INVESTIGATING THE SPATIAL VARIATION AND RELATIONSHIP BETWEEN BUILDING AND TRANSPORTATION ENERGY USE FOR RESIDENTS OF THE PHILADELPHIA METROPOLITAN REGION

Abstract

Buildings connect different networks of transportation and influence the patterns of transit routes. Integrated analyses of urban development—specifically transportation infrastructures and building construction—is critical to mitigating their environmental impacts. The building and transportation sectors together consume approximately 75% of CO_2 emissions. The goal of this study is to determine the spatial variation and relationship between building and transportation energy use for residents of multifamily units in the Philadelphia metropolitan region. Results indicated the average ratio of building to transportation energy use is 3:1. Transportation energy showed a trend of increasing consumption with distance to the urban core (which is the employment center for Philadelphia). Building energy consumption showed a weak negative correlation and was randomly distributed across the region. The driving factors for both building and transportation energy consumption are identified.

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Keywords

Urban Metabolism, transportation energy use, building energy use, Traffic Analysis Zone

Introduction

Over the last century, the US has been under intense urbanization (United Nations, 2014). As a result, urban transport, especially passenger transport, accounts for a significant portion (approximately 45%) of global energy consumption and is also a major contributor to greenhouse gas emissions (ITEDD, 2015). The transportation sector currently uses 27% of primary US energy, followed by residential building energy use at 22% (EIA, 2012). The residential buildings and transportation sectors together consume 43.2 quadrillions Btu (quads) of annual primary energy use.

Rapid urbanization and urban sprawl have not only consumed significant natural resources, such as water and fossil fuels but have also resulted in the transformation of settlement and building patterns through physical and social forms. Factors such as the location of residences and employment districts, social and economic status, neighborhood characteristics, as well as trip modal choice have been impacted (Anderson et al., 1996).

In addition, a person's lifestyle choices are recognized as a major driver of energy use and related global greenhouse gas emissions (Lenzen et al., 2011; Bio et al., 2013). Improved understanding of household building and transportation energy consumption is needed for reducing energy consumption and carbon emissions.

Many researchers (Pivo, 2012; Jain et al., 2014; Modarres, 2013) present disaggregated building and transportation energy use with individual households as observational variables. The impact of different structural, demographic and climatic factors on energy use are evaluated and reported in sector-specific analyses. The most common methods for these studies are multiple linear regression (MLR) and factor analysis (FA), stepwise regression, and support regression.

Transportation energy use data is often analyzed in aggregate where various sources of data are combined. These studies use vehicle miles traveled (VMT) by mode for regional transportation energy estimations. Others use ridership information as a proxy for transportation energy use. The most common finding from aggregate transportation analyses is that households in denser areas, in terms of population, buildings, or employment, use less energy (Makido et al., 2012; Rentziou et al., 2012). Households in sprawling areas have been found to use more energy (Zhao et al., 2013), in addition to households in higher income neighborhoods (Silva et al., 2007).

Although many studies investigate the impact of variables such as urban form and demographic factors that affect household energy consumption (Lee & Lee, 2014), there are very few studies that focus on both building and transportation energy in aggregate. In order to mitigate the impact of these two sectors on urban regions, it is important to quantify the relationship between building and transportation energy use. For example, if the findings show that some neighborhoods consume more energy for buildings than transportation, this suggests these households need more efficient energy systems and better conservation strategies. This could mean that prioritizing efforts to reduce transportation energy, by advocating for and building those region transit systems, is less critical than building energy conservation policies. Defining the energy relationship between each sector will help planners to predict the effects of different policies on total energy consumption. Furthermore, understanding the influence of demographic variables on travel and building energy demand in different regions can allow planners to implement effective sustainability policies and programs for urban regions.

The goal of this study is to identify parameters of building and transportation energy that are directly related, to examine the spatial variation of household energy use, and to determine the impact and relationship of different demographic and socio-economic variables in both transportation and building energy use. The case study is in Philadelphia.

Philadelphia provides an ideal location to analyze building and transportation energy because it hosts a wide variety of land use zones and transportation systems. By studying household energy use and correlating these to transportation energy use across Philadelphia, a better understanding of how different development strategies impact energy consumption and emissions can be obtained.

To address the objective, the research questions below will be answered:

- What is the ratio of annual building and transportation energy use per household and how does this change across the region?
- Is there a direct relationship between building and transportation energy use?
- What are the influential factors affecting both transportation and building energy consumption?

