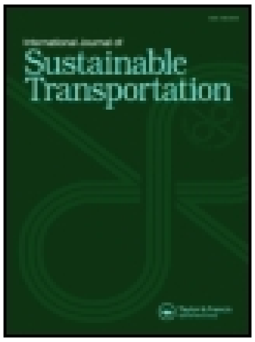

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Real-data-based high-resolution GHG emissions accounting of urban residents private transportation

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ABSTRACT

Worldwide, cities are monitoring their greenhouse gas emissions as a means to inform future greenhouse gas emissions mitigation policies and advance urban sustainability. Most urban GHG accounting frameworks provide data at the overall city scale. Studies have suggested that internal socioeconomic factors and location-specific spatial circumstances influence and shape urban greenhouse gas emissions emission volumes. This manuscript presents a comprehensive high-resolution spatial analysis of private vehicle travel-related greenhouse gas emissions of Tel Aviv-Jaffa (Israel) residents and explores some initial linkages to various socio-spatial explanatory factors. The studied city was divided into 1,121 small areas (ranging between 0.5 and 0.1 km^2). Therefore, it allows exploring the extent to which the unique specific characteristics (social and spatial) of different parts of the city contribute to the private vehicles use levels and their rates of emissions, and identify areas that present different consumption patterns. This type of analysis can be used to advance tailored policies suitable for any socio-spatial circumstances as well as to examine existing and emerging approaches to greenhouse gas emissions mitigation and advancement of urban sustainability.

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Hybrid approach; socio-spatial factors; sub-city analysis: private vehicles; urban GHG emissions

1. Introduction

The role cities have in mitigating greenhouse gas (GHG) emissions has been widely acknowledged (Betsill, 2001; Dhakal, 2010; Kousky & Schneider, 2003; Ramaswami, Hillman, Janson, Reiner, & Thomas, 2008). Measurement of direct and indirect urban GHG emissions provides the public and policy makers with information on the volumes of emissions from different sources (Parshall et al., 2010). It can generate a baseline for examining options for future GHG mitigation policies (Asadoorian, 2008), integration of new technologies, changes in personal behavior and other strategies to advance urban sustainability (May, 2013).

Indeed, a growing number of national, regional, and international initiatives of urban GHG accounting have been undertaken in recent decades (Greenhalgh, Ranganathan, & Sundin, 2010; Gurney et al., 2009). To date most urban GHG accounting frameworks have focused on the overall urban scale, measuring the contribution of different urban sectors to the total urban emission. While this city-wide approach is important, various studies have suggested that internal socioeconomic factors as well as specific spatial circumstances influence and shape urban GHG emissions profiles (Hankey & Marshall, 2010; Ishii, Tabushi, Aramaki, & Hanaki, 2010).

It follows, therefore, that the use of energy and associated emissions are not equally distributed throughout the city. Rather, they change according to socioeconomic and urban elements throughout the city (Brondfield, Hutyra, Gately, Raciti, & Peterson, 2012; Gately & Hutyra, 2013; Jones & Kammen, 2014). Hence, efforts to promote more efficient use of energy and GHG emissions reductions are likely to benefit from a targeted, sub-city approach, informed by an understanding of the ways people in different parts of the city contribute to overall energy use and emissions. Indeed, in recent years a growing number of studies have attempted to understand better the sub-urban scale and explore different shaping factors (Evola, Fichera, Gagliano, & Marletta, 2016; Fichera, Inturri, La Greca, & Palermo, 2016; Liu, Wang, Lin, & Zhao, 2016). However, data availability limited the number of studies at that scale. These studies have attempted to use data with limited coverage (i.e., focusing on specific parts of a studied city, using surveys, modeling based on several assumptions) or by using existing census and expenditure report data at low resolution (i.e., a city quarters).

This paper focuses on a single urban activity which has been widely acknowledged as a major source of GHG emissions—private transportation. It has been estimated that more than 20% of global use of energy and CO_2 emissions can be attributed to transportation (Maragkogianni, Papaefthimiou, & Zopounidis, 2014; Sanz, Cansino, González-Limón, Santamaría, & Yñiguez, 2014). In some countries that proportion is even higher at 30% or above (Heres-Del-Valle & Niemeier, 2011; Kay, Noland, & Rodier, 2014; Sperling & Lutsey, 2014). Of that, private transportation takes up a large share (Brand & Boardman, 2008). In the case of Israel, the use

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of transportation is responsible for 23% of its GHG emissions (Heifetz, 2009).

There is a growing interest in better understanding sub-city scale transportation-related emissions. A sub-city scale analysis of transportation-related emissions can examine the differences between various parts of the city and help better understand the extent to which the complex urban socio-economic and spatial factors influences emissions by different populations. It can then be used to develop policy and planning that respond to the specific needs and circumstances of residents located in different parts of the urban space. Furthermore, in recent years various approaches to urban sustainability became more advanced. These include approaches such as smart cities (Caragliu, Del Bo, & Nijkamp, 2011; Firnkorn & Müller, 2015), "new urbanism" (Trudeau, 2013), and resource decoupling (UNEP, 2011), all of which aim to promote more efficient use of resources and reduce urban environmental impacts. The sub-city scale analysis can also generate a detailed guideline for policy implementation and progress. In the following paragraphs, we refer to some key urban transportation and GHG studies.

