaning that they are primary routes for commuters. This results in concentrated traffic flows during rush hours, further amplifying energy use in these parts of the city.

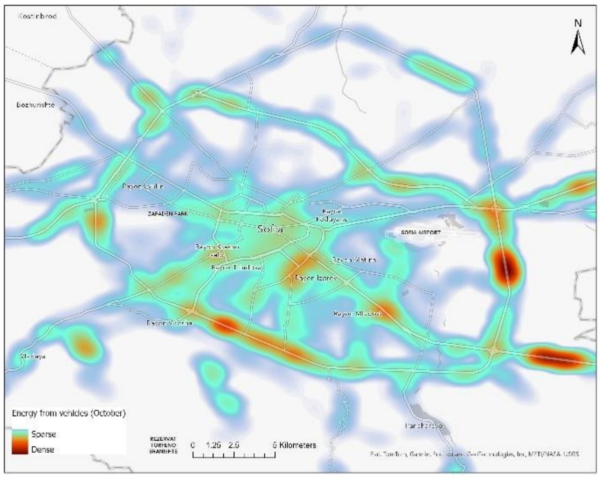

Figure 6. Present Transport Energy Atlas of Sofia.

3.2.2 Spatial comparison between lowest and highest energy consumption: The results show that the spatial traffic energy differences between 3:00-4:00 am and 5:00-6:00 pm are concentrated along central boulevards and the Sofia Ring Road (Figure 7). During the early morning, traffic is minimal, primarily restricted to essential services, leading to lower energy consumption. In contrast, the late afternoon marks the peak of daily activity as residents commute home. Central boulevards and the Ring Road, critical for connecting residential, industrial, and commercial zones, experience heavy congestion during this time, resulting in higher energy use. The Ring Road, functioning as a bypass to avoid inner-city traffic, further intensifies energy disparities by drawing significant traffic during peak hours.

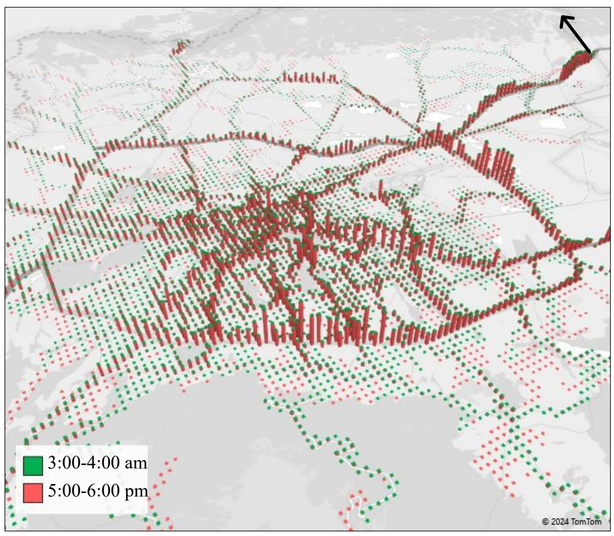

Figure 7. Spatial comparison of present transport energy between 3:00-4:00 am and 5:00-6:00 pm.

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3.3 Energy consumption differences between present and low-energy cases

This study employed two distinct energy cases: present and low energy. In the present case, the proportion of fuel vehicles and EVs is defined as 90% and 10%, respectively. In contrast, the low energy case saw the proportion of fuel vehicles and EVs reversed, with 10% fuel and 90% EVs. Sofia, a central traffic hub in Bulgaria, is transforming its fleet management. The initial fleet comprised 90% fuel vehicles, which the recommended transition strategy reduces to 10% of the total units. This represents a significant shift towards environmental sustainability as the city transitions to an EV-dominated fleet. The results show that in the present case, the higher proportion of fuel-powered vehicles, which generally consume more energy, contributes to higher energy consumption in these areas. Main boulevards, crossroads, Sofia Ring Road and highways typically experience higher traffic volumes, leading to increased fuel consumption and congestion. In contrast, the low-energy scenario likely assumes a more significant share of EVs with significantly lower energy consumption, particularly in high-traffic zones (Figure 8).

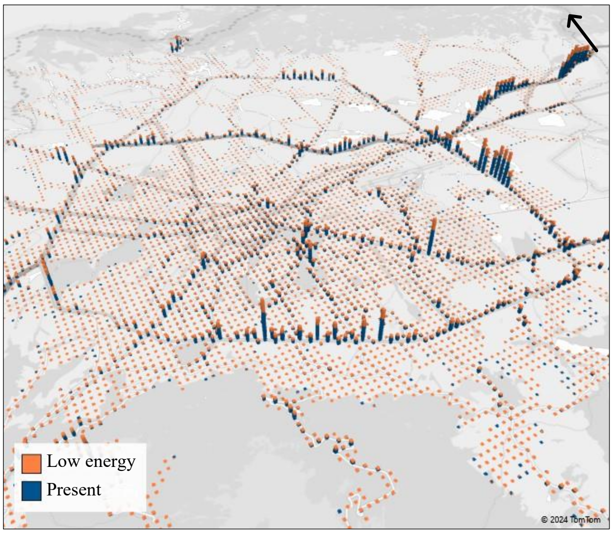

Figure 8. Differences in energy consumption between present and low-energy cases in Sofia.

The results presented above are supported by the data illustrated in Figure 9. In the low energy case, the energy consumption in areas with a high concentration of vehicles and heavy traffic decreases more than twice compared to the present case due to the shift of EVs from 10% to 90%.