Methodology

DATA

The Philadelphia Office of Sustainability Benchmarking Scores and Reports dataset was obtained for large multi-family building energy consumption. This dataset lists 2015 annual energy consumption for 40 large-scale multi-family parcels (or tax lots) in Philadelphia. The definition of large-scale means a parcel have a multi-family building with a gross floor area greater than 50,000 square feet. The number of units for the 400 buildings in Philadelphia was provided to calculate the energy consumption per unit, as the measure of household energy consumption.

The *Delaware Valley Regional Planning Commission (DVRPC)* Travel Demand Model, TAZ's GIS data, and Household Travel Survey (HTS) were used to calculate household transportation energy consumption. The *DVRPC* Travel Demand Model was designed to simulate detailed travel patterns in nine counties of the Delaware Valley region including the Philadelphia Metropolitan Region. It is a traditional four-step travel model, used to estimate trip generation produced in each traffic analysis zone (TAZ), and trip distribution, mode choice, and route choice. Philadelphia includes 4000 TAZs through 18 Planning Districts (Main Zones). The HTS dataset was a year-long effort to collect travel data from households across the nine counties. Household, person, vehicle, and trip data were collected, including work and non-work trip generation, trip distribution, modal split, and average vehicle occupancy. The HTS sample size was 1327.

This study focused specifically on Philadelphia TAZs, which were extracted from all TAZs provided by the *DVRPC* dataset. As Figure 1 shows, two data sources (multifamily buildings and transportation TAZs) are combined to reference the buildings within each TAZ, using ArcGIS. Buildings that were not in a designated TAZ were assigned to the closest TAZ.

Figure 1 shows the map that contains buildings, TAZs, and 18 planning districts (Central, Lower Southwest, West Park, North, Lower South, Upper Far Northeast, University City, Upper North, Lower North, West, Central Northeast, South, and Upper Northeast).

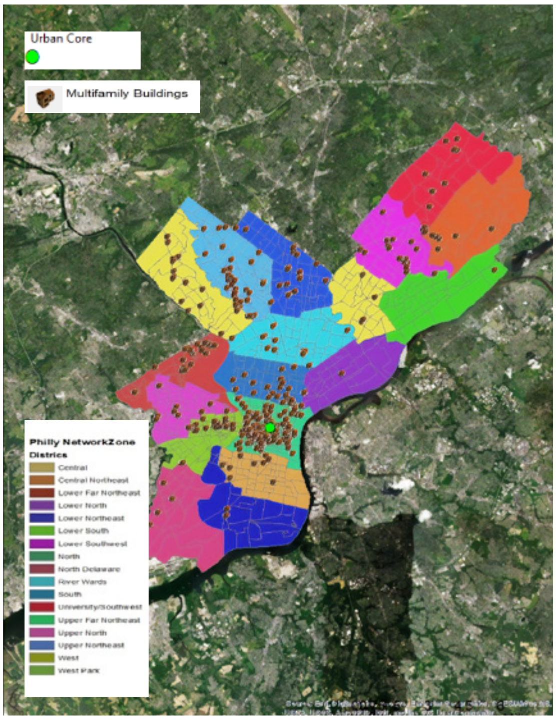

Figure 1: Philadelphia TAZs, Main Zones, and buildings.

MULTIFAMILY PARCEL HOUSEHOLD ANNUAL BUILDING ENERGY CONSUMPTION CALCULATION

One shortcoming of this study is our sample size was limited to buildings with a gross floor area greater than 50,000 square feet. Energy consumption of buildings with a gross floor area of less than 50,000 square feet is not reported in the benchmarking dataset. To estimate the household energy use at the building level, the energy use of parcels that contain more than one building was extracted from the analysis. Then, the annual energy consumption per unit was calculated by dividing total source energy by the number of units. Parcels with the abnormally high energy which may have resulted from misreported energy data or inaccurate data related to a number of units were removed.

TAZ DAILY TRANSPORTATION ENERGY PER HOUSEHOLD CALCULATION

Household transportation energy use depends on household trip generation, the mode involved, fuel type, and trip distance. The household transportation calculation method is adapted from Jiang (2010) and is based on DVRPC's reported daily travel patterns. Equations 1–3 present the calculations for household travel energy consumption. The aggregated energy for each TAZ and main zones are determined.

Fuel economy, fuel energy, and energy intensity factors are applied by the Department of Transportation (2013) tables.