This paper aims to contribute to the emerging research on urban energy consumption and GHG emissions accounting. It integrates data from various scales and sources, and presents the results of a high-resolution urban travel GHG emissions analysis of the city of Tel Aviv-Jaffa, Israel. It then illustrates the use of the spatial analysis as a first step in statistically analyzing the socio-spatial drivers of the research results. In the following paragraphs, we refer to some key urban transportation and GHG studies. A major potential advantage of such high-resolution analysis advanced in this research is its ability to distinguish between vehicle emissions from specific neighborhoods and even smaller areas. To the best of our knowledge, the analysis presented in this manuscript is one of the most detailed using real measured data.

The studied city was divided into 1,121 small areas (ranging between 0.5 and 0.1 km^2, with a median 0.2 km^2 parcel size). Therefore, it allows exploring the extent to which the unique specific characteristics (social and spatial) of different parts of the city contribute to the private vehicles use levels and their rates of emissions, and identify areas that present different consumption patterns. This type of analysis can be used to advance tailored policies suitable for any socio-spatial circumstances as well as to examine existing and emerging approaches of GHG mitigation and advancing urban sustainability.

2. Background

As interest in urban GHG accounting in general and particularly in transportation-related emissions has increased, a growing number of studies using a range of methods have been pursued. Approaches to urban GHG accounting research can be differentiated on several levels: (1) Perspectives—top down (describing the city as a whole, by scaling down national datasets), bottom up (using locally developed data at the neighborhood or sub-city scale), or hybrid (a combination of top down and bottom up); (2) Resolution—city-scale or sub-city-scale; (3) Boundaries—some focus on the activities of urban populations, while other accounts for emissions associated with all vehicles travel within city boundaries; still others include a mix of both; (4) Data type—Researchers use data from a number of sources including surveys, census, focus groups, and databases. Table 1 presents a summary of key private transportation GHG emissions studies based on the above categorization.

The most common approach to urban transportation-related GHG accounting was initiated about two decades ago, and has been developed further in recent years; it embraces the top-down perspective, mostly at the resolution of the city as a whole, and focuses on activities within the boundaries of the city under study. That approach has followed national base inventory methods and uses such data as: national scale fuel sales, assessments of overall annual vehicle mileage, and various models of vehicle use within urban boundaries (Glaeser & Kahn, 2010; Holtzclaw, 2000; Marcotullio, Sarzynski, Albrecht, & Schulz, 2012). This top-down city scale research, which in many cases uses further modeling, has provided policy makers and the public with valuable information about the overall emissions of different modes of urban transportation including: public and commercial vehicles, municipal fleets, private vehicles of urban residents, and visitors, and is commonly used in municipal GHG inventories. However, because it presents city-wide emissions data, that approach fails to reflect the high diversity of transportation modes used at the sub-city neighborhood scale, and it is not sensitive to the impacts of socio-economic characteristics in different parts of the city.

Table 1. A summary of urban car use and GHG quantification approaches and methods.

Study	Approach	Scale	Data type	Boundaries
Chatterton et al. (2015)	Hybrid	ZIP code area sample	Database and census	Residents
Holtzclaw, Clear, Dittmar, Goldstein, & Haas (2002)	Top-down	City scale	Census	Residents
Dodman (2009)	Review	City scale	Review	Residents
Marcotullio et al. (2012)	Top-down	City level	Extrapolation	Within area
Kenworthy (2013b)	Top-down	City scale	Database	Residents
Glaeser & Kahn (2010)	Top-down	City scale	Survey and census	Residents
Jones & Kammen (2014b)	Top-down	Sub-city	Survey	Residents
McDonald & McBride (2014)	Bottom-up	10 km grid	On-site sample	Within state
Krajzewicz & Hertkorn (2011)	Bottom-up	Car level	Sampling	Within area
Gately & Hutyra (2013)	Bottom-up	1 km grid	On-site sample (+ national data)	Within area
Brondfield et al. (2012)	Hybrid	1 km grid	Sample + data base	Within boundaries
Parshall et al. (2010)	Hybrid	10 km grid	On-site sample (+ national data)	Mix
Gurney & Mendoza (2009)	Hybrid	10 km grid	On-site sample (+ national data)	Mix

In response to shortcomings of the top-down city scale approaches, a bottom-up perspective has begun to emerge—one which is based on data gathered locally.

This perspective can also be divided into different approaches based on data gathering method. One approach relies on data such as traffic counts, fuel sales, and inventories of actual ambient gas content in various locations within the urban region (Gurney et al., 2009). Although these bottom-up approaches improve GHG accounting precision and can generate sub-city data, the datasets on which they rely do not usually yield information about the source of the emissions (transportation vs. industry and other sources of emissions). Thus, these analyses do not reveal how much of the gases are emitted by automobiles, nor can they distinguish between different vehicles users or identify which emissions can be related to city residents and which to visitors. Another common bottom-up perspective uses data collected through surveys and travel diaries (Concas & DeSalvo, 2012). Data on various aspects of vehicle use are then converted into emissions equivalents (Concas & DeSalvo, 2012). This approach can provide valuable and detailed information on vehicle use by residents and visitors to an urban area, and the information can provide a base for analysis of socio-economic factors, etc. A drawback of this approach is that significant resources and time are required to generate and analyze travel surveys and diaries. Finally, one already established approach is using a relatively small number of interviews and surveys (Cervero & Duncan, 2006; Crane & Crepeau, 1998). This method is often used in order to understand decision making of residents. Although it cannot generate statistically robust conclusions, it has an important role in qualitatively analyzing factors which may influence decisions leading to high emissions activities otherwise overlooked by policy-makers.

The advantages and limitations of both the top-down and bottom-up perspectives have led to the development of a hybrid perspective. The hybrid perspective integrates bottom up data at the sub-city household or neighborhood scale with top down data in order to fill data gaps. For example, McDonald & McBride, (2014) make use of local traffic counts, and analyze this data with the help of national fuel sales information (Chatterton, Barnes, Wilson, Anable, & Cairns, 2015; McDonald & McBride, 2014).