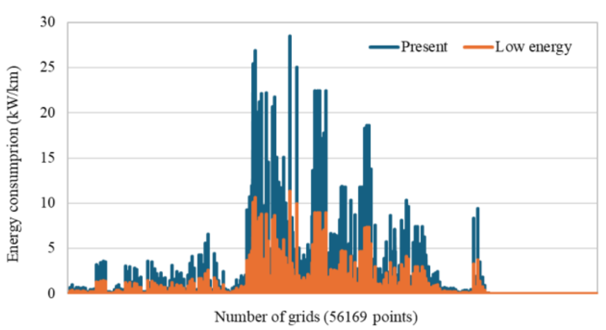

Figure 9. Differences in energy consumption between present and low-energy cases.

In addition, the total energy consumption of both cases is estimated (Figure 10). The results show a 59.5% reduction in energy consumption in the low-energy scenario. The higher proportion of EVs, which are inherently more energy efficient, explains the significant decrease in energy consumption in the low-energy scenario.

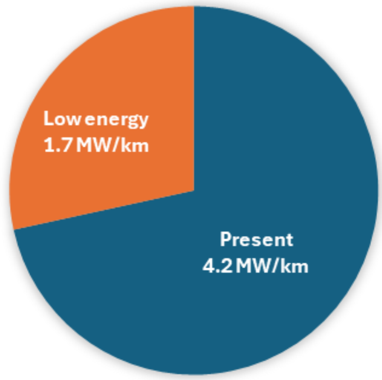

Figure 10. The total amount of energy consumption between the present and low energy cases.

This finding underlines the potential benefits of increasing the share of EVs in the fleet, as their higher energy efficiency directly translates into lower energy demand. The results also suggest that policies or incentives to promote the uptake of EVs could play a crucial role in reducing the energy consumption and environmental impact of urban transport systems.

4.4 The Impact of Transitioning from Fuel to EVs

The shift from fuel-powered vehicles to EVs signifies a significant change in the automotive industry and economy, likely disrupting internal combustion engine manufacturing, fuel distribution, and maintenance jobs due to EVs' more straightforward mechanics. While traditional automotive roles may decrease, new opportunities will emerge in battery production, software development, and charging infrastructure.

The shift to EVs can enhance economic growth and sustainability by reducing fossil fuel reliance and promoting clean energy. However, effective reskilling and workforce adaptation are essential to address job displacement risks and ensure a smooth labour market transition. Analysing employment changes and their macroeconomic impacts, like GDP growth and urban restructuring, will aid policymakers in developing effective strategies.

To boost EV adoption, significant policy and infrastructure changes are essential. Key measures include government incentives, regulatory frameworks, and investments in charging networks. Expanding public charging, encouraging private fast-charging stations, and enhancing the energy grid with renewable energy sources will aid this transition. International collaboration on EV battery supply chains and standardisation will also enhance scalability.

A cost-benefit analysis (CBA) of EV implementation in Sofia is essential for evaluating the financial feasibility and long-term benefits. While significant funding is needed for charging infrastructure and policy incentives, the high upfront cost of EVs poses a challenge. However, potential benefits like reduced fuel dependency, lower maintenance costs, improved air quality, and decreased healthcare costs may outweigh these issues. Integrating CBA into urban planning will help policymakers assess economic savings, job creation in green industries, and the overall social and environmental benefits of EVs in Sofia, facilitating a strategic transition.

4. Conclusions

4.1 Conclusions

This research proposes an approach that combines TomTom Traffic Stats data and a GIS method to develop a comprehensive Transport Energy Atlas in Sofia. Two energy scenarios are considered: present and low energy. Then, the traffic of private vehicles over a range of temporal and spatial scales is investigated. The main findings from the study can be summarised as follows:

- The study highlights significant traffic fluctuations, with peak congestion and energy consumption occurring in October 2022 between 8:00 and 9:00 am and 5:00 and 6:00 pm. The peak pattern marks the start and end of the working day
- Substantial vehicle volumes are observed on the Sofia Ring Road, a critical transit artery connecting highways, industrial zones, and residential areas while helping alleviate city centre congestion.
- The high energy consumption from private vehicles is observed in the southern part of Sofia, particularly along major boulevards, the Sofia Ring Road, and highway junctions. The minimum and maximum number of vehicles corresponds to 1 and 56 cars per grid measuring 250 x 250 m.
- In the low energy case, the energy consumption in areas with a high concentration of vehicles and heavy traffic decreases more than twice compared to the present case due to the shift of EVs from 10% to 90%.
- The results show a 59.5% reduction in energy consumption in the low-energy scenario due to the higher proportion of EVs, which are inherently more energy efficient.

4.2 Limitations and Future Work

The study could not explore seasonal variations and non-private vehicle categories due to the limited available data period. The analysis focused primarily on private vehicles, representing only around 8% of the total number of private cars in Sofia. Despite this limitation, the findings still reflect a meaningful temporal and spatial distribution of traffic in Sofia, offering valuable insights into broader traffic dynamics and helping to identify trends and inefficiencies applicable to the entire vehicle fleet. The energy consumption data for private cars is derived from information on all vehicles, categorised into two groups: fuels and EVs, both in Bulgaria and across the EU. Future research aims to investigate the seasonal impact, including a broader range of vehicle types, and integrate these findings with data on building energy consumption to analyse their combined influence on UHI dynamics. Additionally, integrating sub-meter satellite and unmanned aerial vehicle data for traffic monitoring, energy mapping, and emission assessment can enhance Sofia's Transport Energy Atlas, offering precise insights into road usage, congestion, and EV adoption.

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