Equations 1–3:

$$E_i^T = \sum_m E_i^m$$

$$E_i^m = \sum_j \sum_k (TF_j^m \, i.j.k * \frac{TD^{m_{i.j.k}}}{TO^{m_{i.j.k}}}) * EI^m$$

$$EI^m = FU^m * EC^m$$

i - i^{th}	Household
j - j^{th}	Person in the household
k	Purpose
m	Mode
Et_i	Total household daily transport energy consumption (kWh/HH)
$TFm_{i.j.k}$	Trip frequency for person j in household i for purpose k with mode m
$TDm_{i.j.k}$	Average trip distance for person j in household i for purpose k with mode m (Mile/Trip)
$TOm_{i.j.k}$	Trip occupancy for person j in household i for purpose k with mode m
EIm	Energy intensity factor for mode m (kWh/mile)
FUm	Fuel economy factor for mode m (L/mile or KWH/mile)
ECm	Energy content factor for mode m (kWh/L)

RELATIONSHIP BETWEEN ENERGY CONSUMPTION AND DISTANCE TO URBAN CORE (BIVARIATE REGRESSION)

Both multifamily parcels and TAZ transportation energy consumption were regressed on the distance to urban core (Equation 4). This bivariate regression tests the effect of proximity to the urban core on household energy consumption.

Each parcel was assigned a centroid point and assigned a daily transportation energy use per household in the TAZ. To define the urban core, several techniques for delineating the urban core can be applied. One way is by using common knowledge to find the location centers of employment and population (Liu & Sweeney, 2012; Zhu et al., 2013). The central district (Philadelphia city center) is defined as an urban core and contains the largest employment center and has high traffic and transit use patterns. The Euclidean distance (i.e., straight line or 'as the bird flies') to the urban core was determined in ArcGIS.

Equation 4:

$$Y1 = \beta 1 \, X1 + \beta 0$$
$$Y2 = \beta 2 \, X1 + \beta 0$$

Bivariate linear regression of energy on distance urban core:

- Y1 = Daily Transportation Energy Use per Household
- Y2 =Building Energy Use per Unit
- X1 = Distance to Urban Core
- ß1-3 = Slopes for different tests
- ß0 = Intercept

RELATIONSHIP BETWEEN BUILDING AND TRANSPORTATION ENERGY USE (BIVARIATE REGRESSION)

The second research question was to determine if there was a direct relationship between household transportation and building energy consumption. To do this, daily transportation energy use per household was regressed on building energy use per unit (Equation 5).

Daily transportation energy use was considered a dependent variable and annual building energy use was the independent variable. This is because building energy use is a much greater value than daily transportation use. This only impacts the coefficient value, and not the significance and correlation R2.

Equation 5:

$$Y1 = ß1\ X1 + ßo$$

Regression for correlation between two energy consumption values:

— Y1 = Daily Transportation Energy consumption per Household
— X1 = Building Energy per Unit
— ß1 = Slope of X1
— ßo = Intercept

Abnormally high values for consumption were removed. There were a number of outliers with the values significantly above the mean. To control the outliers, all points above the 97.5 percentile or below the 2.5 percentile were removed.

EFFECTS OF STRUCTURAL AND DEMOGRAPHIC FACTORS ON BOTH BUILDING AND TRANSPORTATION ENERGY (FEATURE IMPORTANCE)

The third research question was to determine the effects of structural and demographic variables on both transportation and building energy consumption. To do this, machine learning random forest algorithms were applied. Random forest is used to find the most influential factors by predicting household transportation energy use and building energy use. Random forest or random decision forest is an ensemble method which fits and combines multiple decision tree predictions.

Random forest for regression has the advantage of being insensitive to decision trees hyper parameter values (Dudek, 2014). Random forests are also less prone to overfitting because of its characteristic ensemble of decision trees trained on different parts of the same training set. One benefit of a random forest is that it can calculate the feature importance. It selects the features that best influence the target variables, using algorithms to identify which is the best set of features from a large space. In order to compare the common variables, the feature importance of building and transportation energy use was compared at the TAZ level.

Results

TRANSPORTATION AND BUILDING ENERGY CONSUMPTION IN PHILADELPHIA

The average ratio of annual building and transportation energy consumption per household is 3:1. Annually, multifamily units in Philadelphia use approximately 3.5 times more building energy than transportation energy. Zones identified as Center and Lower Southwest have the greatest building energy. Upper and Upper Far Northeast have the greatest annual transportation energy use; however, there is a little difference between other regions (Figure 2).