Finally, the increase in data volume and availability in recent years has opened new potential data sources. Large databases built and generated by extensive governmental projects, privately initiated by researchers or by business entrepreneurs, serve as a powerful source of raw information that can be used to produce results with increased levels of precision. The field of big data is still largely untapped. Brought on by the continued spread of cellular technology and the internet, the volume of information is ever growing. Tapping into this huge source of information has already provided high-resolution geographic information which serves private individuals, businesses, and governments in real-time.

Tel Aviv-Jaffa is the second largest city in Israel. Established in 1909 it is home to 418,600 people, and its jurisdiction is 12,797 acres. The city is an important financial, cultural, and commercial hub and the center of the largest metropolitan area in Israel, with 3.6 million inhabitants (Central Bureau of Statistics, 2014). Due to its centrality and social-cultural assets, it has been defined by the 2012 GaWC city roster as a Beta +level global city. Tel Aviv is also a “Forum 15” member—a group of 15 leading self-governing cities in Israel, which receive no “balancing” or development grants from the state and are managed foremost on the basis of their independent financial resources. In 2010, the Forum signed ICLEI’s (International Council for Local Environmental Initiatives) international convention for climate protection, obligating its members to mitigate their GHG emissions by 20% within a decade.

In terms of its transportation characteristics, the number of cars used by the city residents is approximately 200,000 (79% privately owned and the rest are mostly company owned vehicles). An average of 350 cars per 1,000 residents travels ~14,500 kilometers per year, and with an average engine volume of ~1,600 ml, emits ~2,600 kgCO$_2$e per vehicle a year.

While there are no available data on car use frequency or the average distance of a single trip, data on Tel Aviv residents commuting patterns (CBS 2008; Tel Aviv municipality 2016) suggest that 54% of commuting-related travel are by private vehicles, and ~57% of those trips are within the city’s boundaries. (Further statistical description of the data is provided in the appendix.)

Similar to many other cities, Tel Aviv-Jaffa neighborhoods differ from one another in socio-economic aspects as well as aspect of their urban planning and built characteristics.

Socio-economically, the city can be roughly divided into northern and southern areas, where the northern and newer part is inhabited by residents with higher socio-economic characteristics, and the southern parts have been, until recently, inhabited by citizens of lower income rates. Recent years have seen a change in this rough division, for example, some areas in Jaffa, at Tel-Aviv’s south-western end, are going through gentrification processes, and in some northern neighborhoods a larger part of the population has become elderly. The city’s planning and design can be roughly divided in the same manner; its newest neighborhoods are situated in the north, while the oldest neighborhoods are in Jaffa—one of the oldest harbor cities in the world (Margalit, 2013). The central neighborhoods were planned in the late 1920s using the Garden-City vision. The combination of these diverse neighborhood planning and design strategies has led to a city with an impressive urban fabric, featuring an elegant north to south–west to east road grid, mixed-used residential, commercial and open public areas (Amit-Cohen, 2005; Azaryahu, 2007, 2008). It follows that the city transportation characteristics and related GHG emissions may also be diverse and therefore should be examined at the sub-urban scale.

3. Materials and methods

Analyzing private vehicle use and related GHG emissions at the sub-city scale required the integration of five main data sources including: (1) the Israeli Ministry of Transportation 2013 annual vehicle roadworthiness test data-base, (2) GIS layers from the municipality of Tel Aviv-Jaffa, (3) Israel Post Office

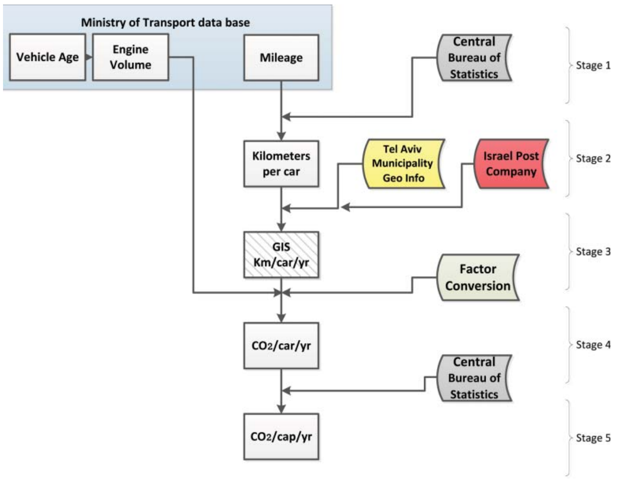


Figure 1. Stages of data processing.

code conversion services, (4) the Israeli Population Census from the Central Bureau of Statistics (2008), and (5) Vehicle mileage to CO_2 equivalent emissions conversion factors.

3.1. *Data preparation and analysis*

Figure 1 presents the stages in which data were processed for this research, including the type of data gathered from each source. A detailed explanation of each step taken by the research team in accounting for GHG emissions from vehicles in each urban area follows.

Stage 1:

The Ministry of Transportation database—The database includes the make, model, engine volume, and year of manufacture of all registered vehicles in Israel, as well as the mileage each vehicle has driven within the recent year. The data were collected and updated during the vehicles' annual roadworthiness check-up. The database provides the current city and postal code of each vehicle's owner. By calculating the mileage driven between the last two check-ups, we were able to calculate the average kilometers driven by each vehicle during the year 2012. In order to reach the highest resolution possible, while maintaining anonymity of vehicle owners, we used the postal codes of the owners as a geographic reference. A postal code represents an area approximating the size of one city block in Tel Aviv.

Stage 2:

Data from the Israeli Postal company and the Tel Aviv-Jaffa municipality—we used the Tel Aviv-Jaffa municipal GIS system, which includes polygonal layers of the statistical areas and point layers of all addresses in the city. Information from the Israeli Postal company allowed us to link postal codes to geographical locations on the city map. Thus, we were able to produce a high-resolution image of annual vehicle mileage by postal code for the entire city of Tel Aviv.

Stage 3:

The next stage in our data processing was generating a map that provides information on the car-usage *per capita*, as well as the CO_2 emissions generated by cars used by the city residents. The Israeli Population Census (Central Bureau of Statistics, 2008) provides a range of information, including car ownership levels, for each statistical area (population size of 3,000 citizens). Applying this information, kilometers per car was converted to kilometers per capita. Further statistical description of the data is provided in the appendix.

Stage 4:

Vehicles GHG conversion factors—CO_2 emissions were computed using a conversion table from the British Department for Environment Food & Rural Affairs (DECC, 2011) which accounts for vehicles' age and engine volume. This conversion method was selected for its availability and simplicity. However, it uses methodology guidelines similar to those used by the European Environment Agency (Ntziachristos & Samaras, 2017). Emission levels found in this study were cross-validated using average household expenditure for fuel in Israel 2013 (CBS, 2013).

Stage 5:

Final product—Highly detailed maps of CO_2 emissions per capita, vehicle, and postal code in each of Tel Aviv neighborhoods were generated.

Socio-spatial statistical analysis—Following the detailed high-resolution GHG emissions analysis, the research explored the statistical correlations of various selected key socio-spatial factors to each studied area emissions. That part included a statistical analysis of the following factors: income, education background, type of employment (white or blue color jobs), urban density, connectivity, and building height. Further on in order to detect any general spatial pattern, and also to identify important spatial anomalies, the next step was preforming the Getis and Ord's G-Statistic test (Brunsdon & Comber, 2015).

4. Results and discussion

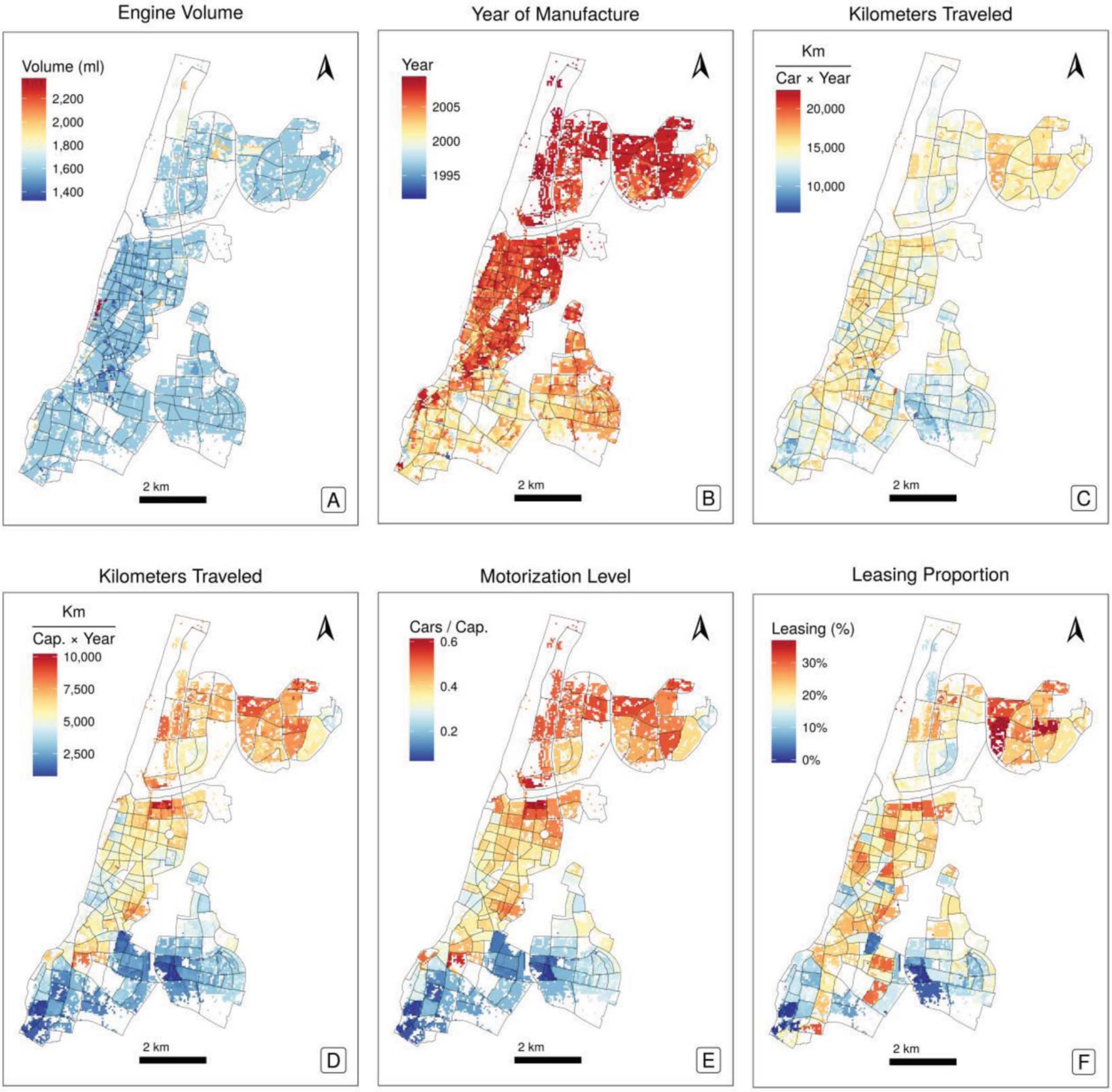
The following paragraphs illustrate Tel Aviv Jaffa residents' sub-city private vehicles GHG emissions. It first presents the various factors analyzed (e.g., vehicle technical aspects, driven mileage, type of ownership). It then analyzes rates of emissions related to the use of cars in different parts of the studied city. Finally, it explores the spatial and socio-economic factors and their implications for the quantified emissions. Further statistical description of the data is provided in the appendix.