Mapping daily transportation energy use per household shows a spatial pattern in which the lowest energy consumption is located in proximity to the central core (City Center). In contrast, TAZs in the Lower Far Northeast have the greatest transportation energy consumption (Figure 3). The annual building energy use per unit shows less of a spatial pattern. Nevertheless, the ratio of annual building energy use per unit and annual transportation energy per household shows an approximate trend, with lower ratios occurring further from urban cores (Figure 4).

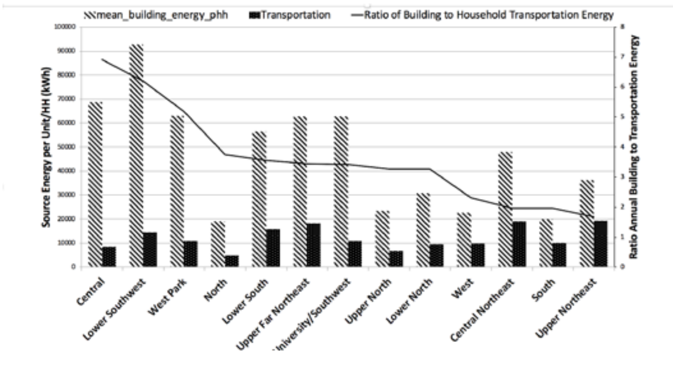

Figure 2: Annual building energy per unit, annual transportation energy per household, and ratio of annual building to transportation energy.

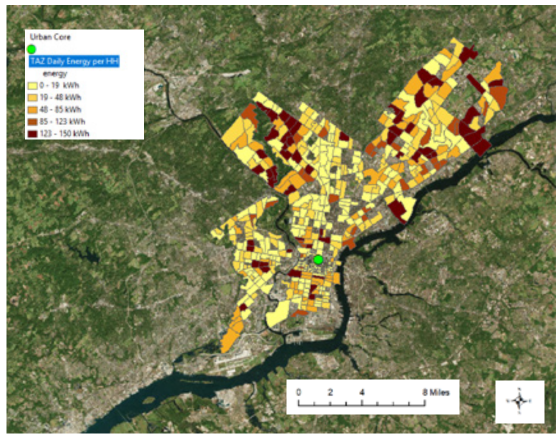

Figure 3: TAZ daily transportation energy use per household map.

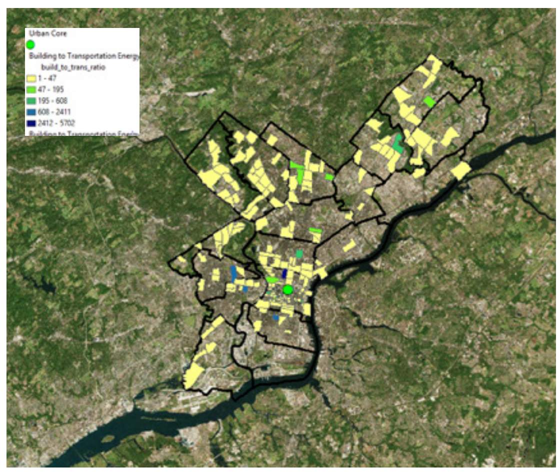

Figure 4: Ratio of annual TAZ building to transportation energy per household map.

RESULTS OF THE STATISTICAL ANALYSIS

Table 1 shows the descriptive statistics for some key demographic variables. 44.9% of surveyed households are single occupant while the next largest share (household size of 2) is 34.89%. 34.6% of households have an income of less than $25K USD and 27.4% have higher than $100K USD. The aver-Zage daily travel distance of households is 12.6 km (7.8 miles).

Household Demographics		
Household Size	1	44.9%
	2	34.85%
	3	10.52%
	4	6.72%
	>4	2.9%
Description of Residence	Single family house not attached	11.6%
	Single family house attached	59.48%
	Building with 2-4 apartment	7.43%
	Building with 5-19 apartment	6.12%
	Building with 20 or more apartments	14.97%
Household annual income	<$25k	34.6%
	$25k-<$50k	27.4%
	$50k-<$100k	20.2%
	$100k+	27.4%
Household total of vehicle	Min	0.00
	Max	7.00
	Mean	1.00
	Std.	0.81
Household total of Bicycle	Min	0.0
	Max	9
	Mean	1
	Std.	2.5

Trip characteristics		
Number of trip	Min	0.0
	Max	30.0
	Mean	5.83
	Std.	4.96
Number of Motorized trip	Min	0.0
	Max	27.0
	Mean	3.0
	Std.	3.9
Number of Non-Motorized trip	Min	0.00
	Max	26.0
	Mean	2.79
	Std.	3.80
Travel distance	Min	0.0044
	Max	120.47
	Mean	7.8
	Std.	10.75
Travel time	Min	0.085
	Max	2077.3
	Mean	22.67
	Std.	47.9
Average Household trip by ethnicity	Black	4.77
	White	6.64
	Hispanic	6.87
	Other	5.61

Table 1: Descriptive statistics–household and trip characteristics.