The following Maps present the key research findings at a high-resolution level (approximately 0.5 km^2 parcel sizes). Such detailed spatial analysis allows capturing the urban spatial and socio-economic diversity, and explore some of its explanatory factors.

Maps 1(a–f) presents different key factors of the quantified emissions. While, each factor is interesting on its own, the integration of all explains the GHG emissions findings.

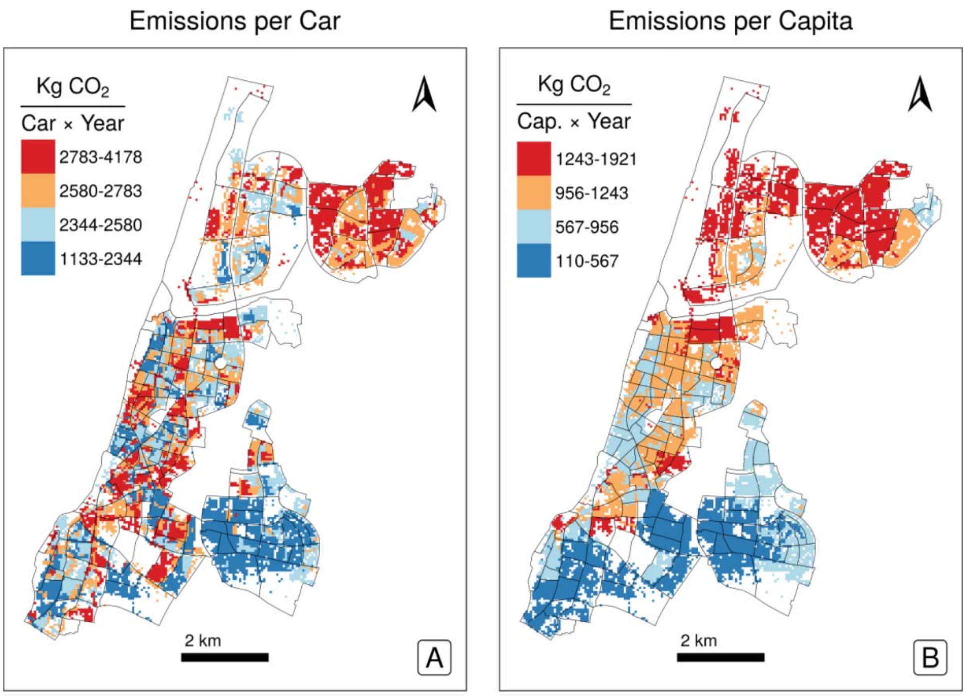
4.1. *Vehicle technological factors*

Maps 1a and 1b present the average engine volume and age of private vehicles in each studied postal code area. It appears from Map 1a that some areas, especially in the



Map 1. Elements of private transportation in high resolution. (a) Average engine volume per postal code area. (b) Average vehicle age per postal code area. (c) Median km traveled per car per area. (d) Median kilometers traveled per capita. (e) Level of motorization. (f) Type of vehicles ownership.

northern parts of the city, have a high percentage of high-volume vehicles (e.g., SUVs, Minivan, etc.). This corresponds with the relatively high socioeconomic status of northern Tel Aviv neighborhoods. A few other smaller pockets of high volume vehicles can be identified in other parts of the city, particularly in some gentrifying areas of Jaffa (south west neighborhoods of the city). Several areas within the city's dense geographic center show high rates of small vehicles, which in general are more fuel efficient and generate fewer emissions per km. Vehicle age presented in Map 1b illustrates a more complex picture easily visible thanks to the high resolution of the map. While the general differences between the southern and northern parts of the city are clear, other parts of the city present less homogenous results. For example, while most city center residents appear to use newer vehicles, a clear area (dark red) within that part of the city use the most recent years' models. Similarly, within the northern part of the city some areas (North East) drive the newest models while other areas (Central North) use relatively older models. The local variety likely reflects socio-economic, demographic, and lifestyle differences between the city's neighborhoods. Integrating the results presented in the two maps highlights some sub-city differences in transportation-related GHG emissions. For example: areas with small and new vehicles emit less than large, new models, etc.



Map 2. High-resolution carbon footprint of private transportation. (a) Median CO_2 equivalents emitted per car per year per postal code area. Median mission levels range between 4,000 kg $CO_2/(car^{*}year)$ (red) and 1,000 kg $CO_2/(car^{*}year)$ (blue) per area. (b) Median CO_2 equivalents emitted per capita per year per postal code area. Median mission levels range between 1,900 kg $CO_2/(car^{*}year)$ (red) and 100 kg $CO_2/(car^{*}year)$ (blue) per area.

4.2. *Behavioral factors*

Map 1c presents the median kilometers traveled per vehicle. It shows a wide range of vehicle use ranging from an annual average of 7,200 km per car to 40,700 km. Once again the differences between north and south parts of the city appear. Within the Northern part of the city, further divisions can be made, roughly separating the North West area where residents travel approximately 14,150 km per vehicle from the North-East area with an approximate mileage per vehicle of 18,900 km. Furthermore, examining vehicle use per capita as presented in Map 1d suggests a socioeconomic effect. The visible north to south pattern is accentuated when factoring in car ownership levels. As due to household size, the gap between south and north in terms of median travel per capita is even more extreme.

In addition to car ownership levels (Map 1e), the single most important socioeconomic factor impacting car use and related emission levels is the type of ownership, i.e., privately owned cars or company cars (Map 1f). In the case of Tel Aviv, employee-held company cars are driven three times more than privately owned cars, since car maintenance and gasoline costs are greatly reduced thanks to prevalent high-tech company policies.

Integrating the above factors allowed the calculations of the GHG emissions at that scale.

Maps 2a and 2b present GHG emissions over a year per vehicle and per capita. The emissions per vehicle range between as low as 1,100 kg (blue areas) to as high as 4,150 kg (red areas). The per capita emissions findings range even wider: between as low as 100 kg of CO_2e per year to over 1,900 kg of CO_2e. The entire city average of vehicle emission is approximately 800 kg/$(cap^{*}year)$. The average emission levels per capita in Tel Aviv found in this study are similar to the average emission levels per capita found in Germany (Miehe, Scheumann, Jones, Kammen, & Finkbeiner, 2016). However, they are less than those found in USA (Ergas, Clement, & McGee, 2016). Note that these numbers may vary greatly according to estimation methods.

Out of the 1,121 areas analyzed 740 areas emit more than the entire city average, while only 380 emit less than the city average. It is evident from the maps that while the highest emission level per *car* is quadruple than the lowest level, the per capita emissions are almost 20 times higher than the lowest level. These differences between the emissions per vehicle and per capita are due to various socioeconomic factors. For example, in Map 2a CO_2 per car in some northern neighborhood are relatively low (gray to light yellow color), these same areas emit relatively higher CO_2 levels *per capita* (pink to dark red color). This difference is due to high car ownership levels in those areas. Such gaps are further analyzed in the statistical analysis presented in the following section.

When comparing between Maps 1d and 2b, the most noticeable difference is in the northern areas, where light red in Map 1d becomes darker red in Map 2b, meaning that the relative CO_2 emissions per capita are higher than the relative kilometers per capita. This can be explained by the fact that residents of the northern neighborhoods own bigger, more fuel-consuming vehicles. The higher engine volume effect is slightly mitigated since those same cars are newer and more efficient. In a scenario where these cars were a few years older, CO_2 car emission levels in that area would have been even higher.

5. Socio-spatial analysis

In order to better understand the findings, socio-spatial impacting factors should be identified and analyzed. Figure 2