The scatter plot (Figure 5) shows a significant inverse relationship between distance to the urban core and annual building energy use per unit. And as expected, a positive significant correlation is shown between distance to the urban core and daily transportation energy per household for TAZ (Figure 6).

The analysis of annual energy per unit and daily transportation energy use per household regression demonstrates that there is a correlation between building and transportation energy use. It is a slight but statistically significant inverse relationship (Figure 7).

We analyzed common variables in both transportation and building energy use to find which features would emerge as important effects. The importance of a feature is computed as the (normalized) total reduction of the Mean Squared Error (MSE) due to each feature. Figure 8 shows the influential factors for transportation energy use at the TAZ level. Travel mode, travel distance, the total number of trips, and employment density have the strongest effect on transportation energy consumption.

The feature importance plot of building energy consumption at the TAZ level (Figure 9) shows employment density, number of schools, and income are the most important factors influencing building energy consumption.

Comparing the feature importance values for building energy and transportation energy can reveal patterns of similarity and differences between features affecting the two sectors (Figure 10). The TAZs with more employment density, households with higher income, a greater number of schools, and retail density correlate with more building and transportation energy consumption. Trip mode and number of motorized trips have significant influence in predicting transportation energy only.

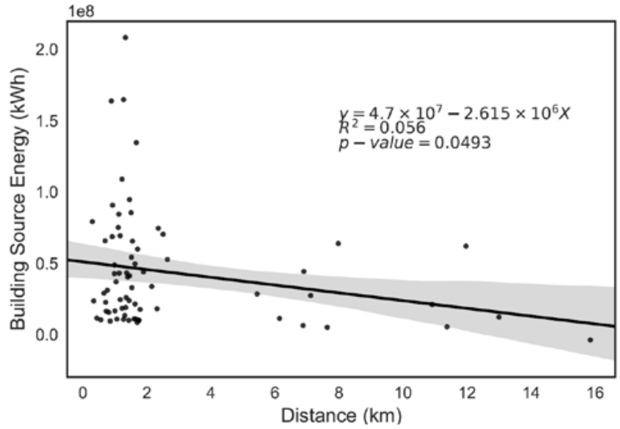

Figure 5: Scatterplot of building energy regressed on distance to urban core.

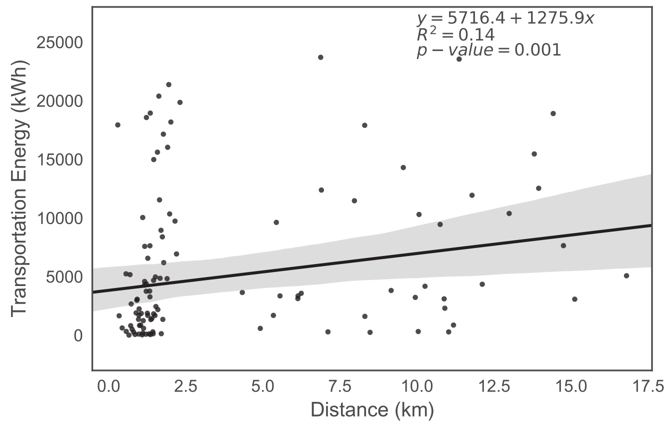

Figure 6: Daily transportation energy per household regressed on distance to urban core.

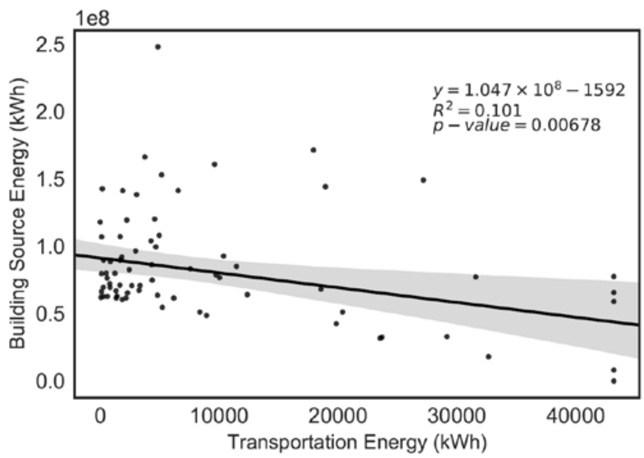

Figure 7: TAZ daily transportation energy regressed on annual building energy per unit.