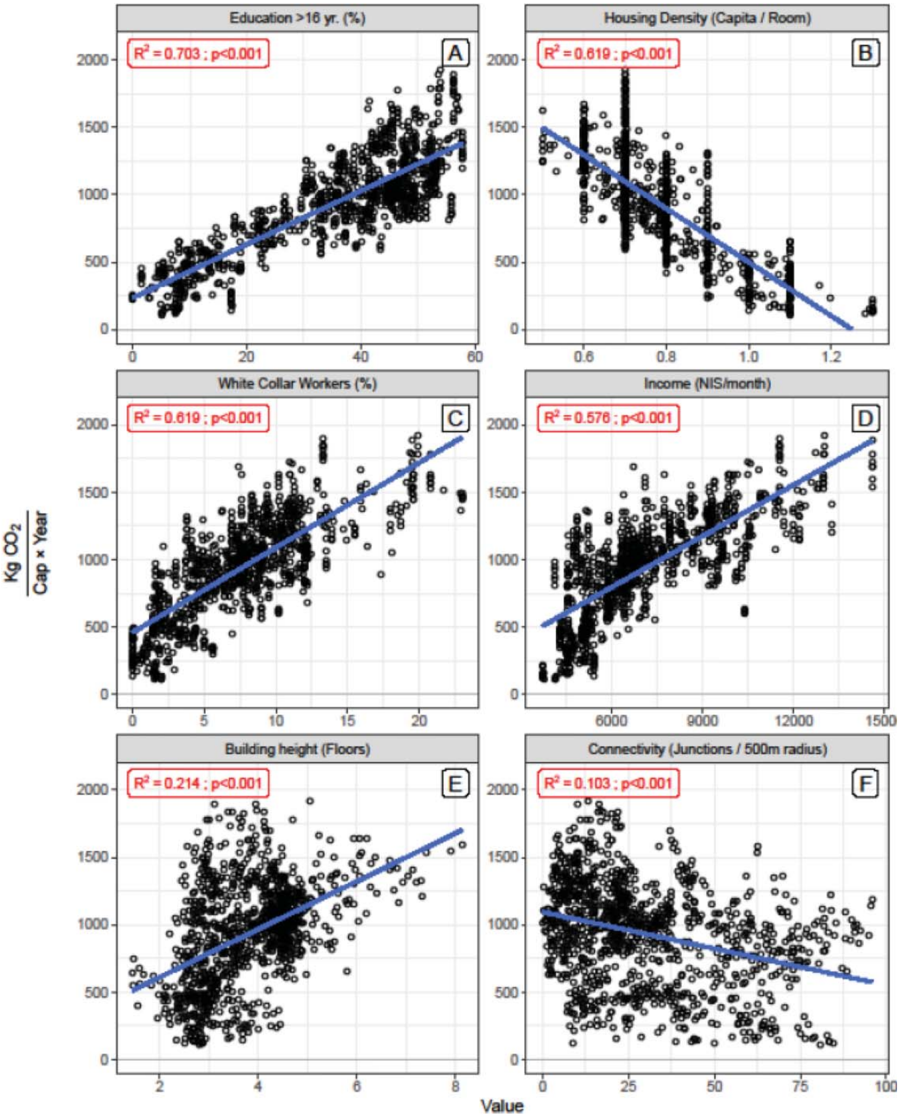


Figure 2. Socioeconomic and spatial factors plotted against neighborhood travel carbon footprint. (A) Percentage of residents going through more than 16 years of education. (B) Housing density (capita/room). (C) Percentage of managers and academics in area. (D) Income for salaried employees (NIS/month). (E) Average building height per area (Floors). (F) Number of four-way or higher junctions in a 500 m radius for each area. Each circle represents a zip code area. Each of the variables was plotted against private travel emissions (equivalents kgCO_2 /year* capita).

presents statistical analysis of various selected key socio-spatial factors and their correlation with GHG emissions. Each circle in the figure represents studied sub-urban area average performances.

Following the figure it appears that private car use and emission levels of Tel Aviv residents is more influenced by socioeconomic factors, with R^2 between 0.576 and 0.703, than by spatial factors with R^2 between 0.103 and 0.214; The analysis reveals that income levels, higher education, housing density, and percent of white collar workers (images A, B, C, and D, respectively) strongly correlate with per capita GHG emissions. However, urban topography (building average height (E)) also had some correlation, as well as road connectivity (Figure 2f).

Another benefit of such a high-resolution analysis is its ability to identify local anomalies, i.e., those small urban areas which function differently than expected. As was shown previously, income can generally predict the local emission levels. However, in Map 3 we performed the Getis and Ord's G-Statistic test in order to locate GHG levels local anomalies. A very clear spatial pattern can be seen, where the North is mostly dominated by relatively high emission levels, the South is almost entirely dominated by relative low emission levels, while the central areas have a mostly average emissions levels. However, marked as clusters A and B, two relative deviants can be identified. In cluster A, the average income levels are relatively low, but their emission levels are among the highest in the city. On the other hand, emission levels in cluster B are significantly lower than their neighboring areas.

In order to understand the reason for these anomalies, we plotted these Clusters' emission levels against income, leasing prevalence and urban density (Figure 3), where cluster A from Map 3 was marked red, and cluster B was marked blue. Cluster

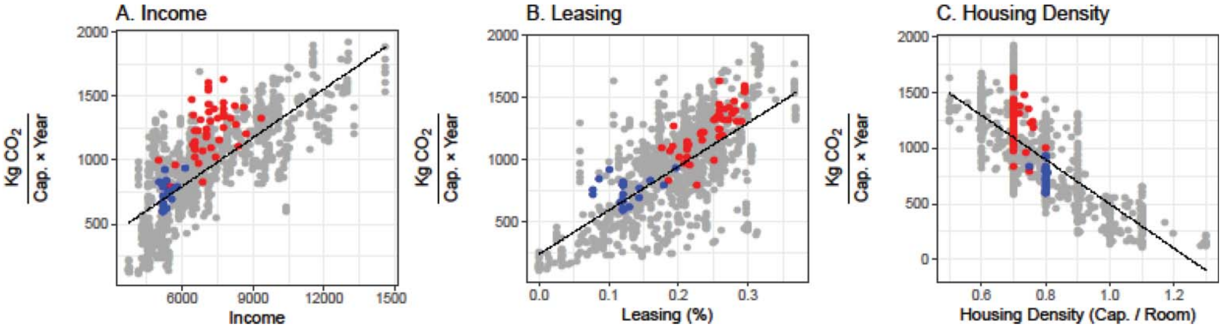
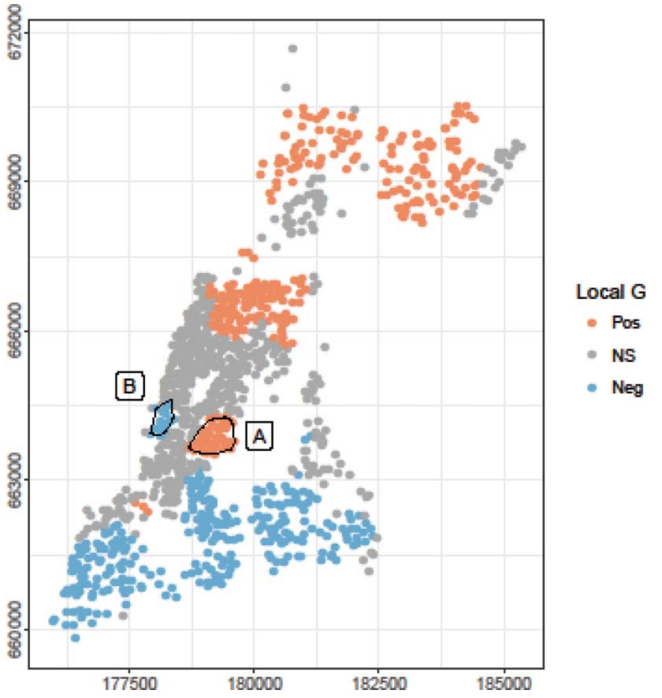


Figure 3. GHG vs. income (A), leasing (B), and housing density (C) with Clusters A and B marked. Cluster A from map 3 was color coded red, and cluster B was color-coded blue. Housing density appears to be the common denominator for areas of both clusters.