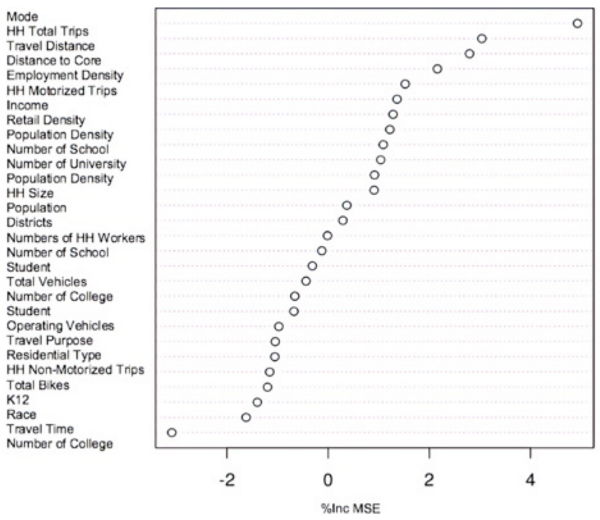

Figure 8: Random Forest feature importance plot for transportation energy use.

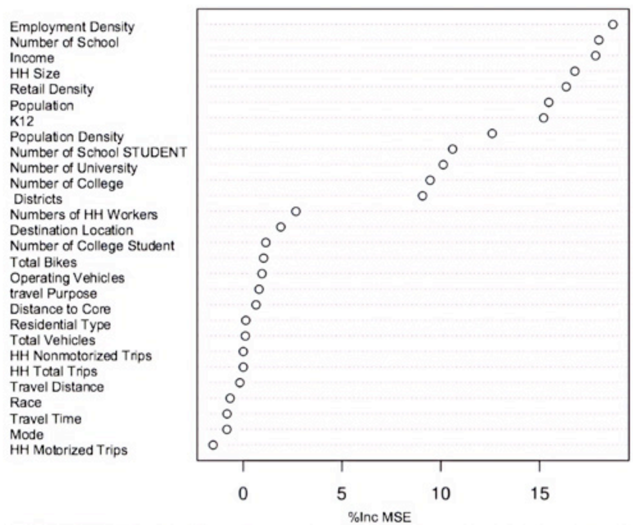

Figure 9: Random Forest feature importance plot for building energy use.

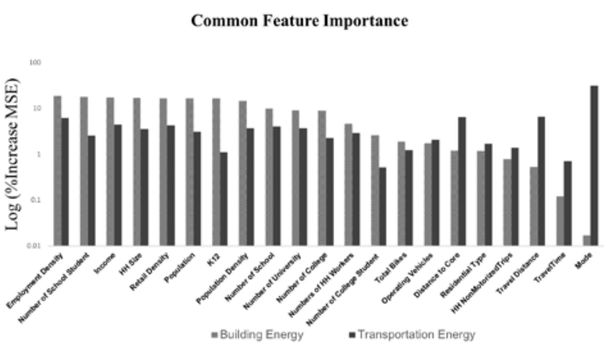

Figure 10: Common feature importance between transportation and building energy use.

Conclusion

The average ratio of annual building and transportation energy consumption is 3:1. We found a clear spatial pattern for transportation energy, with distance to the urban core. We also found a discernible pattern in the ratio of building to transportation energy per household, with lower energy consumption ratios occurring at increasing distance to the urban core.

A key finding of this study is that residential multifamily building and transportation energy use are inversely related. We do not know if this trend holds for different types of buildings given that this analysis was limited to large multifamily building types. We expect that if different building types were included in the study, it is possible that a different pattern would emerge. It may be that the correlation between distance to urban core and transportation energy would be positive and significant.

Indeed, with TAZs that are far from the center, it is not surprising that those households would present a greater transportation demand. This also points to issues of convenience and access to public transit as an important factor for determining household transportation energy demand. This proves to be true especially for households within the central core that have the luxury of multiple transit options. Also, the feature importance results show that employment density and income are the most important factors influencing both building and transportation energy consumption.

For future studies, we plan to conduct this analysis with building data that includes multiple dwelling types. And we intend to include Census polls and neighborhood characteristics, in addition to household characteristics, to better examine the diversity of data points that describe urban systems.

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