Map 3. Local GHG levels anomalies. Geographic clusters of ZIP code areas in which emission levels were higher than Tel Aviv average (pos) were color-coded orange (Local G positive). Agglomerations of lower-than-average (neg) emissions were color-coded blue (Local G negative). Clusters with average emission levels (NS) were color-coded gray (Local G not significant). Cluster A has much higher emission levels than expected. Cluster B has lower emission levels than expected.

A's high emission levels (red dots) diverge greatly from the trend. This indicates that in the case of that particular area in Tel Aviv, socioeconomic factors have a relatively smaller effect on travel and direct emission levels, i.e., the residents of this area have relatively high rates of travel and emissions even though they are socioeconomically average.

6. Conclusions

The growing interest in mitigating GHG emissions has generated various urban accounting frameworks. While there are many studies which provide detailed carbon footprint analyses across sectors, most focus on the entire city scale, thus failing to address the necessity for neighborhood-scale analysis. Studies that have analyzed sub-city emissions have mostly either used indirect data such as expenditure on fuel or low-resolution analysis. However, in order to advance a significant reduction of urban GHG emissions neighborhood-specific characteristics of various urban socio-spatial factors should be considered.

The research presented in this manuscript advances the ability to link the diverse spatial, socio-economic, and physical aspect of the urban environment with its carbon footprint.

By performing spatial statistical analysis on smaller urban areas than previously obtainable, the manuscript addresses the challenge of examining and understanding high diversity of urban areas in general and in the City of Tel Aviv-Jaffa in particular. Such detailed analysis allows exploring both the emissions related to specific parts of the city and the socio-spatial factors shaping those emissions. It can help identify socio-economic differences, linkages between urban characteristics (e.g., infrastructures, densification, accessibility to alternative modes of transportation, etc.), and point to their influence on the way urbanites use transportation. It can also be used in a future research as a statistically robust tool for modeling potential changes and examining the effectiveness of implementing GHG mitigation measures or to examine and challenge various emerging approaches (e.g., smart cities, new urbanism).

The preliminary findings of this study emphasize the need for tailored urban design and planning solutions, as opposed to the more generic approach to the connection between urban density and income to travel volume and related carbon footprint. However, in order for other cities to reach such a high-resolution and be able to perform this type of analysis, data should be available. In Israel, the Freedom of Information Act has made it possible for valuable physical and socioeconomic data gathered by governmental offices to be available to the public (with some security restrictions). In order for higher-level urban studies to occur, cities and governments should allow more access to relevant geographic data.

As part of Israel's commitment to advance GHG mitigation through the 2015 Paris Accord, this study is the first stage in a nation-wide program to quantify and analyze transportation and related emission in Israeli cities. In addition, such a pioneering study, which is based on real, high-volume data (not models), is at the forefront of a new wave of studies that use either large data bases or big-data as an important part of their research methodology. This trend will probably continue and will be used for other cities as more and more large data bases are released around the world.

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Appendix: Israeli Ministry of Transportation Database

Contents

The Israeli Ministry of Transportation 2013 Road Adequacy Test Database contains raw data about the entire Israeli motorized wheeled vehicle fleet—some ~2.5 million vehicles. Of these, this study used more over 100,000 entries of vehicles, which were all the privately owned cars registered under Tel Aviv residents.

Each entry provides information on a single vehicle's year of manufacture, Type (motorcycle/private/4× 4/etc.), maker, country of manufacture, car model, engine volume, owner's city code, owner's postal code, ownership type (owned/leased/company car/ etc.), date of last test, registered distance (km), date of previous test, registered distance (km).

Processing, normalization, and calculations

In order to calculate the distance traveled and the related emissions, we had to first normalize the time between checkups. Time difference between dates of checkups was converted to days. The distance traveled (difference between distance meter in both checkups) was divided by the amount of days between both checkups, giving distance traveled per day. Finally, this was multiplied by 365 to give the distance traveled (km) per year. Related emissions were calculated as was described in the article body.

Since the data contained some outliers, we chose to use median instead of mean kilometers traveled per vehicle per postal code. The number of vehicles in each postal code varied, but since data represented most, if not all registered vehicles in every postal code, there was no lack of robustness.

Data statistical description

After cleaning outliers and errors within the data base, a total of approximately 90,000 vehicles were included in the study, distributed between 1,121 postal code areas they were registered in. The average distance traveled per car per year was 14,367 km. The average engine volume was 1,590 ml, and the average direct CO2e emissions were 2,589 kg per year.

Additional description is provided in the next table:

2013 private transportation per postal code area data statistical description

Variable	min	Q1	Median	Mean	Q3	max
N cars	7	29	55	80.51	95	1,055.00
cars/capita	0.07	0.28	0.37	0.35	0.43	0.61
km/car/yr	6257.89	13199.76	14500.66	14367.04	15570.62	22662.60
CO_2/car/yr	1133.15	2382.11	2613.48	2588.85	2795.73	4177.51
km/capita/yr	637.51	3814.11	5442.61	5171.63	6598.07	10716.21
CO_2/capita/yr	110.08	681.47	975.32	932.69	1184.13	1921.24
eng. vol	972.82	1422.05	1542.35	1590.93	1692.08	9793.25

The above table shows a statistical summary of the data as is distributed and calculated per postal code area. For example, the first row titled "N cars" describes the number of cars in each area, with a minimum of 7 cars per area, a median of 55 cars per area, an average of 80.51 cars per area, and a maximum of 1,055 cars per area. the next rows describe statistics for atomization levels (cars/capita), distance traveled per car per year, direct CO_2e per car per year, calculated distance traveled per capita per year, calculated direct CO_2e per car per year, and finally, engine volumes. A distribution diagram further details these data: