Transit Oriented Development and
The Potential for VMT-related
Greenhouse Gas Emissions Growth Reduction

By

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Preface

The shape our cities take through development, infrastructure and transportation has a powerful effect on greenhouse gas production. Transportation contributes an estimated 28 percent of all GHG emissions -- and as much as 40 percent in some states such as California.[1] Transit-oriented development -- a mix of residential and commercial development within walking distance of public transportation -- can play a substantial part in reducing greenhouse gas emissions.

By simply living in a neighborhood that is within a half mile of public transportation, this study shows that in the Chicago Metropolitan Region such households have lower transportation-related greenhouse gas (GHG) emissions from auto use, 43 percent lower than households living in the average location in the Chicago Metropolitan Region. Households living in a downtown – which typically have the highest concentration of transit, jobs, housing, shopping and other destinations – have 78 percent lower emissions. While this study focuses on the Chicago Metropolitan Area, similar household behavior is observed in other metropolitan area, and is predicted to result in similar reductions.

In order to reduce greenhouse gas emissions we must reduce driving. And in order to reduce driving we have to make it possible for people to walk and bike and take transit, in part by rebuilding our communities so that people live close to jobs, schools, shopping and other destinations – a more compact way of living. This study reveals that, when households choose to live in such neighborhoods they do indeed reduce their driving. Continued sprawling development with an accompanied increase in miles driven (projected to rise a staggering 60 percent by 2030, according to the U.S. Department of Transportation) will negate any gains from more efficient cars and low-carbon fuels.

Location matters. The study shows that for every household, the number of cars owned and the number of miles driven is largely determined by where that household lives. Take, for instance, a worker who lives in a suburb with no access to transit. His or her household will have an average carbon output related to vehicle miles travelled of 7.15 tons of CO_2e per year. If however, he or she decides to move into the city, near a transit system in a walkable neighborhood with access to jobs and amenities, this household's average VMT-related carbon output drops to 4.07 tons. That is a 43 percent reduction from levels of emissions that would have taken place without those strategies.

This study also examines real-world potential to use transit and transit-oriented development as an emissions reduction strategy in three different future development scenarios for the Chicago metropolitan area. The first is business-as-usual. The second assumes that residential and employment growth will continue at the same rate in the city and in the suburbs, but that all of this growth will be accommodated in the half-mile radius around stations. The second scenario is based on growth projections from Chicago's regional planning agency. The third scenario explores concentrating housing and jobs within a half-mile radius of transit stations, regardless of growth projections. The second scenario reduces emissions by 28 percent from levels of emissions growth that would have taken place without those strategies, while the third scenario results in a 36 percent reduction from levels of emissions growth that would have taken place without those strategies. (The study assumes no

[1] U.S. EPA. "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2007." April 15, 2009. Table ES-8.
http://epa.gov/climatechange/emissions/usinventoryreport09.html
http://www.climatechange.ca.gov/inventory/index.html

additional investment in transportation and the same number of car owners). In short, transit-oriented development offers a way to build the future that provides for sustainability and affordability.

Clearly, how a region chooses to grow has a dramatic and substantial effect on GHG emissions because it determines how many cars a household needs to own and how many miles those cars will be driven. These development scenarios highlight the need to look at the impact of development on climate change in a new and more comprehensive way. Greenhouse gas emissions will increase over 2000 levels in each scenario due to population and employment growth. But with a focused TOD growth strategy a region such as Chicago could reduce future VMT-related GHG by 36 percent from levels of emissions growth that would have taken place without those strategies.

The study is especially timely as states, regions and local governments across the country consider ways to reduce emissions that contribute to climate change. The study highlights the importance of creating neighborhoods where households can choose to live more sustainably, and concludes that transit-oriented development is a strategy that should be vigorously pursued.

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Executive Summary

Transit-oriented development, or TOD, offers a mechanism to create efficient urban form, and provides a choice for development with a lower carbon footprint than traditional development. Defined as a type of development that occurs around transit nodes, resulting in a compact, mixed use, pedestrian oriented type of neighborhood, TODs provide an opportunity to reduce household vehicle travel and a reduced carbon footprint. This report examines the greenhouse gas reduction potential of TOD, in terms of the transport sector, and measures the emissions reduction potential of six types of neighborhoods centered on fixed rail transit stops.

The greenhouse gas emissions from the transport sector are approximately 28 percent of all greenhouse gas emissions for the United States. The emissions from household auto use are approximately 61 percent of all of the transport sector's emissions. Therefore, this paper is examining the reduction potential for approximately 17 percent of all of a region's greenhouse gas emissions. Transportation's share of emissions can be even higher in regions with cleaner electricity or fewer industrial emitters.

Specifically, this research calculates the carbon emissions reduction potential associated with household vehicle travel, and how it is affected by urban form and access to transit. For the purposes of this research, the study will focus on households located within "transit zones," defined as the geographic areas within a half mile radius of a fixed rail station or stop.

Estimates for household vehicle miles traveled at the neighborhood level are an essential component for analyzing household travel behavior and the potential for vehicle miles traveled (VMT)-related emissions reduction. This report employs the work done by the Center for Neighborhood Technology and the Center for Transit Oriented Development, in collaboration with The Brookings Institution, which developed the Housing and Transportation Affordability Index (H + T ^{SM} Index). The index and its results provide a reliable method to model household VMT at the Census block group level, which is used to calculate the greenhouse gas emissions associated with household vehicle use.

The differences in transportation demand of a household in a transit zone as compared to a household in general will be examined, and finally a number will be calculated in annual tons of CO_2e reduction that can be attributed to location. This analysis will employ the results of the H + T Index analysis for 54 metros in the U.S, and data from the National TOD Database, also developed by CTOD, which provides Census and Local Employment Dynamics data for 3,572 fixed rail stations in the U.S.

By analyzing several variables of the H + T Index models as they occur in transit zones, such as residential units per acre, transit connectivity, and employment proximity, it is possible to group all rail transit zones in the U.S. into six distinct "types."

Name of Transit Zone Type[2]	Average Residential Density (Households per Residential Acre)	Average Employment Proximity (Jobs/Sq Mile)	Average Block Size (Acres)	Average Transit Access (Walkable Transit Options)	AMI[3] CO_2e/HH (Metric Tons)	Local[3] CO_2e/HH (Metric Tons)
Highest Location Efficient Transit Zones	61.7	671,546	3.4	97.7	1.46	1.86
High Location Efficient Transit Zones	30.4	171,750	4.1	25.6	2.66	3.57
High Medium Location Efficient Transit Zones	9.3	66,973	5.4	13.2	4.61	5.25
Medium Location Efficient Transit Zones	3.8	46,086	12.6	6.4	6.06	6.29
Low Location Efficient Transit Zones	4.5	41,088	9.2	1.7	6.51	6.65
Lowest Location Efficient Transit Zones	0.7	17,065	39.6	0.9	8.81	8.47

Table 1: Six National Transit Zone Types - Executive Summary

This typology has been ordered by the amount of GHG emitted per household. It is important to emphasize that this classification is for all transit zones whether or not they are characterized by transit-oriented development. However, Table 1: Six National Transit Zone Types - Executive Summary shows that if more transit zones were developed in a manner that made them fit into the top two or three types, by using TOD, significant reductions in household greenhouse gas (GHG) emissions could be expected in these types of neighborhoods.

[2] The names assigned are arbitrary and are for reference purposes only; they are not meant to have any value judgments associated with them.
[3] Note that the "AMI" stands for the "Area Median Income" and for the purposes of this report an "AMI Household" earns the annual area median income, has the average number of people and workers in it, and they commute the average time to work. This typical household is useful so that we can compare results, i.e. "the average household will emit X less tons of CO2e when they live in Location A rather than Location B." However, in order to examine how households that are located in a specific area behave, we have also modeled the "Local Households," for these results we use the household income, size, workers and commute time from the household that actually lives in the Census Block Group in 2000. These local measurements are useful when examining the overall effect of location efficiency, i.e. "households in Location A emit Y less tons of CO2e than those living in Location B." These "Local" model runs are also useful when we are modeling the total overall emissions of the region or sub-region.

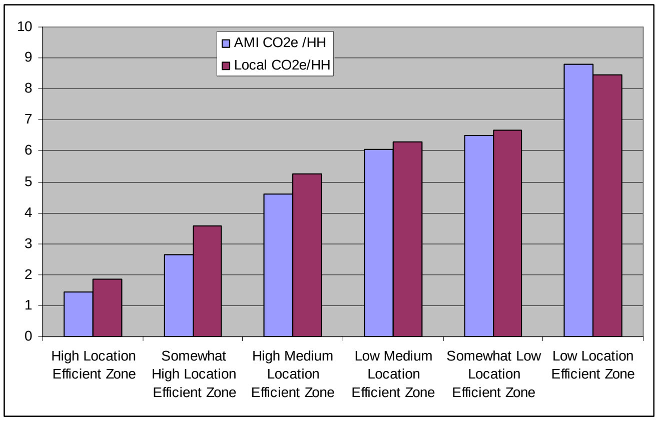

Figure 1: CO2e/Household from AMI and Local Households[3] by National Transit Zone Types - Executive Summary

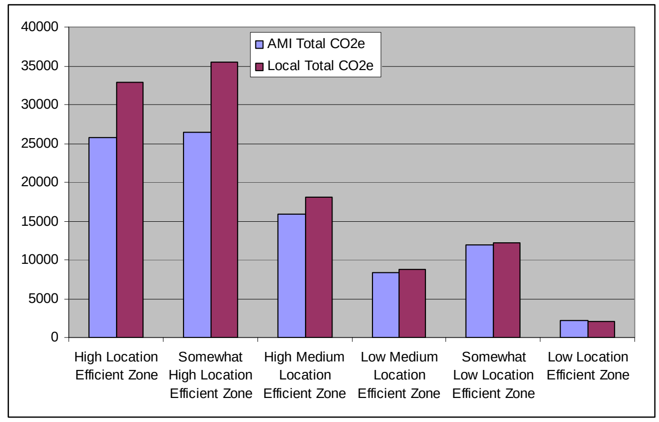

Figure 2: Zone Total CO2e emissions from AMI and Local Households[3] by National Transit Zone Types - Executive Summary

Even though location efficient zones are characterized by higher total emissions, the tables above illustrate that emissions per household are actually lower in more location efficient zones. The average modeled household GHG emissions associated with VMT for all the Census block groups, both within and outside of a transit zone, in 52 metropolitan areas studied is 6.7 metric tons CO_2e/Household[4]. The average household emissions allow us to compare how an AMI[3] household living in the average place differs from one located in the various types of transit zones. Table 2: GHG Reductions by National Transit Zone Type - Executive Summary shows this difference.

Name of Transit Zone Type	Average Number of Households in Transit Zone	CO_2e/HH (Metric Tons)	Total CO_2e (Metric Tons)	CO_2e/HH for Average Census Block Group (Metric Tons)	Total CO_2e from an Average Census Block Group (Metric Tons)	Reduction (Metric Tons)	Percent Reduction
Highest Location Efficient	17,668	1.46	25,795	6.7	118,373	92,578	78%
High Location Efficient	9,938	2.66	26,434	6.7	66,583	40,148	60%
High Medium Location Efficient	3,434	4.61	15,830	6.7	23,007	7,177	31%
Medium Location Efficient	1,390	6.06	8,421	6.7	9,310	889	10%
Low Location Efficient	1,840	6.51	11,977	6.7	12,326	350	3%
Lowest Location Efficient	251	8.81	2,208	6.7	1,679	-529	-31%

Table 2: GHG Reductions by National Transit Zone Type - Executive Summary

4 Note that average household emissions are slightly larger than that shown in Table 2: GHG Reductions by National Transit Zone Type - Executive Summary since the Chicago metropolitan area is in general more location efficient that the average of all 52 metropolitan areas.

The table above shows that the carbon footprint for a household varies greatly depending on where a household chooses to live. The best place to reduce transportation household greenhouse gas emissions is in the “Highest Location Efficient Zones,” where the household could expect to reduce its impact by as much as 78 percent, compared to living in the average place.

The analysis is expanded to study the emissions reduction potential of three different development scenarios for the Chicago metropolitan area. In order to accommodate the growth projected by the regional planning agency, Chicago Metropolitan Agency for Planning (CMAP), three growth scenarios were devised that will allow an estimation of the GHG reduction potential of promoting TOD in the entire region. The first scenario will estimate what would happen if there were no TOD initiatives, or a “business as usual” scenario. The second scenario will look at accommodating all employment and household growth within the transit zones, and constrain that growth to the CMAP projection of the ratio of growth in Chicago and the suburbs. This scenario is “constrained” by retaining the projected proportion of population growth in the suburbs and the city of Chicago. Labeled “TOD with Constraints,” this scenario will give a middle ground of potential reductions that are attainable. Finally, the third scenario allows the growth to occur in the transit zones proportional to the land use development that is there now. This “TOD with No Constraints” sets an upper limit to what GHG reductions can occur if all growth were accommodated in only transit zones.

The table below summarizes the differences in GHG production from the three scenarios above. Note that, due to population and employment growth, GHG is expected to increase from 2000 levels. However, the level of increase varies remarkably among the three scenarios.

	2000	2030		
		Business as Usual (BAU)	TOD with Constraints	TOD with no Constraints
VMT Chicago Near Transit	7,745,741,757	8,285,173,170	8,687,254,460	11,660,137,831
VMT Chicago Not Near Transit	4,285,555,892	4,603,070,257	4,075,821,974	3,964,404,884
VMT Suburban Not Near Transit	24,040,998,557	29,395,198,100	23,029,662,247	23,440,782,201
VMT Suburban Near Transit	10,883,593,731	13,204,330,162	17,311,117,363	13,365,757,580
VMT Total Region	46,955,889,937	55,487,771,688	53,103,856,043	52,431,082,496
Increase of VMT from 2000		8,531,881,752	6,147,966,107	5,475,192,559
CO_2e (Metric Tons)	21,280,502	25,140,539	24,057,193	23,753,041
Increase in CO_2e from 2000		3,860,037	2,776,691	2,472,539
CO_2e Reduction from BAU			1,083,346 (28%)	1,387,498 (36%)

Table 3: Summary of Aggregate GHG Emissions from 2030 Growth Scenarios in Six-County Chicago Region – Executive Summary

The results of this analysis of households, transit zones, and regional development scenarios indicate that location matters - for any given household the number of autos it owns, and how many miles its members drive them, is largely determined by where the household lives. A household’s VMT and carbon footprint can be dramatically reduced by living in a location efficient neighborhood, with compact development within half a mile of a transit stop. By simply living in a central city near transit, the average household can reduce its GHG emissions by 43 percent. In the most location efficient transit zones, a household can reduce its GHG emissions by as much as 78 percent. Finally, the total GHG emissions from household transportation depend on how that region chooses to grow. VMT-related

GHG emissions growth can be reduced by 36 percent if development in that region proceeded in a more compact and efficient manner. All this leads to the potential for TOD to contribute to reductions of future VMT-related GHG emissions. In order to create neighborhoods where households can make the choices to live efficiently and reduce their impact on climate change, TOD should be vigorously pursued.

1 Introduction

Transit-oriented development, or TOD, is a term used to describe a type of development that occurs around transit nodes, and results in a compact, mixed use, pedestrian oriented type of neighborhood. It also offers a mechanism to create efficient communities, and provides a choice for development with a lower carbon foot print than traditional development. This report examines the greenhouse gas reduction potential of TOD development, in terms of the transport sector. Specifically, this research calculates the carbon emissions reduction potential associated with household vehicle travel, and how that is affected by urban form and access to transit. For the purposes of this research, the study will focus on households located within and outside of "transit zones," defined as the geographic areas within a half mile radius of a fixed rail station or stop.

Reconnecting America and the Center for Transit-Oriented Development define TOD as:

> "Transit-oriented development …..is defined as higher-density mixed-use development within walking distance – or a half mile – of transit stations."
>
> A performance-based definition also includes efforts that:
> - Increase "location efficiency," so people can walk, bike, and take transit
> - Boost transit ridership and minimize traffic
> - Provide a rich mix of housing, shopping and transportation choices
> - Generate revenue for the public and private sectors, and provide value for both new and existing residents
> - Create a sense of place
>
> We believe that TOD is really about creating attractive, walkable, sustainable communities that allow residents to have housing and transportation choices and to live convenient, affordable, pleasant lives – with places for our kids to play and for our parents to grow old comfortably."[5]

This paper will employ this definition of TOD to evaluate how such development has the potential to provide a lower carbon footprint for the households that locate in it. In exploring this relationship, the study will focus first on a single household and its transportation demand, how that varies depending on where it locates, and in particular, what efficiencies are available for it when locating in a TOD. Then, the greenhouse gas (GHG) reduction potential within a single transit zone TOD will be examined, looking at various types of transit zones[6] and the amount of emissions reduction that could be realized. Finally, GHG reduction potential will be examined at the regional level, including the potential of TOD development to lower a region's carbon footprint.

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[5] http://www.reconnectingamerica.org/public/tod

[6] For the purposes of this paper we will define a **transit zone** as a ½ mile radius around a fixed guide way transit station, such as a subway, or a commuter rail station.

2 Climate Change Metrics and TOD

To begin, it is useful to review some basics of climate change and greenhouse gas production. Greenhouse gas accounting tracks the amount of carbon put into the atmosphere by human behavior. This can be measured in several different ways, but the most common measure is metric tons of CO_2e that are produced by all human activity.

The United Nations (UN) has established The Intergovernmental Panel on Climate Change (IPCC) to monitor greenhouse gas emissions. The IPCC describes itself as follows:

> The IPCC was established to provide the decision-makers and others interested in climate change with an objective source of information about climate change. The IPCC does not conduct any research nor does it monitor climate related data or parameters. Its role is to assess on a comprehensive, objective, open and transparent basis the latest scientific, technical and socio-economic literature produced worldwide relevant to the understanding of the risk of human-induced climate change, its observed and projected impacts and options for adaptation and mitigation.[7]

The IPCC has broken down human activity as it relates to climate change into a hierarchical series of sectors. The top level of this hierarchy includes energy; under energy is the transport sector. This report is focused on the transport sector.

The IPCC defines a greenhouse gas as:

> …a gas that absorbs radiation at specific wavelengths within the spectrum of radiation (infrared radiation) emitted by the Earth's surface and by clouds. The gas in turn emits infrared radiation from a level where the temperature is colder than the surface. The net effect is a local trapping of part of the absorbed energy and a tendency to warm the planetary surface. Water vapor (H_2O), carbon dioxide (CO_2), nitrous oxide (N_2O), methane (CH_4) and ozone (O_3) are the primary greenhouse gases in the Earth's atmosphere.[8]

There are other greenhouse gases; the Kyoto Protocol commits countries to reduce six of these greenhouse gases, To simplify the accounting the IPCC has defines "Equivalent CO_2" or CO_2e as "Equivalent CO_2 is the concentration of CO_2 that would cause the same amount of radiative forcing as the given mixture of CO_2 and other greenhouse gases." [8]

Thus, the consistent measure of greenhouse gas production is metric tons of CO_2e produced. It may be important to note that, often, greenhouse gas production is measured in terms of carbon, but this complicates matters since the carbon content of the different greenhouse gases vary, and do not directly convert to greenhouse warming potential. However, the simple ratio of carbon to CO_2 is a way to convert to CO_2. For example, a carbon footprint in terms C metric tons of carbon would be

[7] http://www.ipcc.ch/about/index.htm
[8] http://www.ipcc.ch/pdf/glossary/ipcc-glossary.pdf

approximately equivalent to C*44/12 of CO_2 (since the atomic mass of CO_2 is ~44 and the atomic mass of carbon alone is ~12).

Converting from vehicle miles traveled to metric tons of CO_2e requires an emission factor for gasoline and an average fuel efficiency (in Miles per Gallon or MPG), to convert from miles to gallons of gasoline. The emission factor of gasoline is customarily applied to every liter of gasoline burnt, which translates into 0.0024 metric tons of CO_2e per liter created, or 0.0092 metric tons per gallon. In the year 2000, the average fuel efficiency for all the autos on the road was 20.3 MPG according to the Federal Highway Administration, and this metric will be used for this paper. There is a recognition that the type of auto owned by a household will vary with location (higher income areas may have larger cars and more SUVs), but this average is employed here in order to make comparisons across geographic areas. Further research would be useful to develop a better emission factor, taking into account local vehicle speed, and fleet age and mix. However for the purposes of this paper the overall average is accurate enough to reveal the underlying reductions from TOD.

3 Household Transportation Use and Demand

"A household living in a dense urban location does not drive as much, or spend as much money on transportation, as the same household living in a sprawling suburban location." This statement is often quoted as a known fact, but putting an actual number to it has been an elusive endeavor. This section will employ the work done by the Center for Neighborhood Technology and the Center for Transit Oriented Development, in collaboration with The Brookings Institution, which developed the Housing and Transportation Affordability Index (H + T Index). The index and its results, including local modeled VMT, will be used to interpret the greenhouse gas reduction potential of the above statement. The differences in transportation demand of a household in a TOD transit zone as compared to a household in general will be examined, and finally a number will be calculated in annual tons of CO_2e reduction that can be attributed to location.

In the following section, the H+T Index model and its usefulness in estimating the climate benefits of TOD is described. The Chicago region is used as an example. It is important to note that although the Chicago metropolitan area has the second largest transit system in the country, and has dense urban neighborhoods that are not often present in other smaller regions, the general trends demonstrated here are consistent all over the country in regions varying from New York City to Ft. Wayne, Indiana.

3.1 Household Transportation Model

Predicting and measuring the amount of transportation demand is a very important component of transportation planning. Most transportation demand models have focused on peak travel times in order to better predict congestion. The primary time interval for this type of modeling is the morning and afternoon rush hour and focuses largely on journey to work trips. The most common method to examine this type of demand is the "four-step model" of trip planning: trip generation, trip distribution, mode choice, and trip assignment.[9] These models are successful in modeling congestion on a region's streets, roads and highway network. However these models are optimized for regional transportation planning, and lack the ability to assign total households transportation use. The journey to work, according to the 2001 National Household Travel Survey, is only 17.8 percent of all household trips.[10] Therefore, the traditional approach to transportation demand modeling is not adequate for assigning total household auto use.

The household transportation model developed for the H+T Index uses a different approach to examine household transportation. By looking at fine geographical segmentation, and examining transportation use in the past as a function of household and local environment variables, a more complete picture of household transportation use is available. The H+T Index has been described in detail in other publications.[11] The model demonstrates how location is the major determining factor of the number of autos a household owns, and how far they drive those autos. One of the key outputs of the model is average household vehicle miles traveled (VMT) at the Census block group level, which provides the basis for calculating GHG reduction potential based on housing location. This model is based on a multidimensional regression analysis, where a formula describes the relationship between

[9] See for example http://www.mwcog.org/transportation/activities/models/
[10] http://www.bts.gov/publications/highlights_of_the_2001_national_household_travel_survey/pdf/entire.pdf
[11] Haas, Peter M., Makarewicz, Carrie, Benedict, Albert, and Bernstein, Scott (2008).Estimating Transportation Costs by Characteristics of Neighborhood and Household. *Journal of the Transportation Research Board. No. 2007*, 54-61.

dependent variables (auto ownership, and driving) and independent household and local environment variables. See Appendix 1 for a summary of the development of the Household Transportation Model.

Figure 3 shows a schematic of how this model works. Four environment independent variables and four household variables are combined with a set of formulas to model the number of autos the average household with these characteristics will have, and how far households will drive those autos.

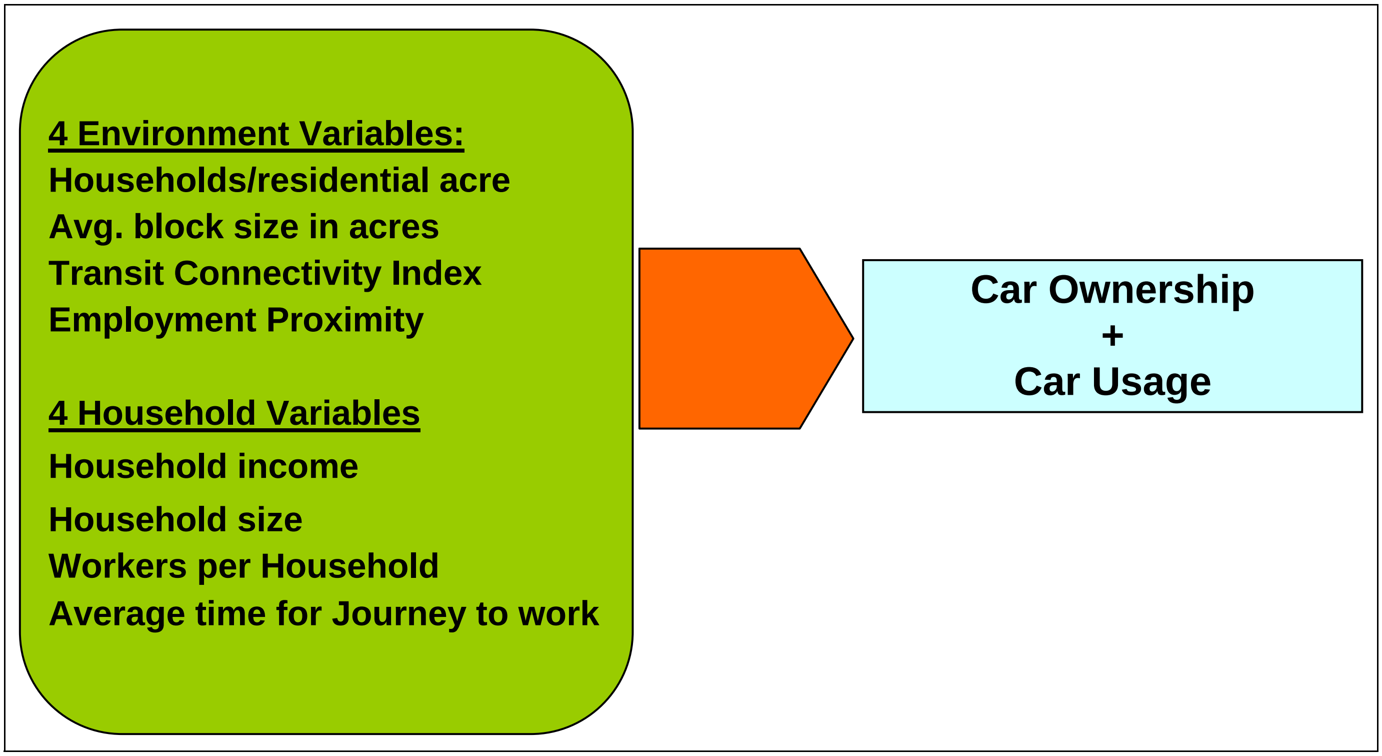

Figure 3: Schematic of Household Transportation Model

3.2 Carbon Footprint from Transportation

This paper will only focus on direct emissions produced from household driving. The greenhouse gas emissions from the transport sector are on average approximately 28 percent of all greenhouse gas emissions for the United States. The emissions from household auto use are approximately 61 percent of all of the transport sector's emissions. In the Chicago region, transportation accounts for approximately 17 percent of all GHG emissions.[1]

The first task is to calculate how much greenhouse gases are produced by driving a standard auto one mile, and then generalizing that metric to the entire household. The greenhouse gas emissions associated with transit use is relatively minor compared with emissions associated with driving and therefore will not be considered in this paper.

3.2.1 Emission factors for driving

Using the emission factor in Section 2, driving the average auto one mile will use 0.049 (1/20.3) gallons of gasoline, which will produce 453.2 grams of CO_2e per mile.

3.2.2 Greenhouse Gases Produced from Household Driving as it Depends on Location

The following table looks at the Chicago–Gary–Kenosha metropolitan area to examine the differences of general locations according to the H+T Index; these averages are weighted by households. Table 4 assumes the average household is earning $53,000 per year, with 2.7 people, and 1.8 workers who travel an average of 30 minutes to get to work.

Location Type	Average Residential Density (Households per Residential Acre)	Average Transit Access (Walkable Transit Options)	Average Employment Proximity (Jobs/Sq Mile)	Average Block Size (Acres)	Modeled Annual HH VMT (Miles)	CO_2e Generated (Metric Tons)
Average location	10.34	4.96	56,824	16.6	12,801	5.60
Average location near fixed rail	17.4	8.83	85,206	9.3	10,874	4.75
Average location NOT near fixed rail	5.4	2.24	36,920	21.7	15,168	6.63
Average suburban location	4.3	2.24	32,315	21.8	15,925	6.96
Average Suburban location near fixed rail	5.1	3.82	40,215	13.7	14,898	6.51
Average Suburban location NOT near fixed rail	4.0	1.63	29,228	25.0	16,365	**7.15**
Average Chicago location	12.0	10.67	108,445	5.6	9,875	4.32
Average Chicago location near fixed rail	27.9	13.14	123,884	5.4	9,310	**4.07**
Average Chicago location NOT near fixed rail	12.2	5.22	74,317	5.8	11,766	5.14

Table 4 Total Household VMT and GHG Generated for Different Areas in the Chicago–Gary–Kenosha, IL–IN–WI Metropolitan Statistical Area

Table 4 shows that for an average Chicago area household living in an urban area, with access to jobs, in a walkable neighborhood with good transit, has an average carbon output related to VMT of 4.07 tons of carbon. Alternatively, a household living in a more remote suburban area, without access to fixed rail and far from employment centers, will have an average carbon output related to VMT of 7.15 tons of CO_2e per year. If the suburban household chose to move to the aforementioned urban location, it would reduce its annual transportation carbon footprint from 7.15 to 4.07 tons of CO_2e, or a reduction of 43 percent. This demonstrates how important it is for a region to have areas that are well served by transit, with enhanced residential density so that households may choose to live in a location efficient community.

4 The Carbon Reduction of a Single Transit Zone

In the previous section, the importance of location to a single household demonstrated how its choice of location determines its transportation options, and thus its carbon footprint. In this section, the importance of transit-oriented development to an area's carbon footprint will be examined. To begin, 2000 Decennial Census data and local transit data has been collected for 3,572 existing fixed rail transit locations in the US in the National TOD Database. Of the 52 metropolitan regions in the US shown in Figure 4, 34 of them have a fixed rail line or system (the regions shown in blue).

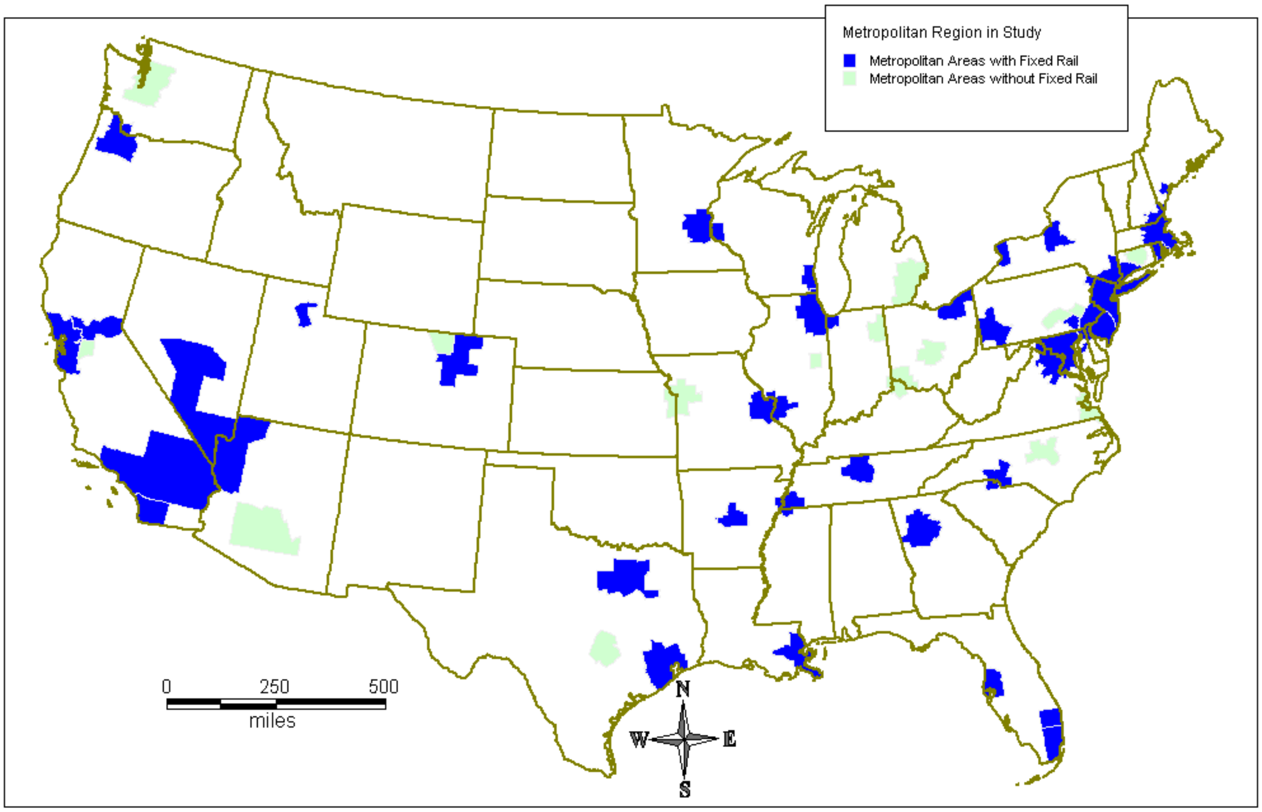

Figure 4: Map of US Showing Metropolitan Areas Used

These transit zones were analyzed to develop a typology, which is then used to evaluate how the different types of transit zones compare in GHG emissions from auto use.

4.1 Types of Transit Zones

The following scatter plot shows how two of the environment variables, residential density and transit connectivity,[12] are correlated in transit zones.[13] It is useful to recall that these transit zones are not necessarily the result of Transit Oriented Development, but rather just a collection of where transit is an important part of the urban form of the local neighborhood. See Appendix 2 for a complete discussion of transit zone classification. A common statistical method of K-Clustering is used to identify groups of

[12] The Transit Connectivity Index (TCI) is a geographic information system (GIS)-based measure developed by the Center for Neighborhood Technology that quantifies access, intensity and frequency of transit at the neighborhood level.
[13] A "Transit Zone" is defined, for purposes of this report, as ½ mile radius around a fixed guide-way transit station."

transit zones that are similar in relation to these two variables. Figure 5 shows the correlation between two of the independent variables used in the K-Clustering. The graph illustrates that residential density and transit access influences how the transit zones are classified.

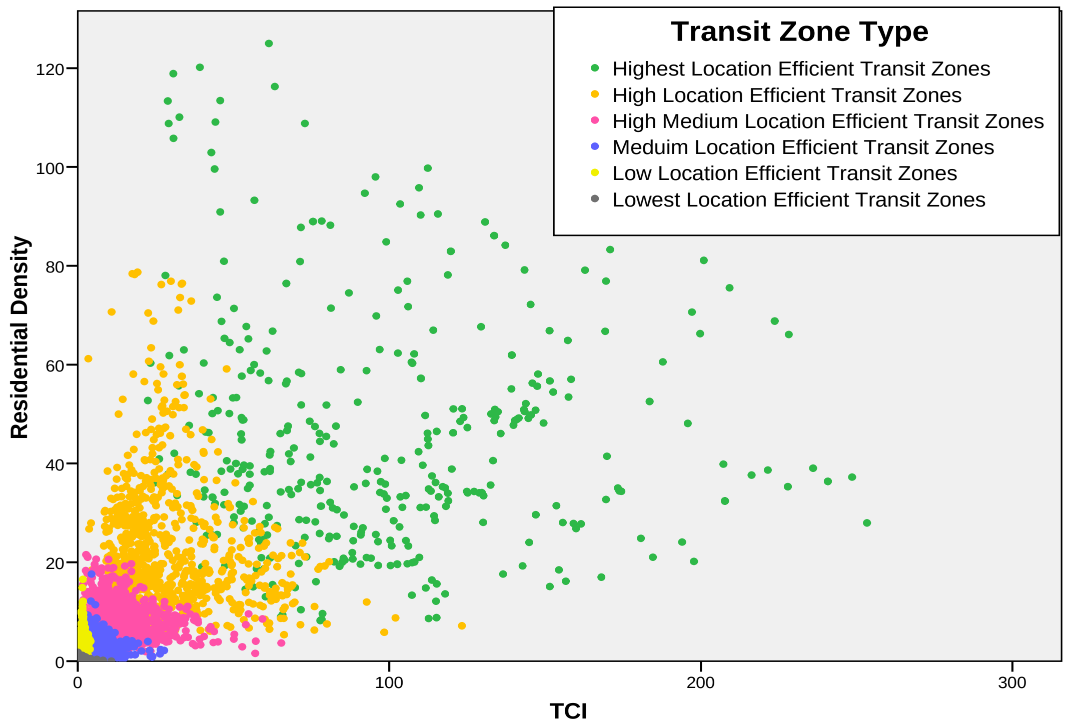

Figure 5: Residential Density vs. TCI - Displaying Transit Zone Type

The following table shows how these stations break out for 6 distinct clusters. These types have been ordered by the amount of VMT-related GHG emitted per household. It is important to emphasize that this classification is for all transit zones regardless of existing transit-oriented development. However, Table 5 shows that if more transit zones were developed in a manner that made them fit into the top two or three types, by using TOD, we could expect significant reductions in GHG emissions in these types of neighborhoods.

Name of Transit Zone Type[14]	Residential Density	Employment Proximity	Block Size	TCI	AMI[3] CO_2e/HH	Local[3] CO_2e/HH
Highest Location Efficient Transit Zones	61.7	671,546	3.4	97.7	1.46	1.86
High Location Efficient Transit Zones	30.4	171,750	4.1	25.6	2.66	3.57
High Medium Location Efficient Transit Zones	9.3	66,973	5.4	13.2	4.61	5.25
Medium Location Efficient Transit Zones	3.8	46,086	12.6	6.4	6.06	6.29
Low Location Efficient Transit Zones	4.5	41,088	9.2	1.7	6.51	6.65
Lowest Location Efficient Transit Zones	0.7	17,065	39.6	0.9	8.81	8.47

Table 5: Transit Zone Types

4.2 Summing Benefits to the Transit Zones

Table 6 and Figure 6 show that in places that are more location efficient, GHG emissions per households are reduced. Table 6 and Figure 7 show that, in general, due to higher residential density and thus higher total number of households, total overall emissions increase in the more location efficient transit zones. However, the "Highest Location Efficient Transit Zones" actually have overall lower total emissions than the "High Location Efficient Transit Zones" even though there are typically 78 percent more households in those transit zones. The is due to that compact urban form found in the "Highest Location Efficient Transit Zones," which allows for a much lower average auto ownership rates, and requires less driving to meet everyday needs.

[14] The names assigned are arbitrary and are for reference purposes only; they are not meant to have any value judgments associated with them.

Type of Transit Zones	Residential Density	Percent Residential Land	Residential Acres	Number of Households	AMI[3] CO_2e /HH	Total CO_2e AMI[3]	Local[3] CO_2e /HH	Total CO_2e Local[3]
Highest Location Efficient	61.7	60%	286	17,668	1.46	25,795	1.86	32,862
High Location Efficient	30.4	67%	327	9,938	2.66	26,434	3.57	35,478
High Medium Location Efficient	9.3	75%	369	3,434	4.61	15,830	5.25	18,028
Medium Location Efficient	3.8	74%	366	1,390	6.06	8,421	6.29	8,740
Low Location Efficient	4.5	85%	409	1,840	6.51	11,977	6.65	12,234
Lowest Location Efficient	0.7	74%	358	251	8.81	2,208	8.47	2,123

Table 6: Total CO_2e Emission from AMI[3] and Local[3] Households by National Transit Zone

Figure 7 shows again that the aggregate total CO_2e emissions in the "Highest Location Efficient Zones," are less overall than in the "Low Location Efficient Transit Zones," even though they represent almost 8,000 additional households.

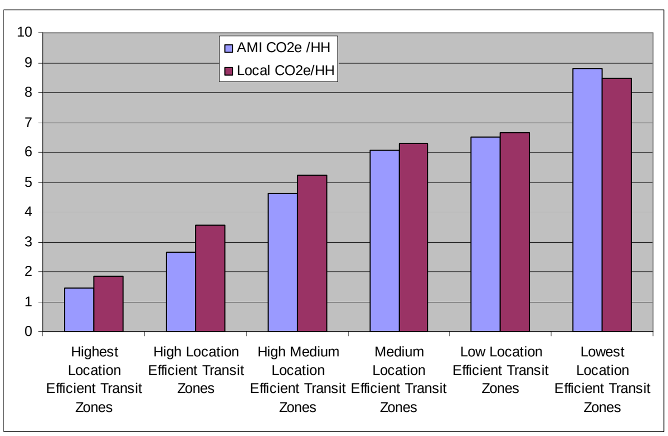

Figure 6: CO2e/Household from AMI[3] and Local[3] Households by National Transit Zone Types

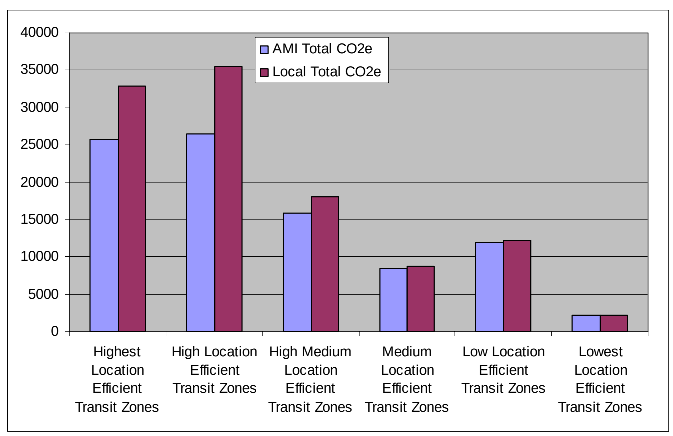

Figure 7: Zone Total CO2e emissions from AMI[3] and Local[3] Households by National Transit Zone Types

4.3 Comparing Benefits by Transit Zone Types

Even though the household emissions from these transit zones are lower as one gets to the more location efficient zones, the overall reductions are much higher. The average modeled household GHG emissions associated with VMT for all the Census block groups, both within and outside of a transit zone, in the 52 metropolitan areas is 6.7 Metric tons CO_2e/Household[15]. Average household emissions allow us to compare how an AMI[3] household living in the average place differs from one located in the various types of transit zones. Table 7 shows this difference.

Name	Average Number of Households in Transit Zone	CO_2e/HH	Total CO_2e	CO_2e/HH for Average Census Block Groups	Total CO_2e from an Average Census Block Groups	Reduction	Percent Reduction
Highest Location Efficient Transit Zone	17,668	1.46	25,795	6.7	118,373	92,578	78%
High Location Efficient Transit Zone	9,938	2.66	26,434	6.7	66,583	40,148	60%
High Medium Location Efficient Transit Zone	3,434	4.61	15,830	6.7	23,007	7,177	31%
High Medium Location Efficient Transit Zone	1,390	6.06	8,421	6.7	9,310	889	10%
Low Location Efficient Transit Zone	1,840	6.51	11,977	6.7	12,326	350	3%
Lowest Location Efficient Transit Zone	251	8.81	2,208	6.7	1,679	-529	-31%

Table 7: GHG Reductions by National Transit Zone Type

Table 7 shows that the carbon footprint for a household varies greatly depending on where a household chooses to live. The best place to reduce household greenhouse gas emissions is in the "Highest Location Efficient Transit Zones," where a household could expect to reduce its impact by as much as 78 percent, compared to living in the average place. The "Lowest Location Efficient Transit Zone" has 31% more emissions than the average.

4.4 Relationship of Zone Types with TOD

The six zone types reviewed in Table 5 through Table 7 and Figures 6 and 7 refer only to the ½ mile radius around fixed rail transit stations. The three highest location efficiency zone types are more densely developed station areas and may represent where the TOD process has taken place or where development happened at a time when transit oriented development was more of the norm. The last three station area types represent the areas where good TOD development may allow future households to reduce their carbon footprint if development in these areas happens in a way that is commensurate with TOD principles.

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[15] Note that average household emissions is slightly larger than that shown in Table 4 since the Chicago metropolitan area is in general more location efficient that the average of 52 metropolitan areas studied.

5 Regional TOD Strategy and Overall Greenhouse Gas Reductions

In this section the study examines the potential for increasing location efficiency at the regional level and how that will impact GHG reduction potential for an entire region. For the purposes of this study, the six-county Chicago region is used as a case study. According to the introduction of the 2030 plan from Northeastern Illinois Planning Commission (now merged with the Chicago Area Transportation Study to form Chicago Metropolitan Agency for Planning or CMAP) this region is expected to grow between now (2008) and 2030, by 1,958,715 people, and 1,237,550 jobs.[16] The following table shows this projected growth for the region.

Additional:	Population	Households	Jobs
Region	1,958,715	728,907	1,237,550
Chicago	364,881	159,235	246,640
Suburbs	1,593,834	569,672	990,910

Table 8: 2030 Population, Household and Job Growth

As shown above, the amount of GHG emissions from auto use by household is estimated, and then extrapolated to that geography. This study employs the same method to estimate the region's total GHG emissions from all households in the six-county region, and how that would vary given different growth scenarios.

The opportunity to accommodate the projected growth around transit, and an examination of how that can be accomplished within and around existing transit is reviewed in section 5.2. The overall regional reduction in GHG emissions is then reviewed in section 5.3.

5.1 Current (2000) Situation

Data inputs were collected and aggregated to Census block groups in the six county region in order to estimate the regional CO_2e emissions for the year 2000. The following map shows the region and the transit system; note that the transit system serves the entire region.

[16] http://www.chicagoareaplanning.org/data/forecast/2030_revised/

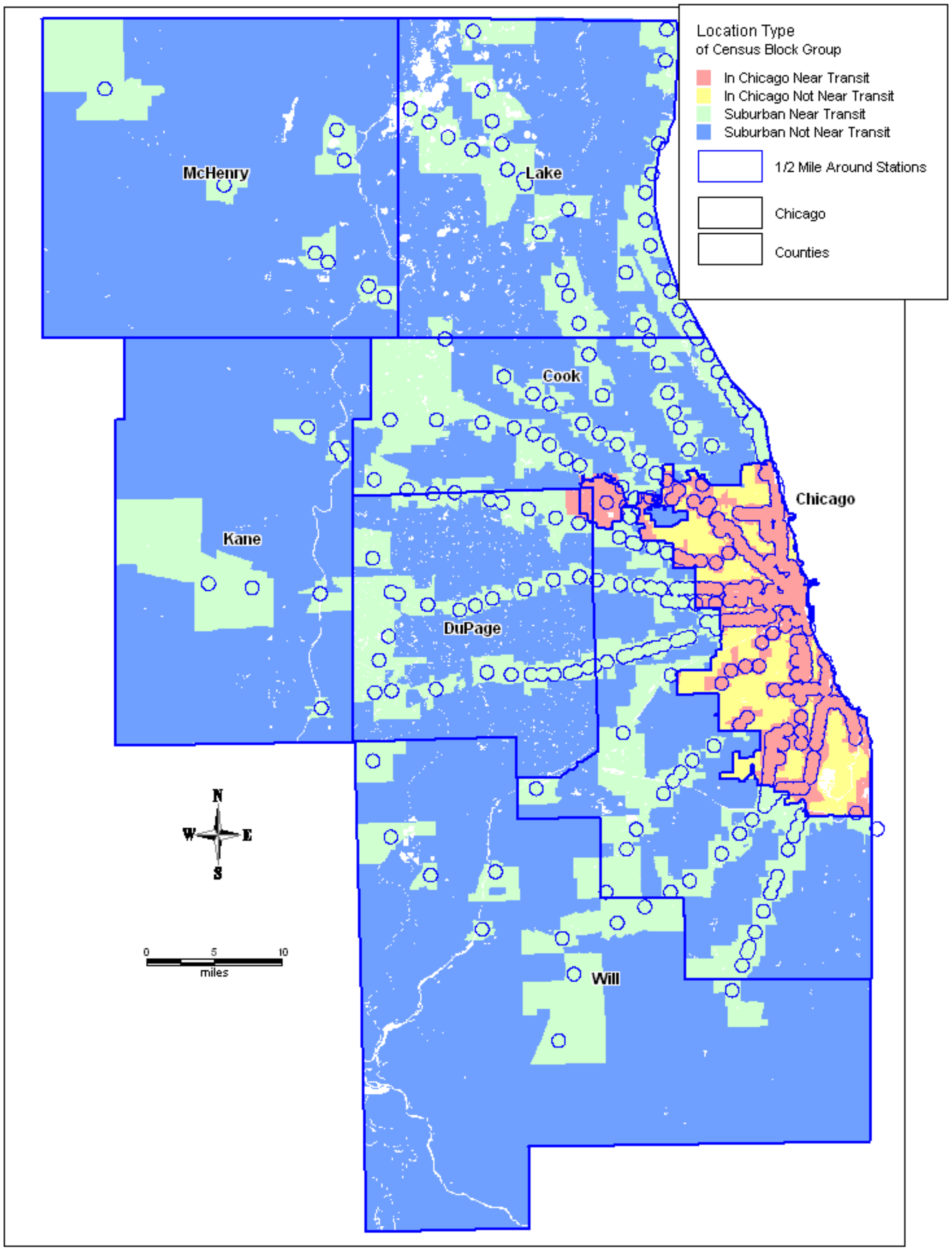

Figure 8: Map of 6-County Chicago Region

The following maps show the inputs for the transportation model at the Census block group level that will be varied for the different scenarios.

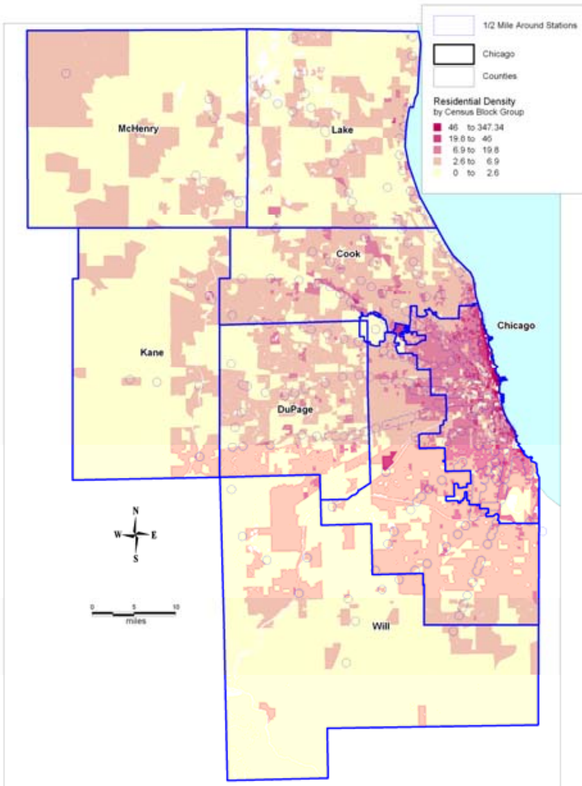

Figure 9: Residential Density 2000

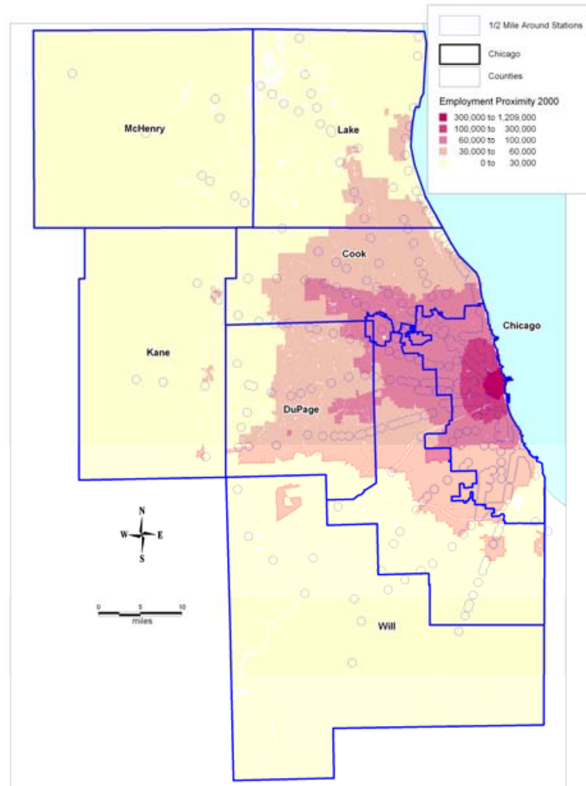

Figure 10: Employment Proximity 2000

The H+T Index model is then run on all Census block groups in metropolitan Chicago. Table 9 shows the inputs and results.

	Total	Chicago	Suburbs
Average Residential Density[17]	11.2	23.0	4.5
Employment Proximity[17]	62,676	108,556	36,294
Average Block Size[17]	12.9	5.5	17.2
Transit Connectivity Index[17]	5.5	10.7	2.5
Median Household Income [17]	55,664	41,021	64,084
Average Household Size[17]	2.7	2.7	2.8
Average Household Workers[17]	1.3	1.1	1.4
Average Time to Work[17]	32.0	35.6	30.0
CO_2e/HH Local[17]	7.3	5.1	8.6
Households ***(Census 2000)***	2,904,093	1,060,242	1,843,851
Aggregate CO_2e ***(CO_2e/HH Local * Households)***	**21,279,811**[18]	**5,451,917**	**15,827,894**

Table 9: Summary of Household Transportation Model Inputs and Outputs for Chicago Six-County Area

[17] This is the average of all the Census block groups, weighted by households.
[18] This is consistent with the research results for the Chicago region that CNT conducted in 2007 for the city of Chicago's "Climate Action Plan," with household transportation emissions being 62% of all transportation emissions (assuming 80% of light trucks are for household use).

The 21.3 Million Metric Tons/Year of CO_2e emitted from household transportation represents approximately 21 percent of all GHG emission from the six-county region in 2000.[19]

5.2 Potential Growth Scenarios

In order to accommodate the projected growth, discussed in Section 5, three growth scenarios were devised that will allow an estimation of the GHG reduction potential of promoting TOD in the entire region. The first scenario will estimate what would happen if there were no TOD initiatives, or a "business as usual" scenario. The second scenario will look at accommodating all of the growth in both employment and households within the transit zones, and constrain that growth to the CMAP projection of the ratio of growth in Chicago and the suburbs. This scenario is "constrained" by retaining the projected proportion of population growth in the suburbs and the city of Chicago. This "TOD with Constraints" scenario will give a middle ground of potential reductions could be attainable. Finally, the third scenario allows the growth to happen in the transit zones proportional to existing land use and development. This "TOD with No Constraints" sets an upper limit to the GHG reductions that could occur if all growth were accommodated in only transit zones.

In all three of these scenarios the following assumptions have been made, and all are meant to be conservative in nature, as to not overestimate the effects of compact growth:

- Transit access is kept constant.
- The street grid does not change; this keeps the block size the same everywhere.
- People who are here now do not move.
- No new residential acres are developed:
    - Since 2000, agricultural land has been developed into housing; if there is more disperse development in the outer ring suburbs the Business as Usual Scenario will have even higher emissions.
    - Since 2000, some industrial land in Chicago and inner suburbs also has been developed into residential land. If this were accounted for, the two TOD scenarios would allow for more growth in Chicago and inner ring suburbs making these scenarios' emissions even lower.
- Household income, size, workers, and commute time remain the same for each Census block group, allowing us to emphasize the change in the regions development and not changes in household make up.
- The underlying proclivity to own and use automobiles will not change.
- No new transit stations are built.

The following analyses will apply the three growth scenarios to the region and examine the GHG emission from each. Thus we will fix the overall population, household and job growth but realign where those activities locate, and examine how auto ownership and VMT change under each scenario. Simply stated - the regional number of year 2030 households is held constant in each scenario, whereas the region's average number of autos per household and VMT will change due to application of the regression models.

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[19] Center for Neighborhood Technology (2008).Chicago Greenhouse Emissions: An Inventory, Forecast, and Mitigation Analysis for Chicago and the Metropolitan Region.

5.2.1 Scenario 1: Business as Usual

In order to model the increase in jobs and population for a growth scenario that will represent business as usual (BAU), the increase in jobs and households are allocated where they were in 2000. This is accomplished by increasing both jobs and households, and constraining the Chicago and suburban totals to match those in Table 8.

To allocate jobs, Census tract job numbers from Census Transportation Planning Package (CTPP) 2000 are used, and are increased in each tract by the fraction needed to add up to the correct number. Then an inverse-square law algorithm (see Appendix 1.01 for a more detailed discussion) is run on this Census tract table to estimate how the employment proximity changes at the Census block group level. For households the same reallocation of households is performed, again constraining the growth to match the predicted growth in Chicago and the suburbs. The following two maps show this new residential density and employment proximity (as compared to the maps above).

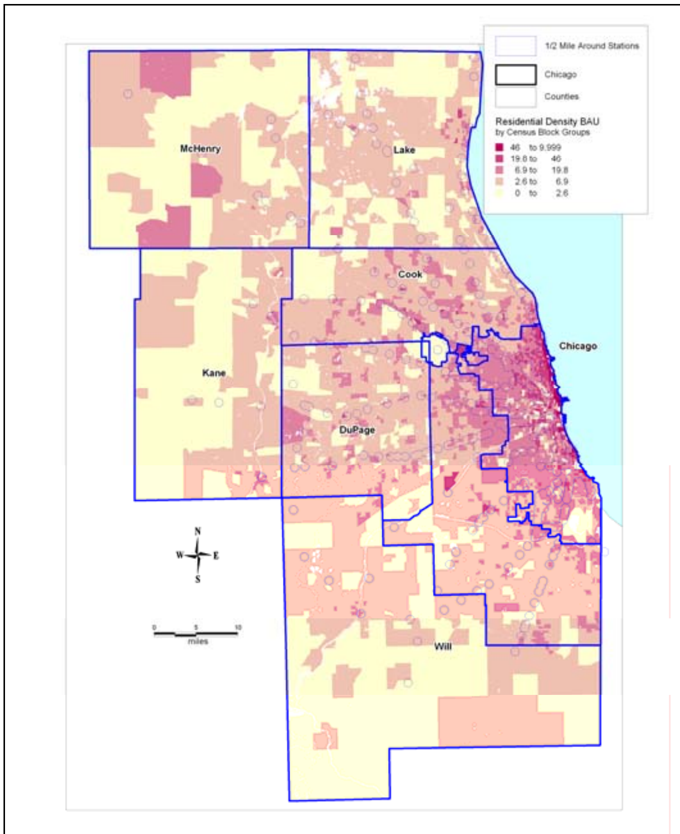


Figure 11: Residential Density BAU

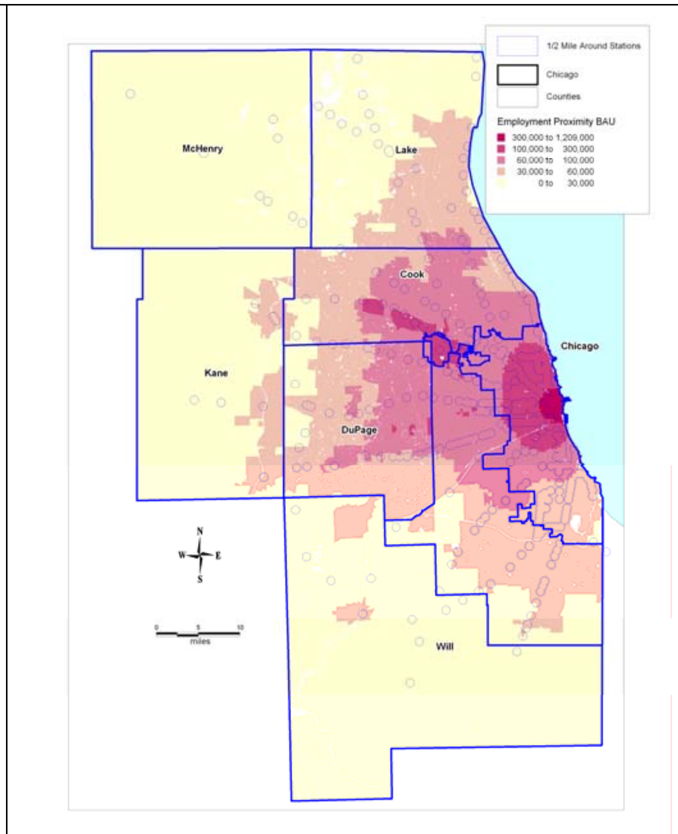


Figure 12: Employment Proximity BAU

5.2.2 Scenario 2: TOD with Constraints

Scenario 2 illustrates how growth could be accommodated if TOD were emphasized as a development strategy. As stated above, CMAP predicted population and job growth to be greater in the suburbs than in Chicago. This TOD scenario uses those growth numbers and allocates the increases accordingly. However, unlike the BAU scenario, all jobs and households are allocated within urban and suburban transit zones (½ mile radius around fixed rail transit stations see section 4.1) in accordance with the CMAP suburban/city ratio projection. The following two maps illustrate how the household density and employment proximity differ from those above.

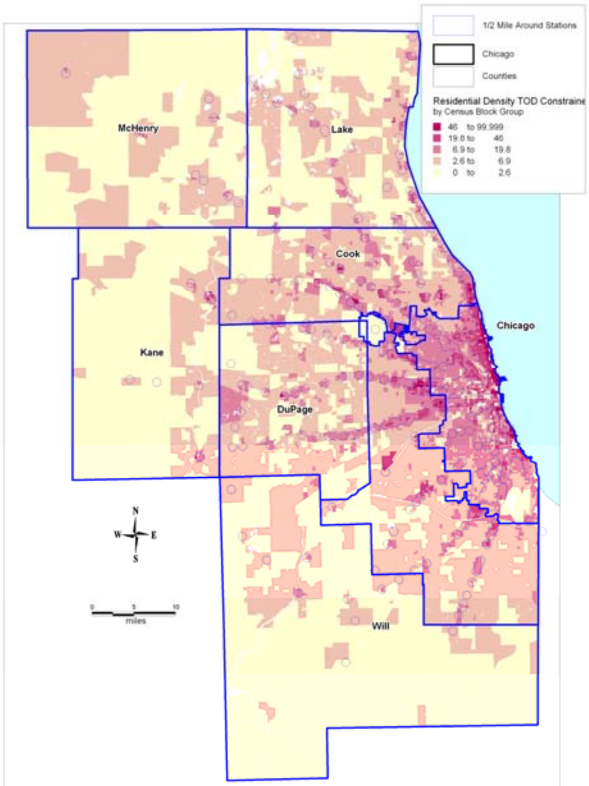


Figure 13: Residential Density TOD Constrained

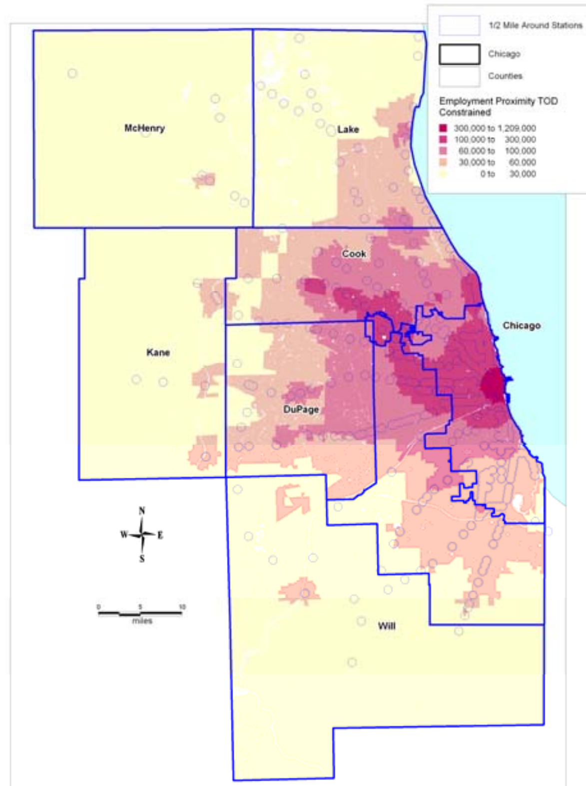


Figure 14: Employment Proximity TOD Constrained

5.2.3 Scenario 3: TOD with No Constraints

Scenario 3 illustrates how the growth could be accommodated if TOD were emphasized as a development strategy. In this scenario, the CMAP allocation of population and job growth in the suburbs and city is ignored. However, unlike the BAU and constrained TOD scenarios, all jobs and households are allocated within ½ mile of fixed rail transit stations following the existing development pattern. The following two maps illustrate how the household density and employment proximity differ from those above.

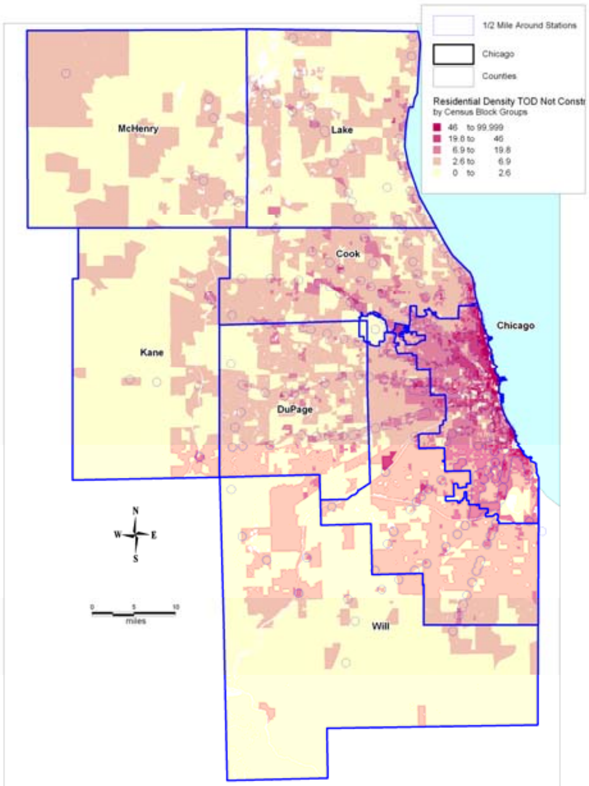


Figure 15: Residential Density TOD Not Constrained

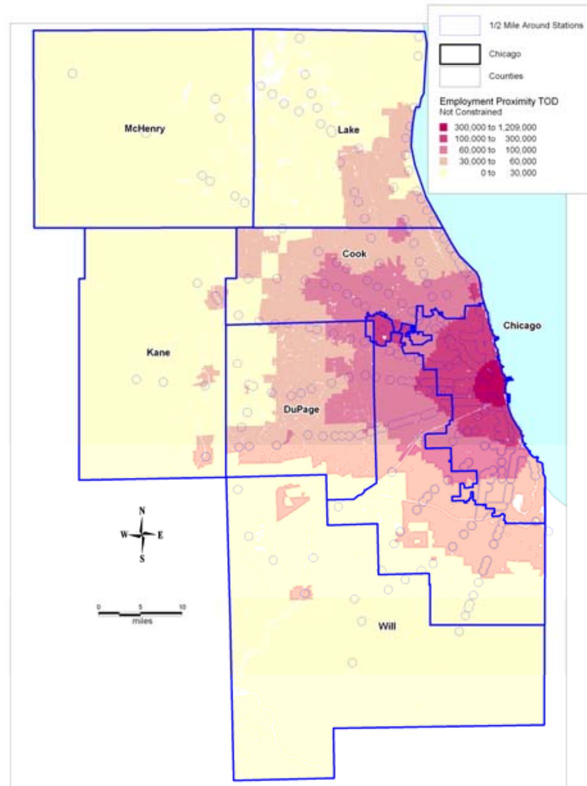


Figure 16: Employment Proximity TOD Not Constrained

5.3 Emission Results

The following table summarizes the differences in GHG production from the three scenarios above. Note that, due to population and employment growth, GHG is expected to increase from 2000 levels. However, the level of increase varies remarkably among the three scenarios.

	2000	2030		
		Business as Usual (BAU)	TOD with Constraints	TOD with no Constraints
VMT Chicago Near Transit	7,745,741,757	8,285,173,170	8,687,254,460	11,660,137,831
VMT Chicago Not Near Transit	4,285,555,892	4,603,070,257	4,075,821,974	3,964,404,884
VMT Suburban Not Near Transit	24,040,998,557	29,395,198,100	23,029,662,247	23,440,782,201
VMT Suburban Near Transit	10,883,593,731	13,204,330,162	17,311,117,363	13,365,757,580
Average Autos per Household	1.54	1.50	1.44	1.40
Total Household Autos	4,461,339	5,445,647	5,262,957	5,084,750
VMT Total Region	46,955,889,937	55,487,771,688	53,103,856,043	52,431,082,496
Increase of VMT from 2000		8,531,881,752	6,147,966,107	5,475,192,559
CO_2e (Metric Tons)	21,280,502	25,140,539	24,057,193	23,753,041
Increase in CO_2e from 2000		3,860,037	2,776,691	2,472,539
CO_2e Reduction from BAU			1,083,346 (28%)	1,387,498 (36%)

Table 10: Summary of Aggregate GHG Emissions from 2030 Growth Scenarios in Six-County Chicago Region

Table 10 shows that GHG reduction potential attributable to the promotion of a TOD growth strategy in a region is substantial. In the Chicago region, given a good TOD growth strategy, the region's increase due to projected population growth in VMT related GHG could be reduced by 28 percent to 36 percent. Note that since this reduction is from the 17 percent of all greenhouse gas emissions from the transportation sector.

6 Summary and Conclusions

Location matters. For any given household, the number of autos it owns, and how many miles households drive those autos, is largely determined by where the household lives. A household's VMT and carbon footprint can be dramatically reduced by living in a location efficient neighborhood. Section 3 of this paper shows that by simply living in a central city near transit, the average household can reduce it GHG emissions by 43 percent, compared to the average household. Section 4 provides evidence that in the most location efficient transit zones, a household can reduce its GHG emissions by as much as 78 percent. Section 5 demonstrates that the total GHG emissions from household transportation depend on how that region chooses to grow. Growth in VMT-related GHG emissions can be reduced by 36 percent if development in that region proceeded in a more compact and efficient manner. All this leads to the potential for TOD to contribute to reductions of VMT-related GHG emissions. In order to create neighborhoods where households can make the choices to live efficiently and reduce their impact on climate change, TOD should be pursued vigorously.

The following two maps show, from the model, how GHG production per household decreases in more urban areas, even if the over all GHG production per area is greater. These maps highlight the need to look at the climate change impact of development in a new and more comprehensive way, to create communities that are "attractive, walkable, sustainable communities that allow residents to have housing and transportation choices and to live convenient, affordable, pleasant lives."

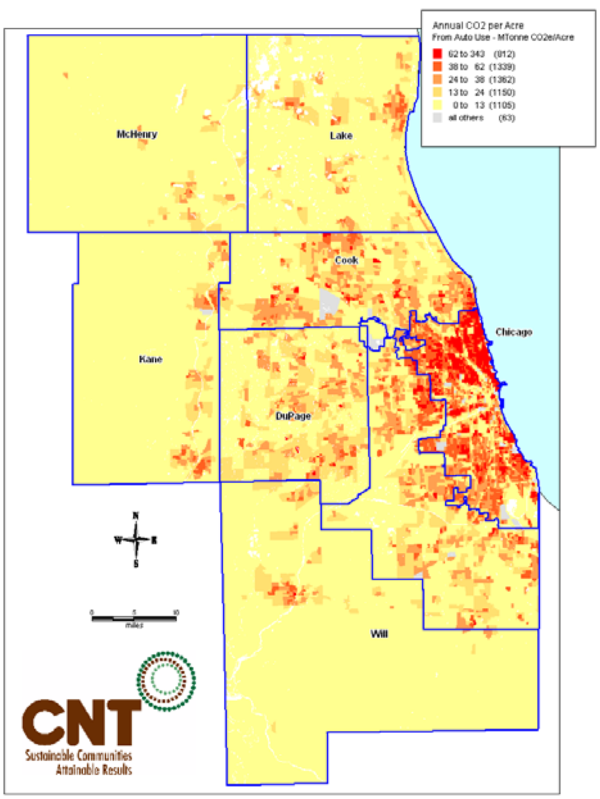


Figure 17: Traditional View of City Dwellers' Carbon Footprint

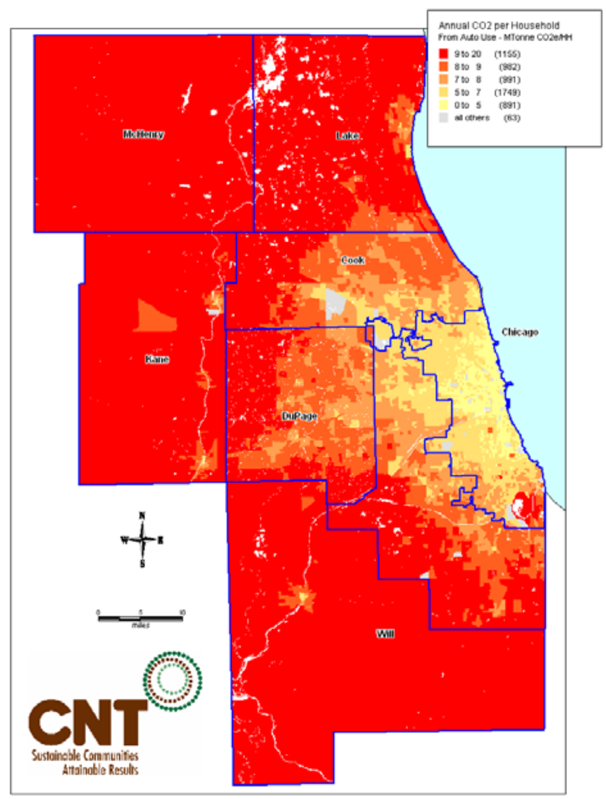


Figure 18: Emerging View of City Dwellers' Carbon Footprint

The results of this study are for conditions found in the Chicago region, and further research is planned to investigate if similar findings would result in other regions. The H + T household transportation model has been developed for regions all over the United States, and now includes the 337 metropolitan statistical areas (as defined in 2000). Similar behaviors with regards to urban form and auto use and ownership have been found in every region.

Further research is needed to show that the relationship between GHG emission reduction and regional TOD can be extrapolated to all regions in the US. The results of this study present an opportunity for regions to incorporate TOD into regional growth scenarios and climate mitigation strategies, and develop in a manner that enhance household's ability to live in neighborhoods with less dependency on automobiles. Further research can also examine future demographic assumptions. This study however, is focused on changes in development patterns and not demographics, and therefore maintains consistent demographic assumptions for all scenarios.

Appendix 1. Household Transportation Model

This appendix describes the Housing and Transportation Affordability Index household transportation model in more detail. This model was developed in 2006 with support from the Brookings Institution. The discussion in this appendix focuses specifically on the results found in Chicago, although the model has demonstrated similar behavior in other large metropolitan areas like New York and Los Angeles, as well as in smaller regions like Fort Wayne, Indiana; Norfolk, Virginia; and El Paso, Texas.

The independent variables, which co-vary and are not independent to each other, are combined to calculate transportation use in two separate components: auto ownership, and auto use. In order to develop this model we relied heavily on Census 2000 data. The following table lists the source of our dependant variables for model development and calibration:

Table 11: Dependent Variables for Household Transportation Model.

Variable	Source
Auto Ownership (vehicles per household)	Census 2000
Auto Use (annual miles driven per household)	Odometer reading from the Chicago Metropolitan area

To reliably model an accurate and fine-grained transportation demand, the model must account for the various characteristics specific to locations that influence transportation. It must also control for certain household characteristics that also determine transportation use, somewhat independently of location, such as household income and household size. Therefore, this transportation use formula incorporates a set of independent variables that represent the relevant local environment and household characteristics that each influences the dependent variable - household transportation use. The following table lists the variables that we have found drive household transportation use/demand.

Table 12 Independent Variables for Household Transportation Model.

Variable	Source	Underlying Phenomenon
Household Characteristics		
Household Income	Census 2000	Influences auto ownership and use. The most important household variable correlates highly with all dependent variables. Traditionally the only variable used in auto ownership models.
Household Size	Census 2000	Influences auto ownership and use.
Workers per Households	Census 2000	Influences auto ownership and use. This shows good independent correlation with all dependent variables.
Combined Household/Local Environment Characteristics		
Average time for workers commute to work	Census 2000	A measure of congestion and distance to work combined with the choices people in this Census block group made as to where they work. There is good correlation between this and auto ownership.
Local Environment Characteristics		
Households per residential acre	Census 2000	Provides a measure of density which influences auto ownership and use. Uses the land area from the constituent blocks where there were

		households as residential land. This technique was developed in order to make it possible to model metro areas where good land use data is unavailable.
Average block size in acres	Census/TIGER	Block size contributes to walkability of the area, which influences auto ownership and transit use.
Transit Connectivity Index (TCI)	FTA and local transit agency data	Availability and extent of transit influences auto ownership and use.
Employment Proximity- Number of jobs per square mile	CTPP 2000	Number of nearby jobs influences probability of working at the nearby employment center. Using an inverse-square law model the total access to jobs in the metropolitan area is determined by the sum of the number of jobs divided by the square of the distance to those jobs.

In the following sections we will show how these independent variables affect the dependent variables and show that an equation can be found that will model this behavior. Note that this research was conducted at the Census block group level, which is a small geographical area, and allows us to examine the relationship without too much variation within such a small area. This analysis is performed using the 5,831 block groups in the Chicago six county area covered by CMAP's model. Of the 5,831, only 5,608 have at least 100 household in them. The missing block groups are typically in areas where there is no housing, i.e. parks, industrial corridors etc.

Appendix 1.01 Employment Proximity

In order to examine the actual prevalence of jobs in and around a given census block group we have calculated a quantity we are calling the "Employment Proximity." This quantity allows us to examine both the existence of jobs and the accessibility of these jobs. We have used the following equation to calculate this:

$$E \equiv \sum_{i=1}^{n} \frac{p_i}{r_i^2}$$

Equation 1 Employment Proximity Definition

Where E is the Employment Proximity for a given Census block group, n is the total number of census tracts in the region, p_i is the number of jobs in the i^{th} census tract, r_i is the distance (in miles) from the center of the given census block group to the center or the i^{th} census tract. Note that this is in units of jobs per square mile.

The Employment Proximity for a block group is the sum of all jobs within a region, weighted by one over the square of the distance to them. This quantity gives a measure of job opportunity by census block group. This measure is better for understanding access to jobs than the simple employment density, since it accounts for neighboring jobs. As an example consider two census tracts each having no employment within them. Census tract A is in the Near North Side, of Chicago and the other, tract B, is in unincorporated Kendall County. The local job density for both may be zero, but tract A has much better access to jobs, and the Employment Proximity is much higher (because tract A is closer to the Loop, where most jobs are concentrated), and for B the Employment Proximity is lower, both reflecting the actual job accessibility of these tracts.

The Employment Proximity is correlated to household transportation demand. In the following sections this relationship will be explored.

Appendix 1.02 Auto Ownership

In the Chicago Metropolitan region the following histogram shows the distribution of autos per household.

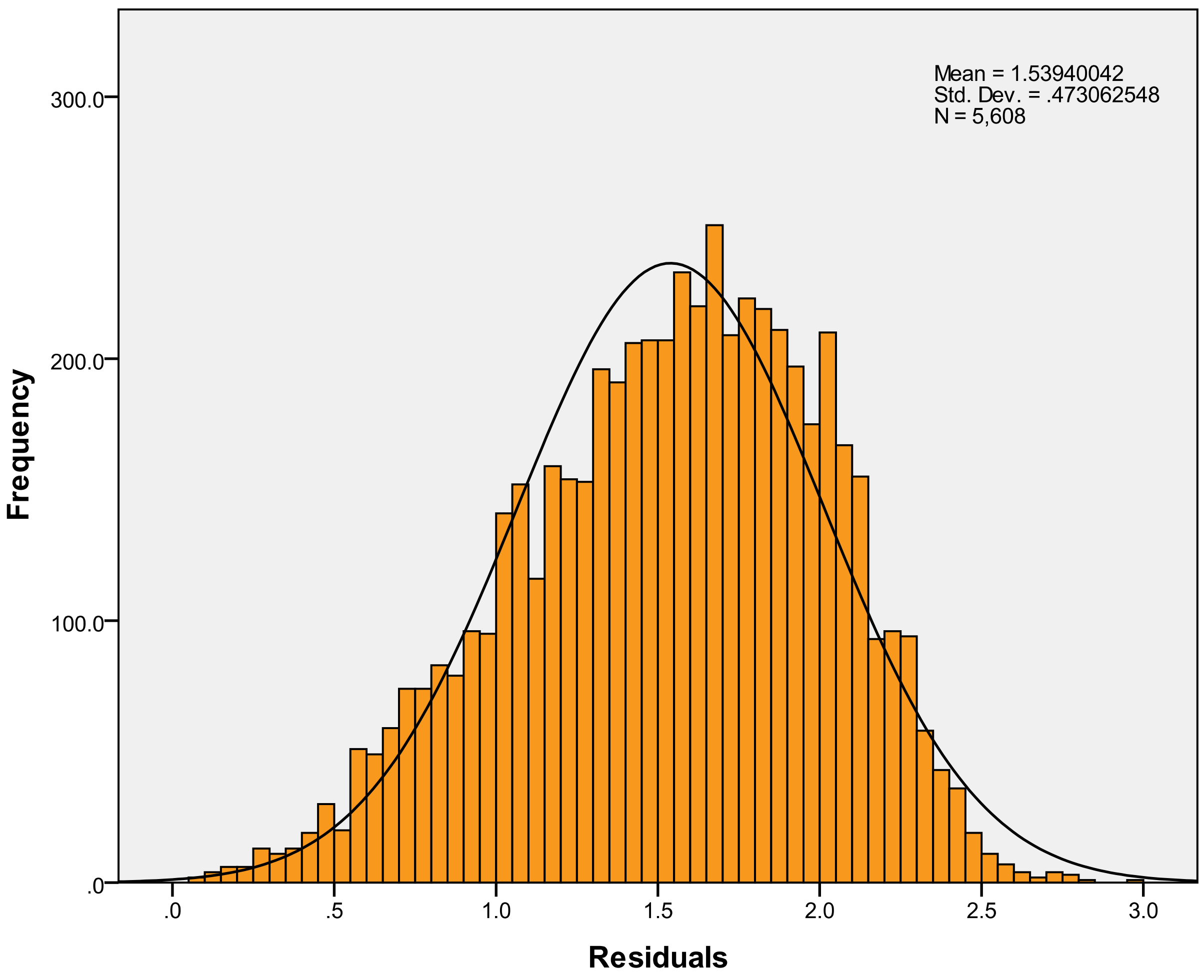


Figure 19: Histogram of the Autos per Household by Census block group in the Chicago Metropolitan Region

The distribution in this graph reflects that households within the region own a wide range of autos. The following "error bar graphs" show how auto ownership varies with the eight independent variables listed above.

The largest variation is with residential density. The following graph shows that as residential density goes up the average household owns fewer autos. Note that at a residential density of 2 households per acres, the average household owns 2 autos, and at 18 households per acre the average household owns only 1 auto.

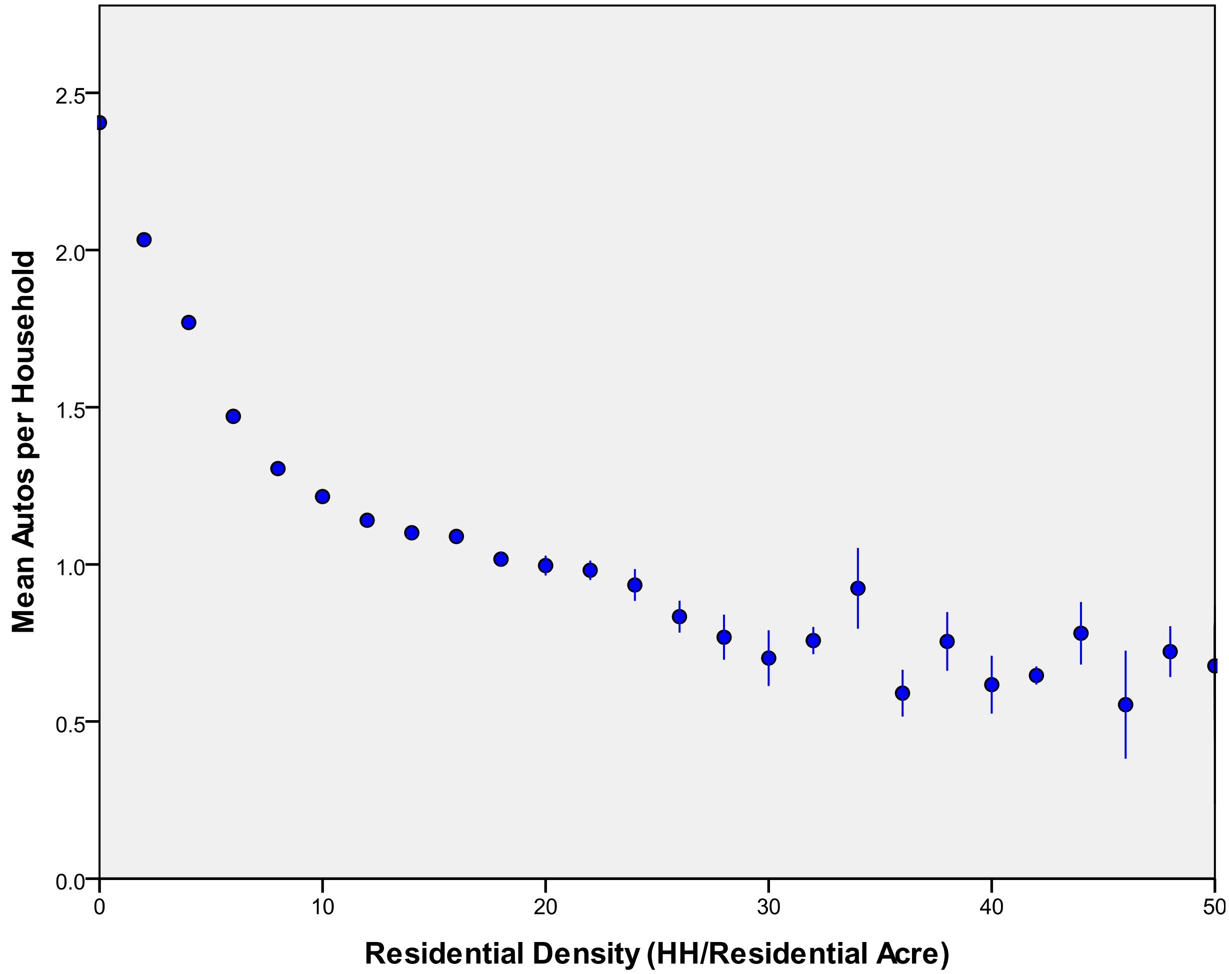


Figure 20: Autos per Household vs. Residential Density

The next plot shows the most important household variable, household income. Note that as the average income in a Census block group is higher, the more autos the average household owns, but it peaks at around two autos per household at annual income of approximately $75,000/year.

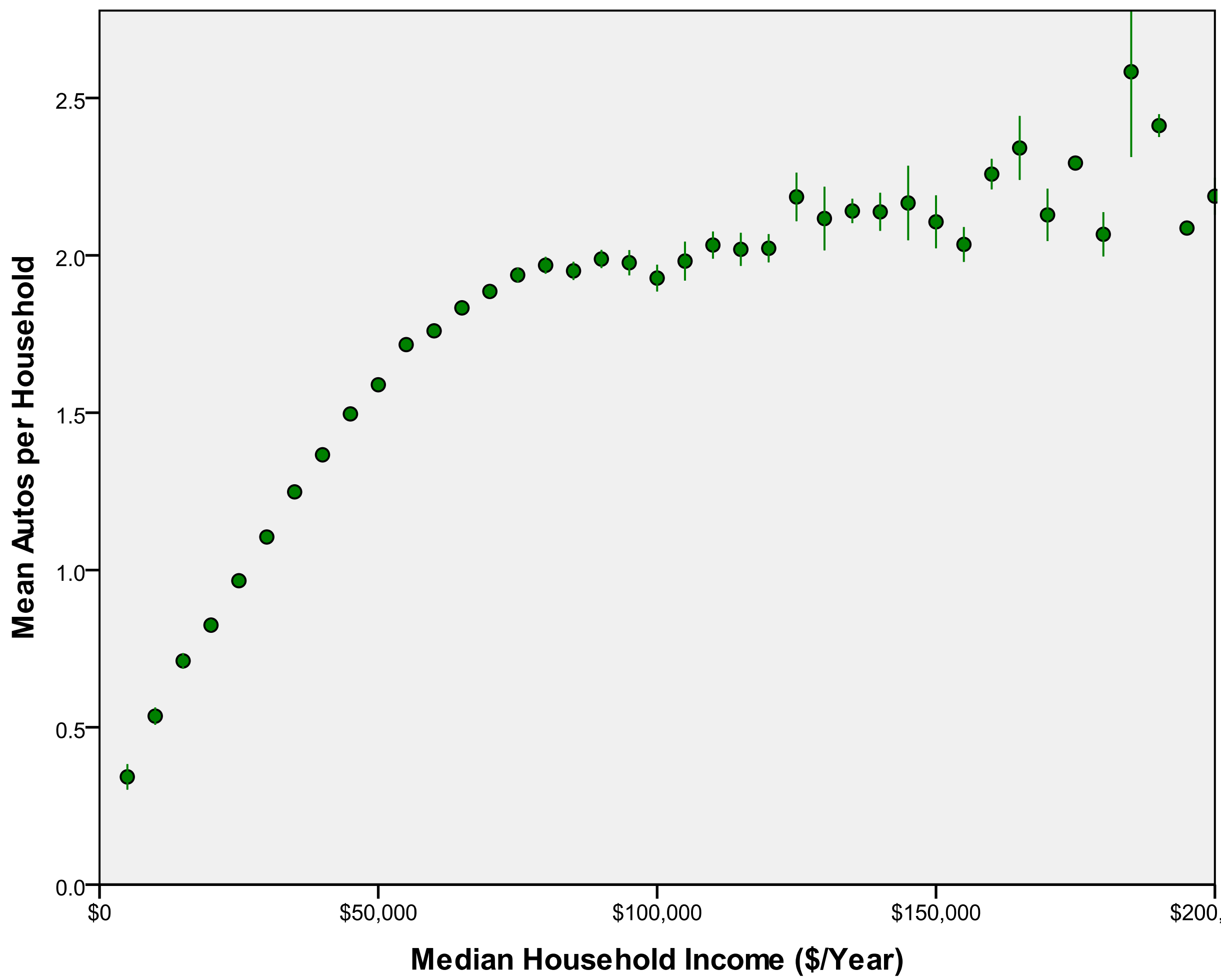


Figure 21: Autos per Household vs. Annual Household Income (1999)

The following 6 plots show this variation for the other variables.

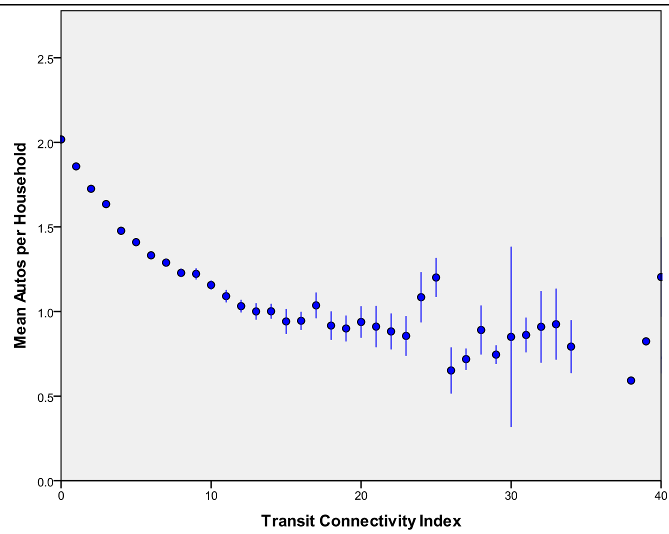


Figure 22: Autos per Household vs. Transit Connectivity

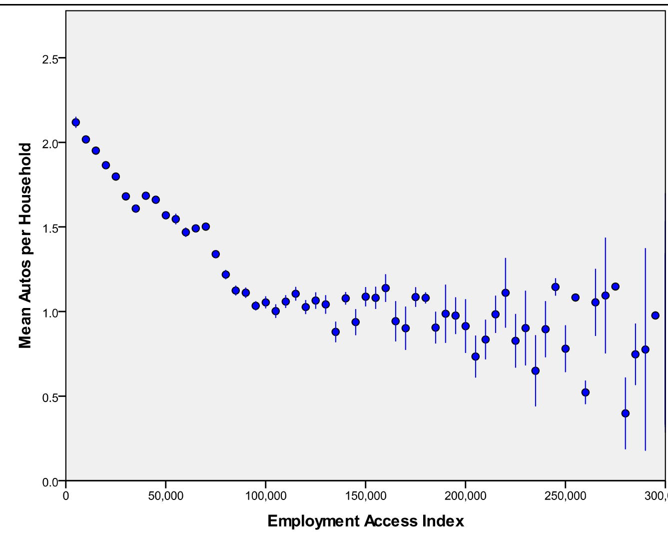


Figure 23: Autos per Household vs. Employment Proximity

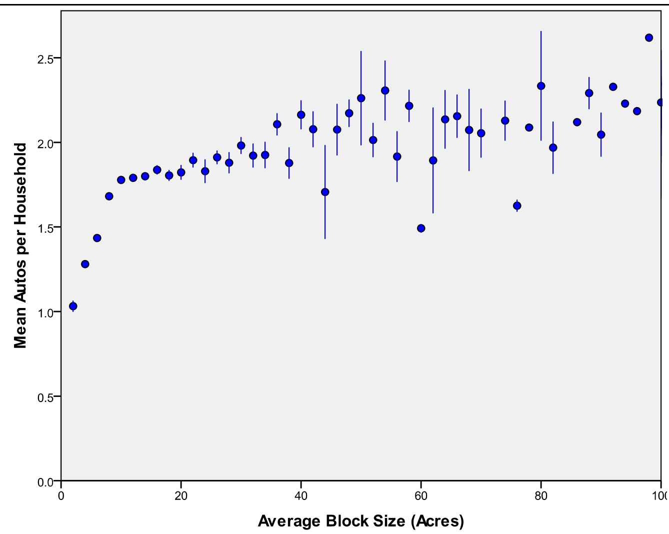


Figure 24: Autos per Household vs. Average Block Size

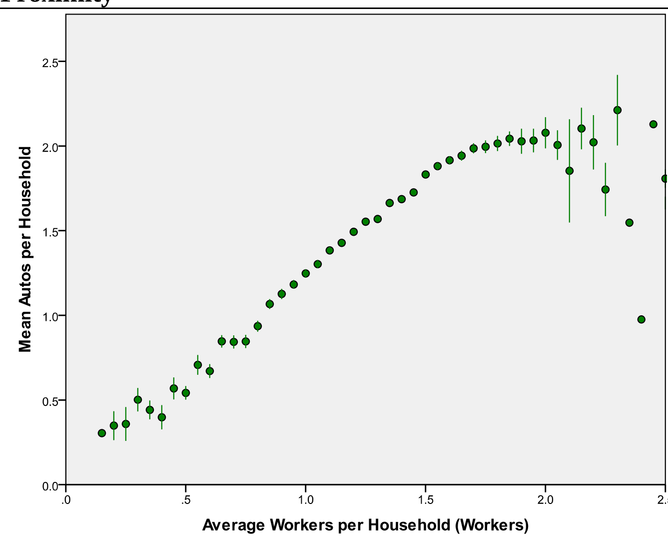


Figure 25: Autos per Household vs. Workers per Household

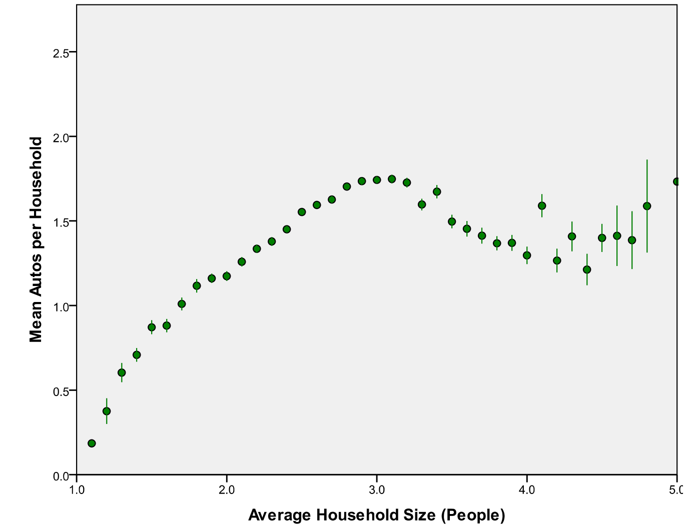


Figure 26: Autos per Household vs. People per Household

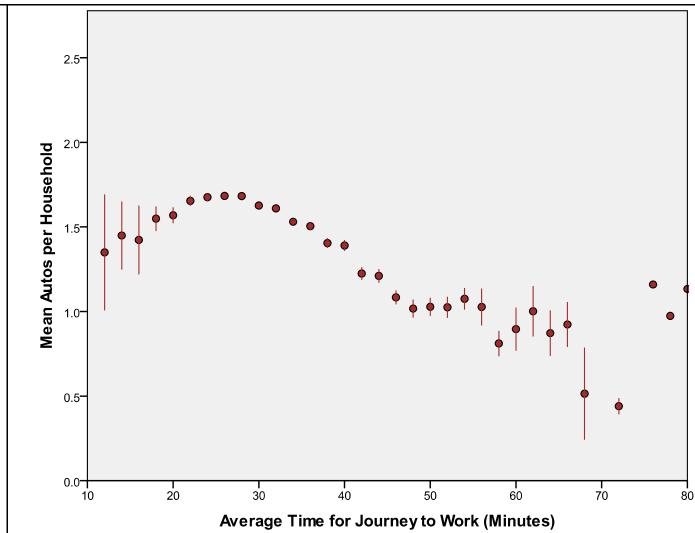


Figure 27: Autos per Household vs. Average Time Journey to Work

The distributions displayed in Figure 20 through Figure 24 show that in general as the place gets more compact, walkable, with higher jobs and transit access, the number of autos the average household owns is reduced. This is good for the carbon footprint of such households, and in general this is exactly the change in the local environment that a TOD is going to produce.

This result is obtained using a rational model[20] for each of these variables. The overall functions can be represented as:

$$Y = a + \sum_{i=1}^{8} \frac{(C_{i1} \times X_i + C_{i3} \times X_i^2 + C_{i5} \times X_i^3)}{(1 + C_{i2} \times X_i + C_{i4} \times X_i^2 + C_{i6} \times X_i^3)}$$

Equation 2 Auto per Household Regression Equation

Where: Y is the modeled autos per household, a is an intercept coefficient, X_i are the eight independent variables listed in “Table 12 Independent Variables for Household Transportation Model.,” divided by a simple normalization factor so that the fit coefficients are of similar order of magnitude, and C_{ij} are the fit coefficients. The final values for these coefficients are determined using a standard multidimensional regression technique.

appendix 1.02.a Goodness of Fit – Auto Ownership

The goal of the regression analysis is to find a formula that can mimic the distribution show in Figure 20 through Figure 27. This has been accomplished with the complex formula in Equation 2. The following scatter plot shows the measured autos per household vs. the modeled autos per household; note that this shape is consistent with the R^2 of 86 percent obtained from this fit.

[20] For a simple discussion of rational model use see for example http://www.itl.nist.gov/div898/handbook/pmd/section6/pmd642.htm

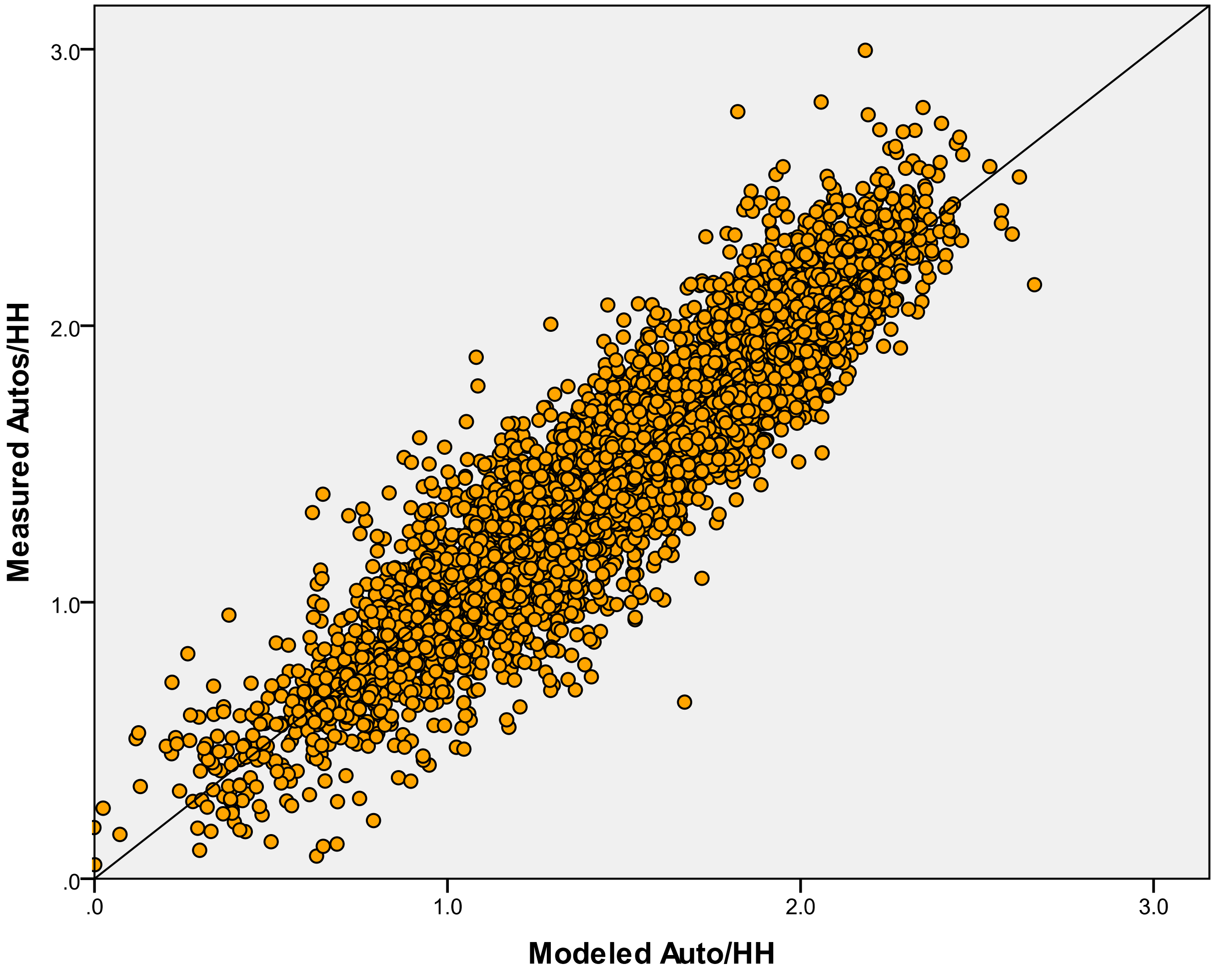


Figure 28 Measured vs. Modeled Autos per Household

The following histogram shows the residual of the fit (the difference between the Measured and Modeled Autos per HH); note that most of the variation in Figure 19 has been eliminated.

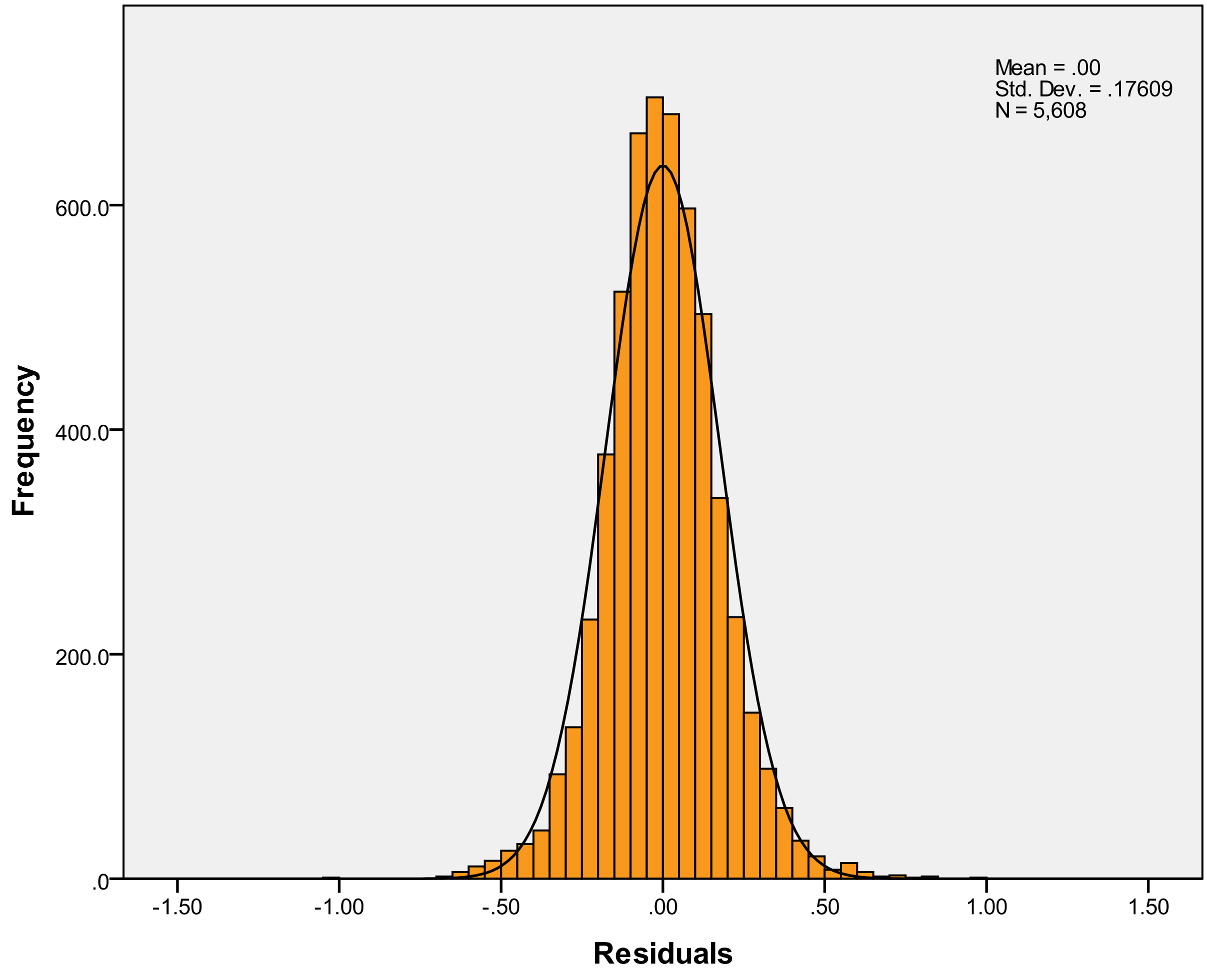


Figure 29 Residual from Auto per Household Fit

The following plots show this residual plotted against the independent variables, to check for biases. Note that the smooth variations displayed in Figure 20 to Figure 27 have been eliminated, within the error bars.

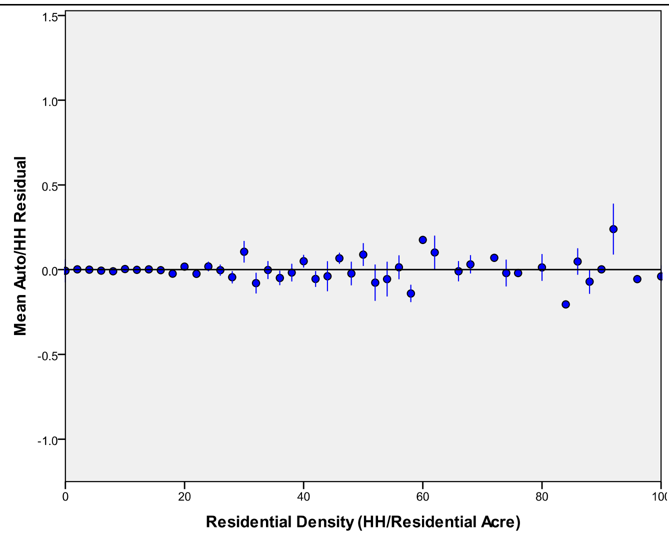


Figure 30 Autos/HH Residual vs. Residential Density

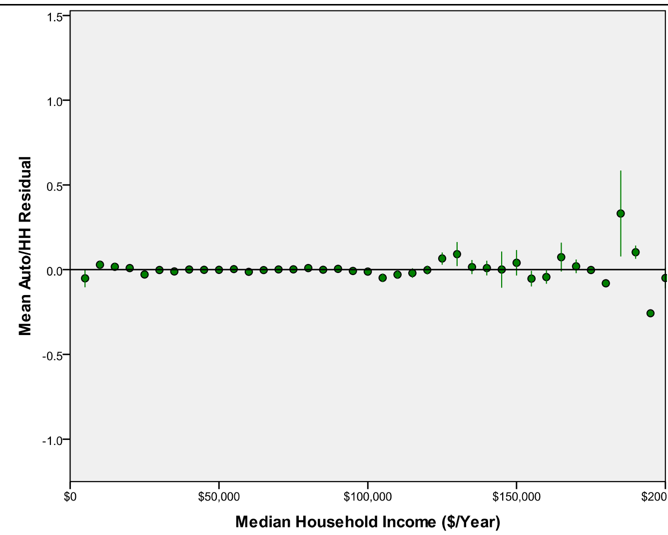


Figure 31 Autos/HH Residual vs. Household Income

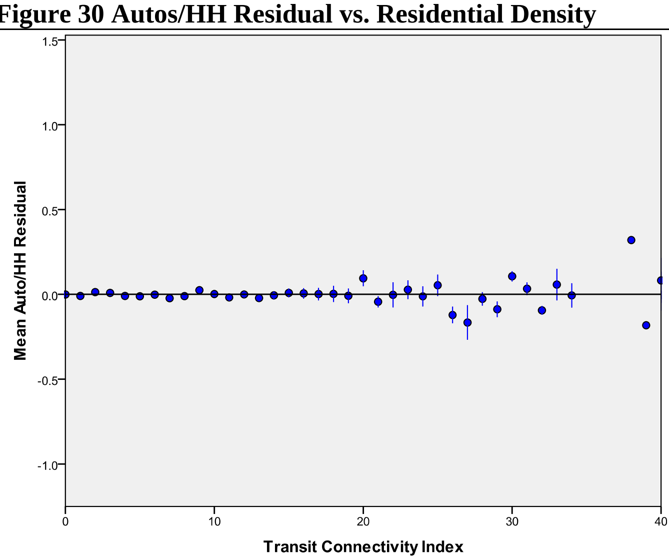


Figure 32: Autos/HH Residual vs. Transit Connectivity

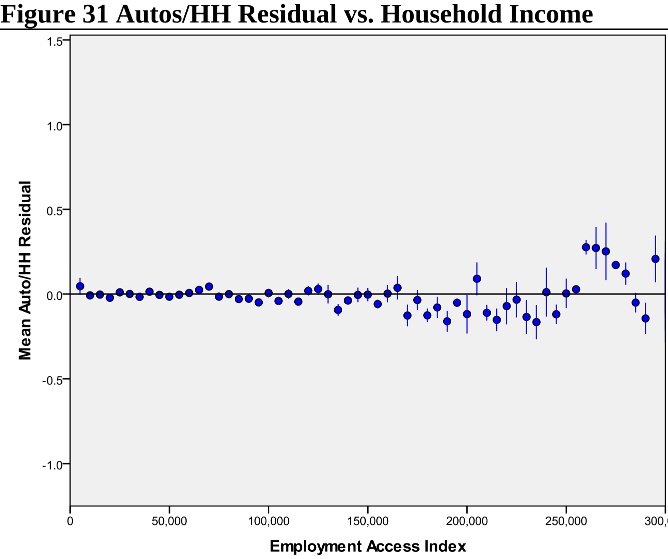


Figure 33: Autos/HH Residual vs. Employment Proximity

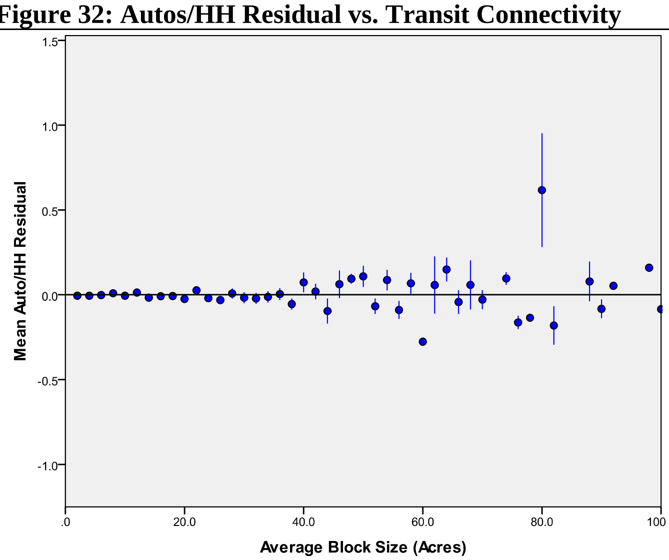


Figure 34: Autos/HH Residual vs. Average Block Size

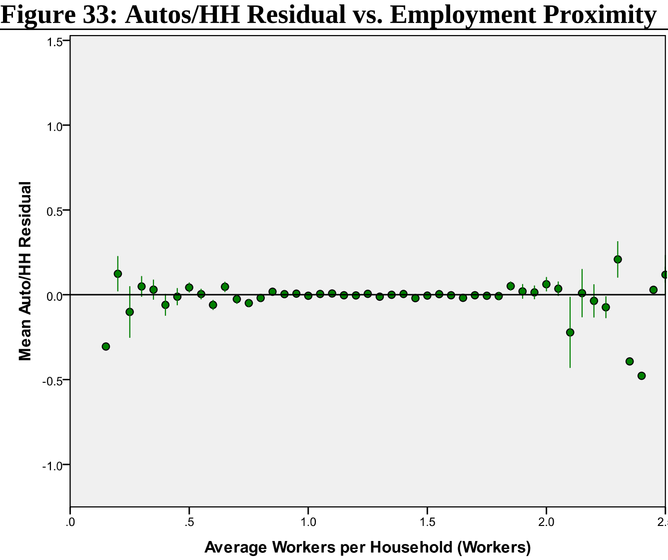


Figure 35: Autos/HH Residual vs. Workers per Household

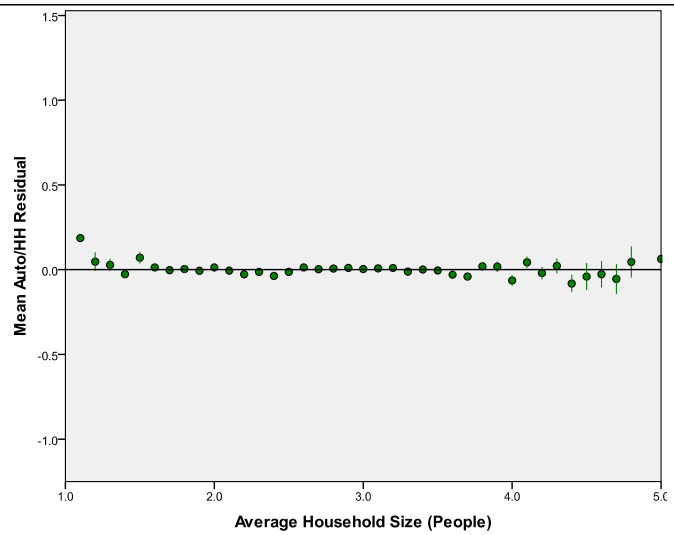


Figure 36: Autos/HH Residual vs. People per Household

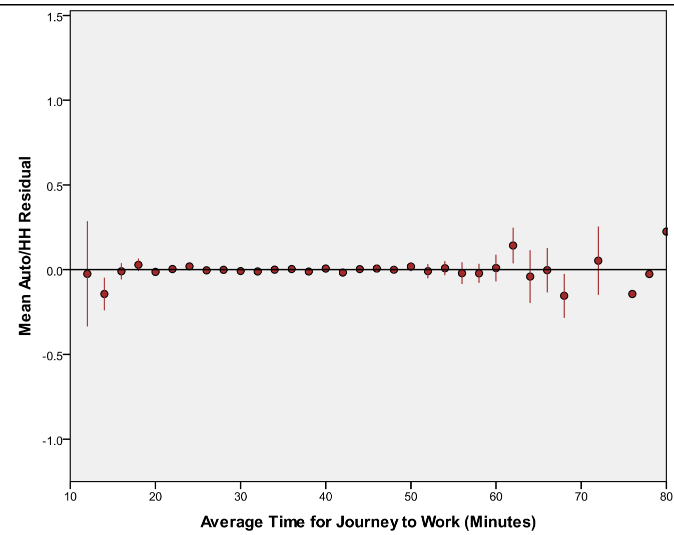


Figure 37: Autos/HH Residual vs. Average Time to Work

As a further check of any bias in the model we aggregated both the measured and modeled autos per household and looked to see if these aggregate numbers were consistent. For the unit of aggregation we used both counties and municipalities. The following scatter plots show that the model is consistent with the measurement for both levels of aggregation.

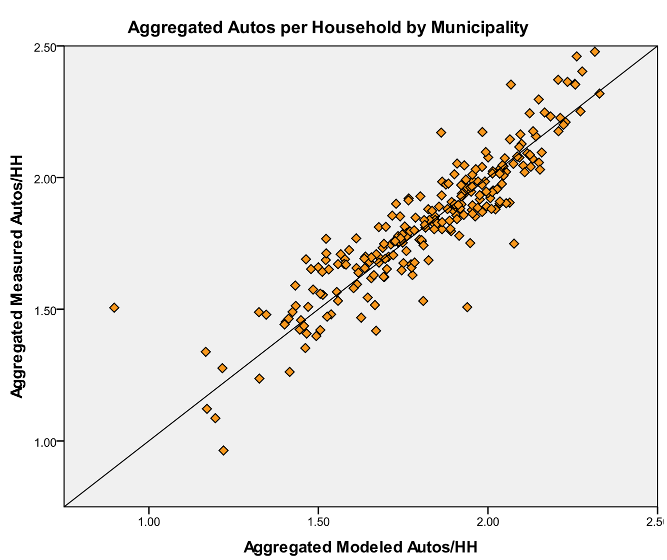


Figure 38 Aggregated Autos per Household Comparison for Municipalities of Measured vs. Modeled

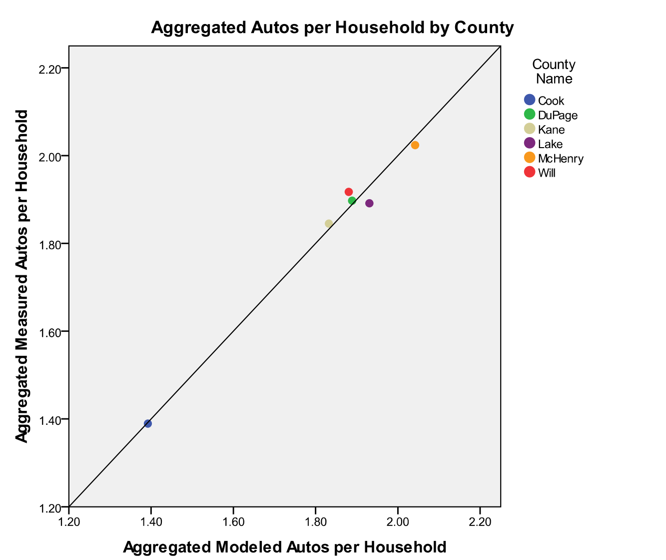


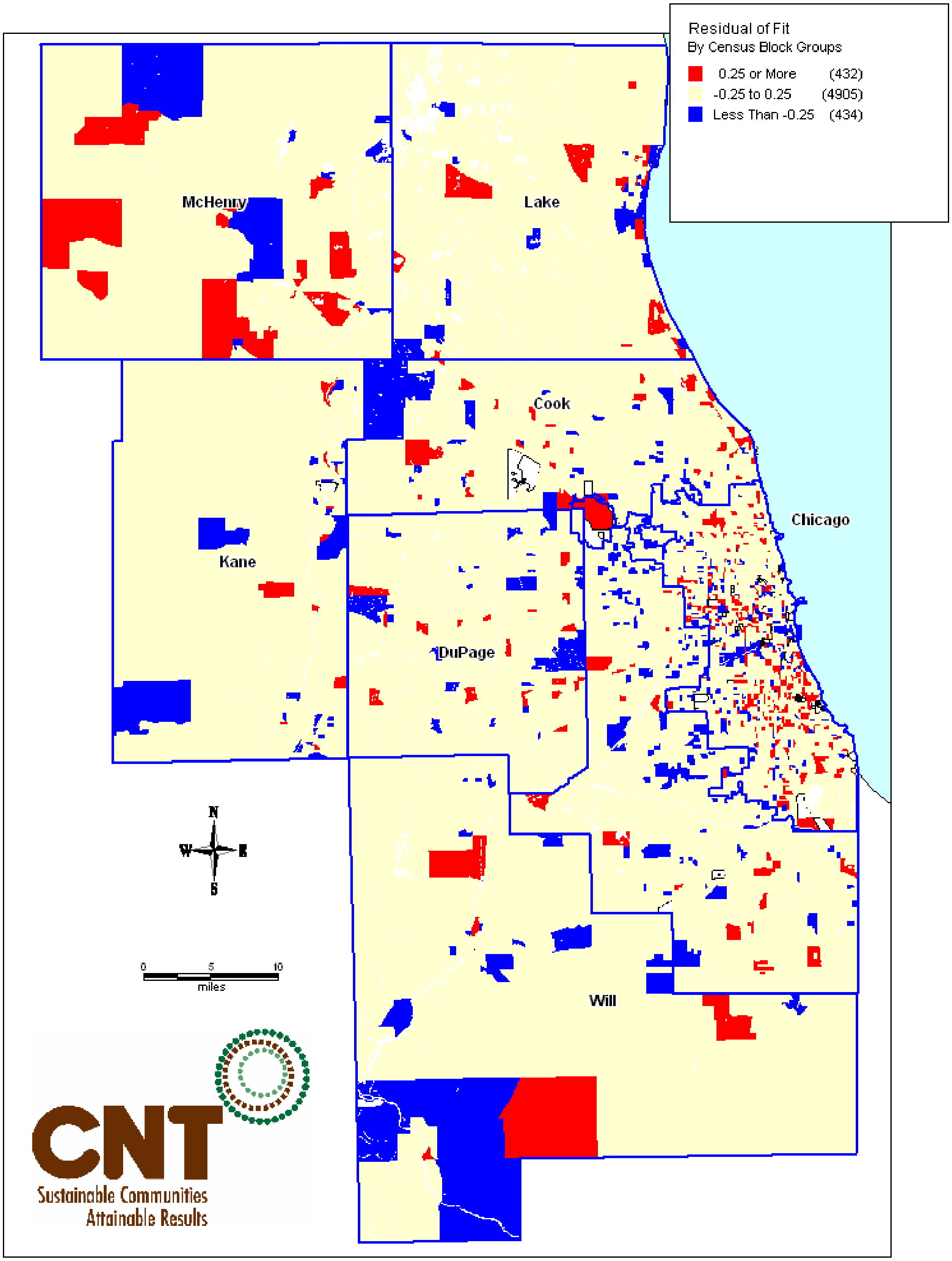
Figure 39 Aggregated Autos per Household Comparison for Counties of Measured vs. Modeled

The following table shows the measured vs. modeled for the 4 sub areas:

Area	Measured Autos per Household	Modeled Autos per Household
In Chicago Near Transit	1.07	1.09
In Chicago Not Near Transit	1.29	1.30
Suburban Near Transit	1.71	1.73
Suburban Not Near Transit	1.85	1.82

Table 13: measured vs. modeled for the 4 sub areas

Finally the following map shows the residual for the fit, but only highlights the cases where that residual is significant. There is no systemic location for extreme fits.



Appendix 1.03 Auto Use (Driving)

In order to determine the amount that people drive their autos, CNT developed a database of odometer readings from the Illinois office of motor vehicles at the zip code level. In the Chicago metropolitan area, every auto over 5 years old is required to have an emissions inspection once every two years. We have found that by aggregating these odometer data to block groups from zip code areas (and or disaggregating, depending on the relative size of zip code areas and Census block groups), and estimating mileage for late model vehicle, the resulting model simulates local VMT per household. The following histogram shows the distribution of the annual miles driven by autos per household in 5,353 block groups that overlap the zip code areas where odometer data were available, in and around the Chicago metropolitan area. Once these data were collected, and then aggregated to the block groups, the independent variables, in Table 11, are used to perform a similar regression analysis as in Section Appendix 1.02 above on auto ownership.

The following histogram shows this distribution:

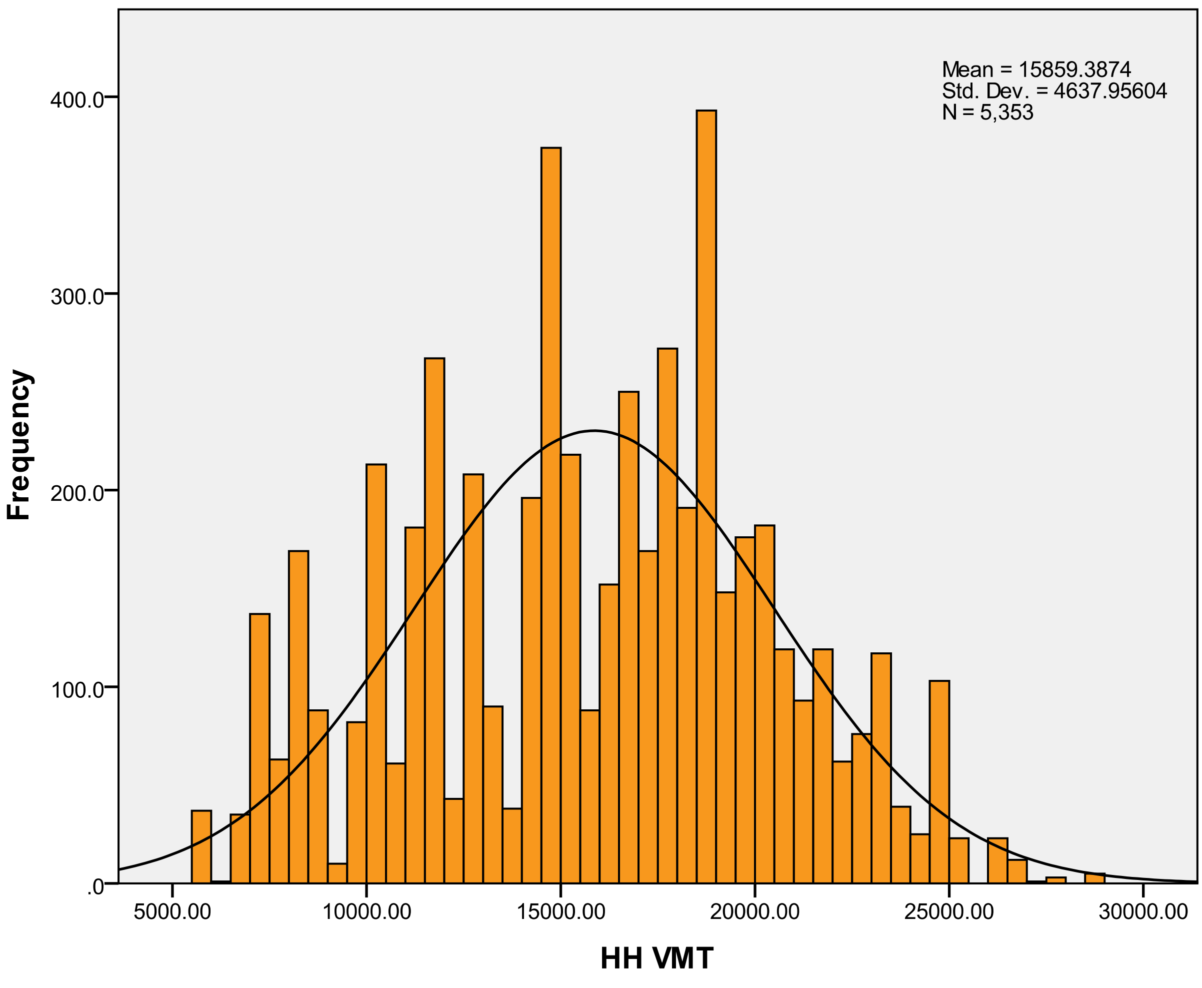


Figure 40: Histogram of the Miles Driven per Household by Census Block group in the Chicago Metropolitan Region

The variation in this graph shows that households within the region drive their autos differently. The following "error bar graphs" show how driving varies with the eight independent variables listed in Table 12.

The following graph shows that as residential density goes up the average household drives less.

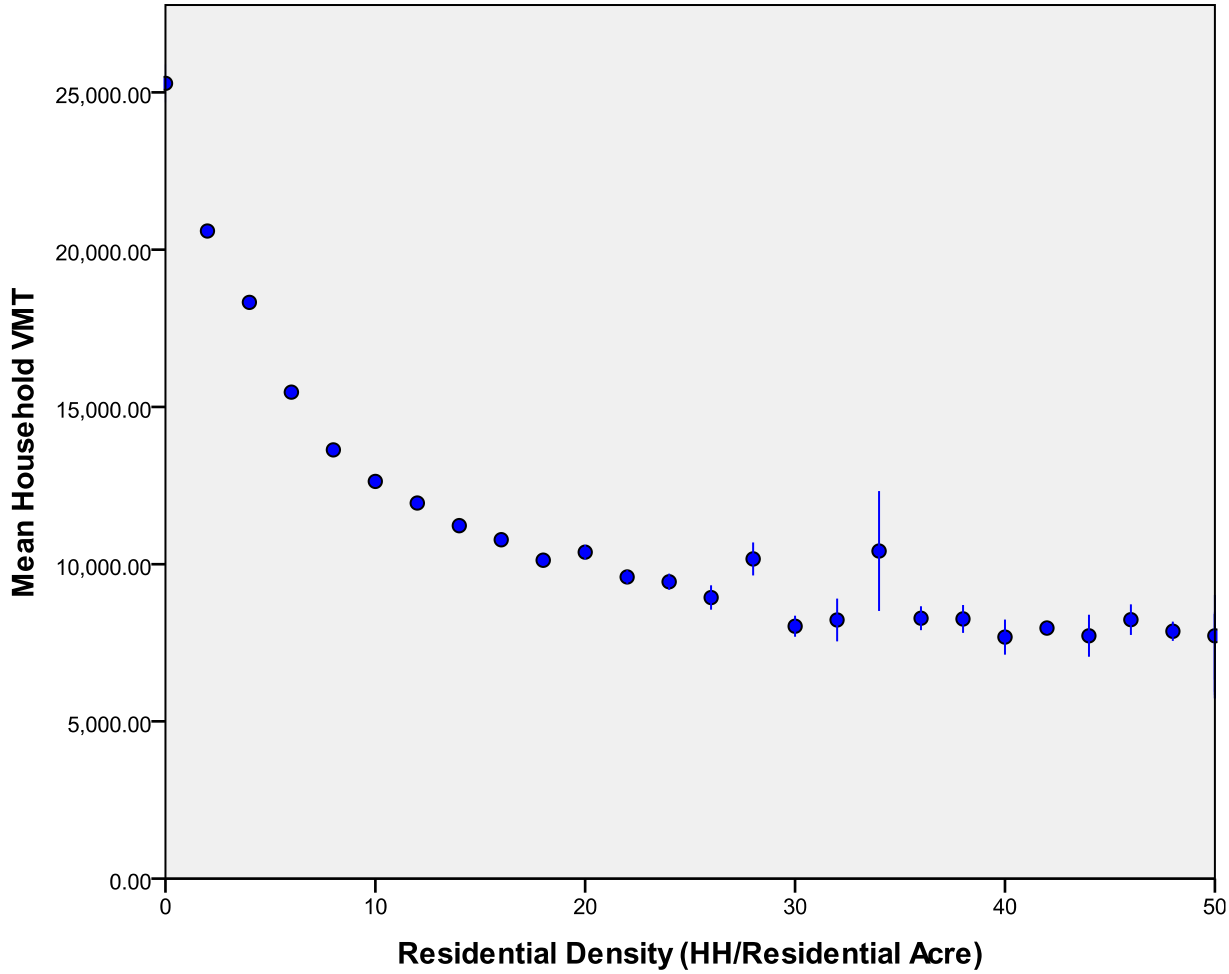


Figure 41: VMT vs. Residential Density

The next plot shows how driving varies with household income.

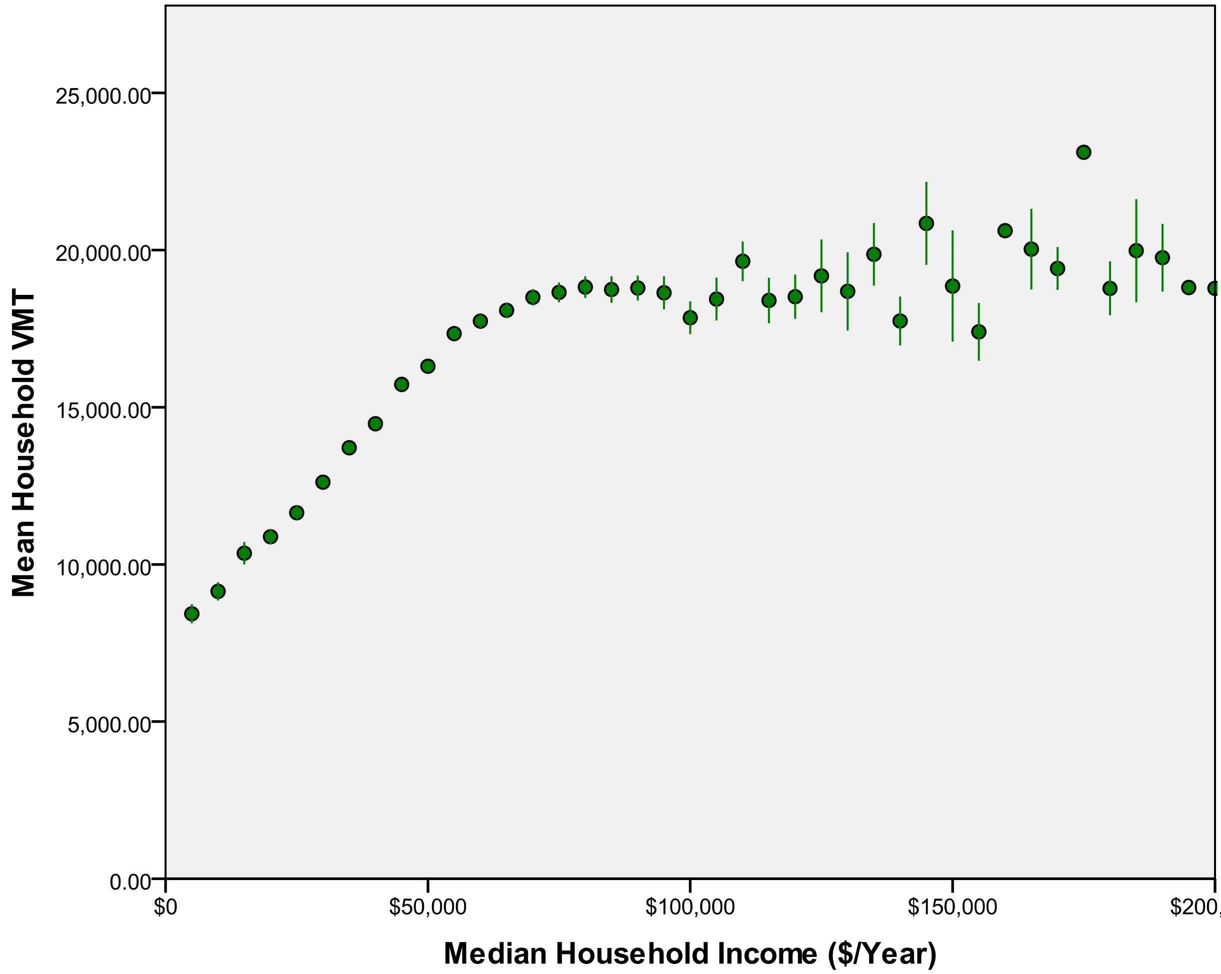


Figure 42: VMT vs. Annual Household Income (1999)

The following 6 plots show this variation for the other variables.

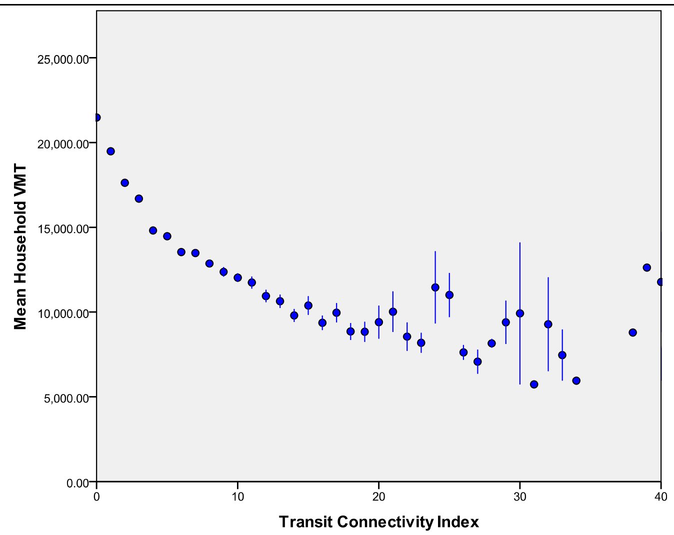


Figure 43: VMT vs. Transit Connectivity

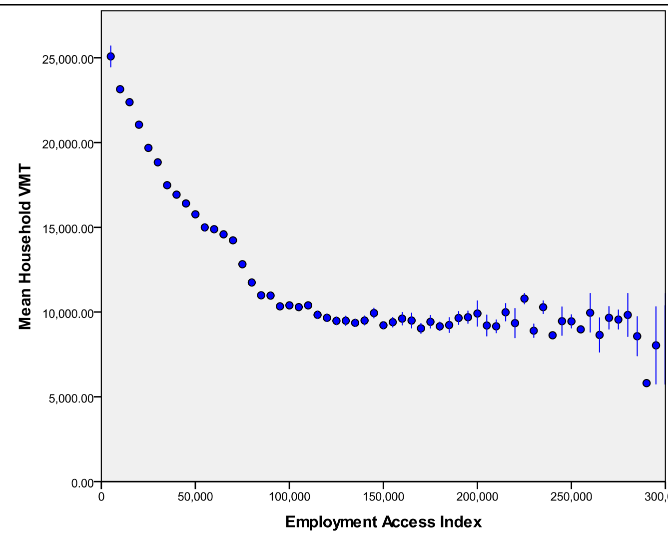


Figure 44: VMT vs. Employment Proximity

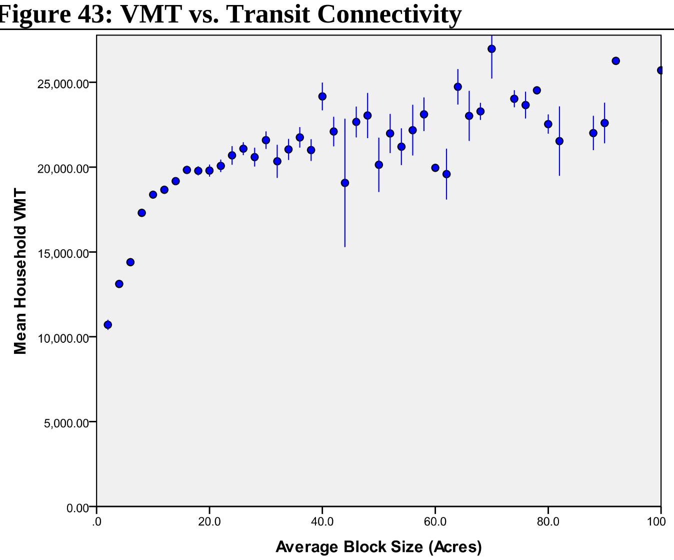


Figure 45: VMT vs. Average Block Size

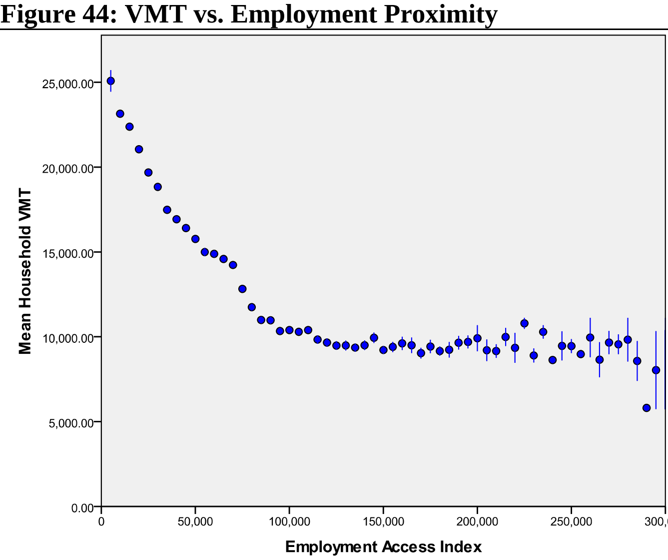


Figure 46: VMT vs. Workers per Household

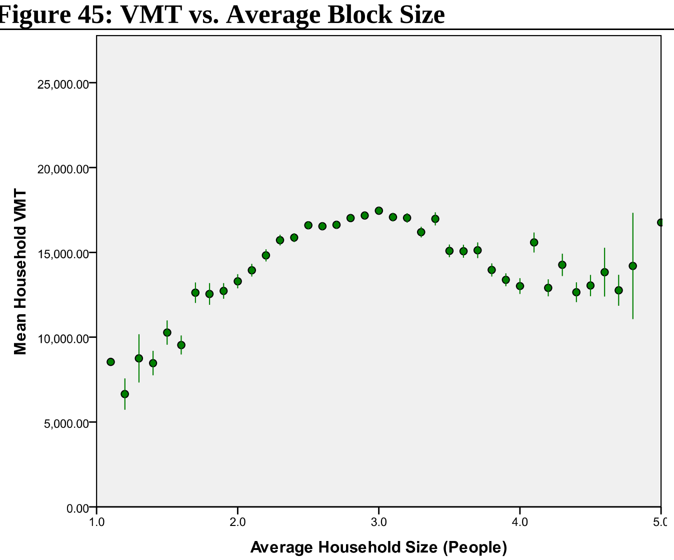


Figure 47: VMT vs. People per Household

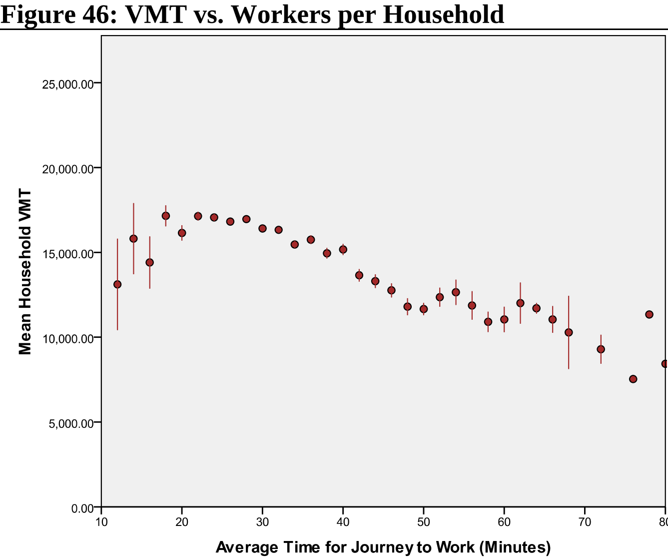


Figure 48: VMT vs. Average Time Journey to Work

The following plot shows that the amount of driving also depends on the number of autos owned by households.

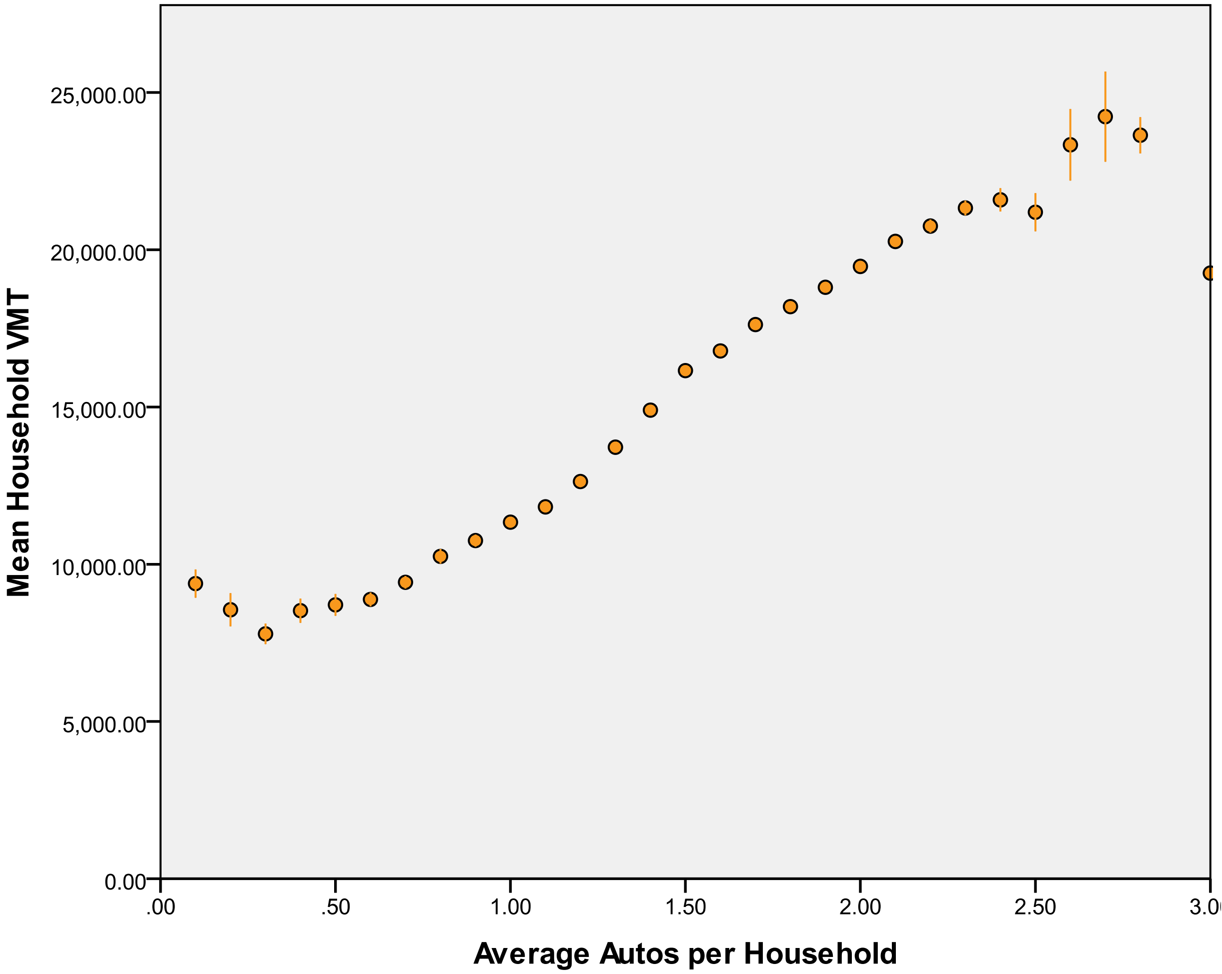


Figure 49 Driving Depends on Auto Ownership

The distributions displayed in Figure 41 through Figure 49 show again that as the place gets more compact, walkable, and jobs and transit access are higher the average driving is reduced. This is good for the carbon footprint of such households, and in general this is exactly the change in the local environment that a TOD is going to produce.

This result is obtained using a rational model[21] for each of these variables. The overall functions can be represented as:

$$VMT = 10{,}000 \times \left(a + \sum_{i=1}^{9} \frac{(C_{i1} \times X_i + C_{i3} \times X_i^2 + C_{i5} \times X_i^3)}{(1 + C_{i2} \times X_i + C_{i4} \times X_i^2 + C_{i6} \times X_i^3)} \right)$$

Equation 3 VMT Regression Equation

[21] For a simple discussion of rational model us see for example http://www.itl.nist.gov/div898/handbook/pmd/section6/pmd642.htm

Where: VMT is the modeled household VMT, a is an intercept coefficient, X_i are the eight independent variables listed in "Table 12 Independent Variables for Household Transportation Model.," (with the addition of Autos per Household for i=9) divided by a simple normalization factor so that the fit coefficients are of similar order of magnitude, and C_{ij} are the fit coefficients. The final values for these coefficients are determined using a standard multidimensional regression technique.

appendix 1.03.a Goodness of Fit – Auto Use

The following scatter plot show the measured household VMT vs. the modeled household VMT, note that this shape is consistent with the R2 of 84 percent obtained from this fit.

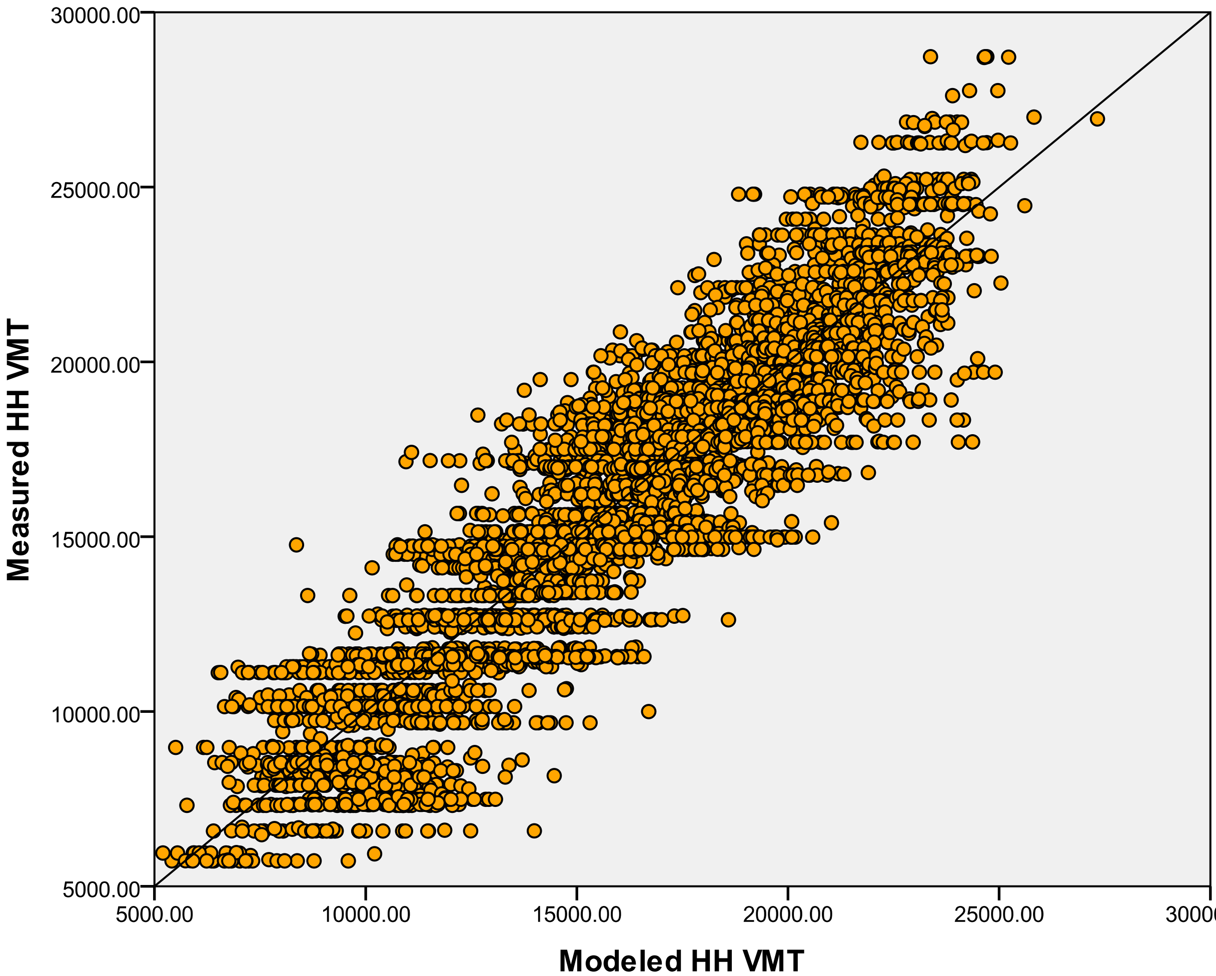


Figure 50 Measured vs. Modeled VMT per Household

The following histogram shows the residual of the fit (the difference between the Measured and Modeled Household VMT) note that most of the variation in Figure 40 has been eliminated.

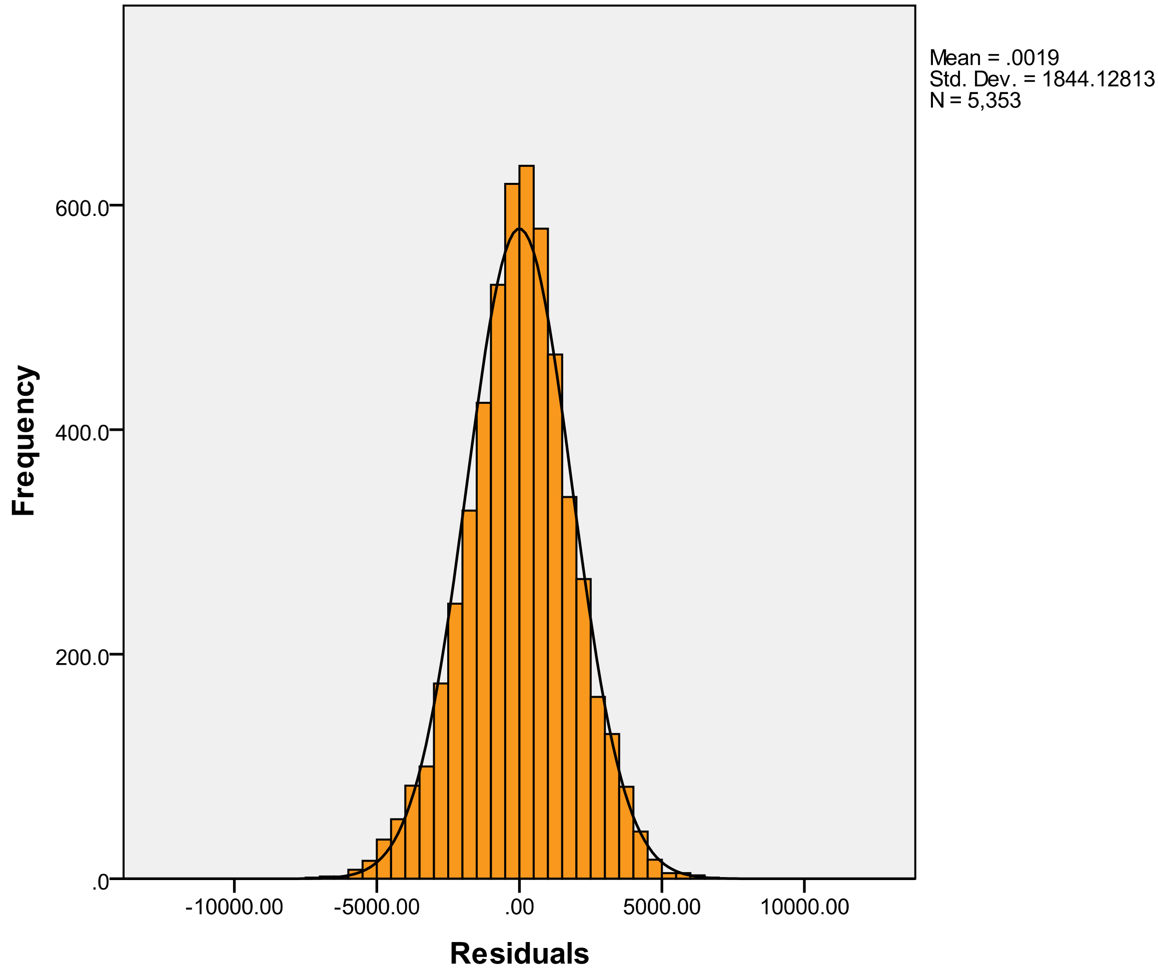


Figure 51 Residual from VMT per Household Fit

The following error bar plots show the residual of the fit vs. the variables themselves, if this were a perfect fit there would be no variation and they would be flat and centered on zero. Note that most of the variation in Figure 41 through Figure 49 has been eliminated.

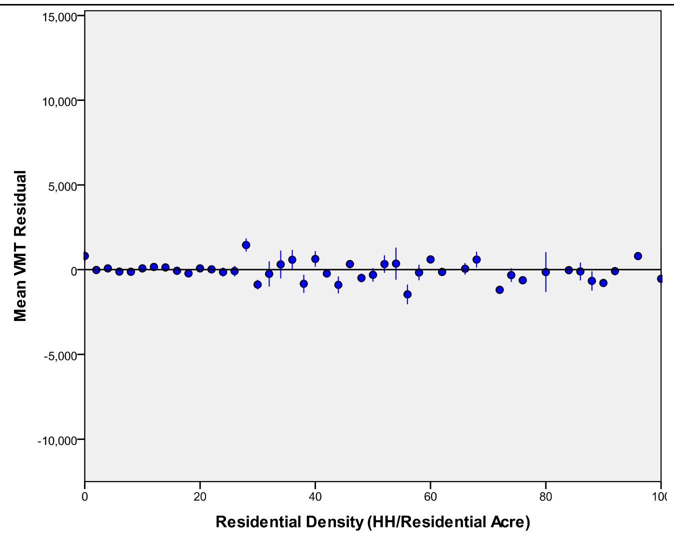


Figure 52 VMT Residual vs. Residential Density

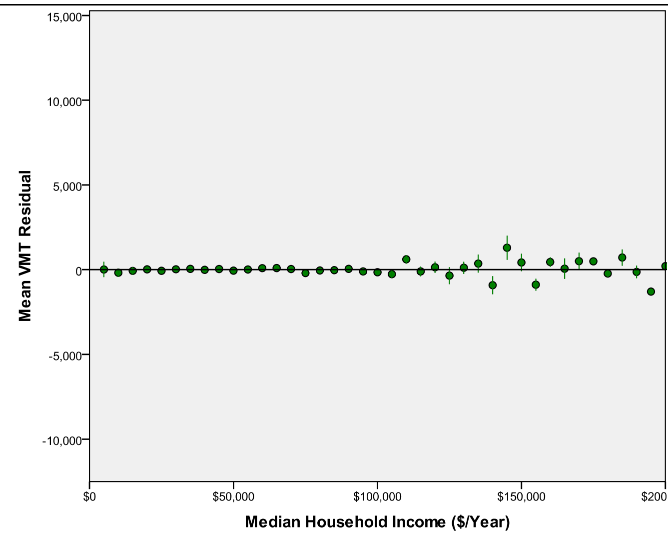


Figure 53 VMT Residual vs. Household Income

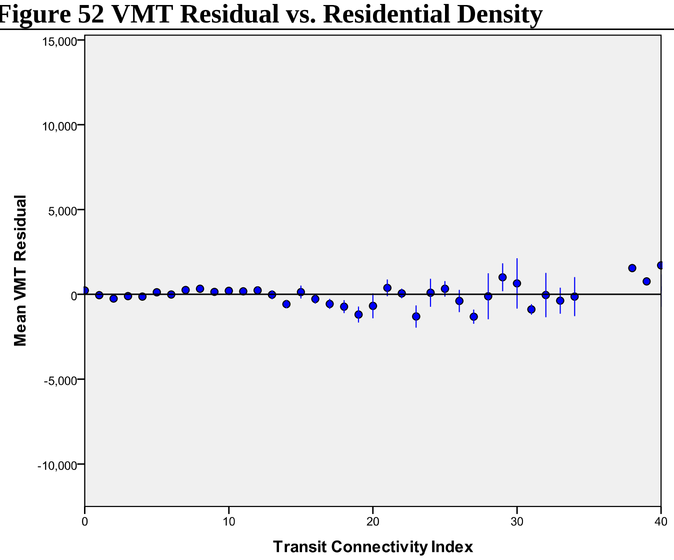


Figure 54: VMT Residual vs. Transit Connectivity

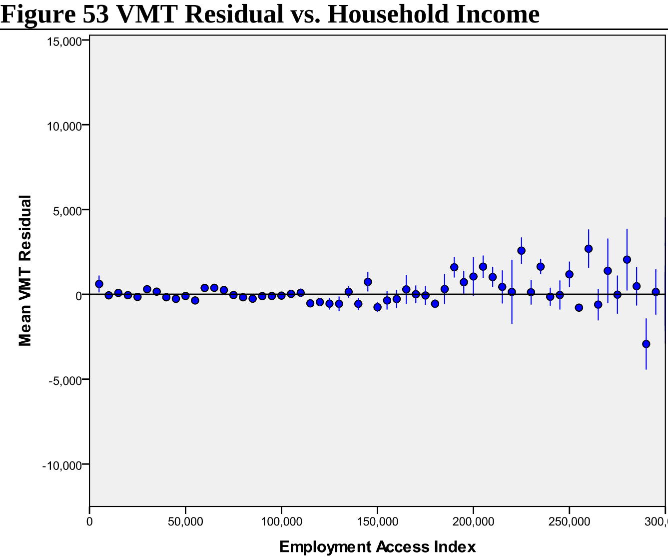


Figure 55: VMT Residual vs. Employment Proximity

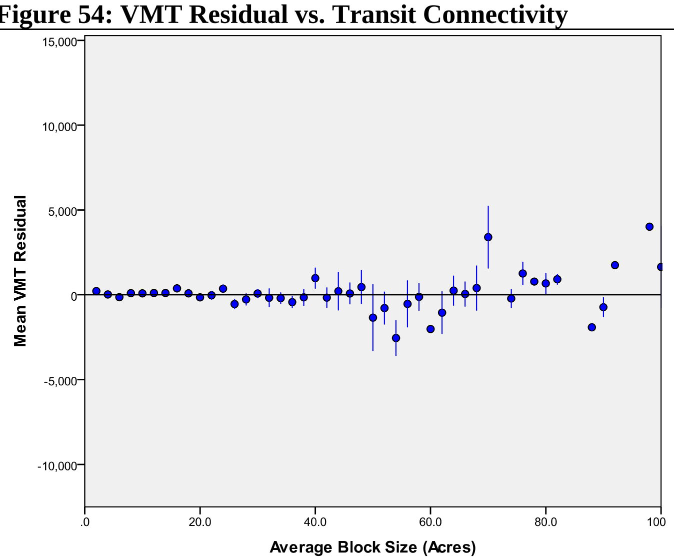


Figure 56: VMT Residual vs. Average Block Size

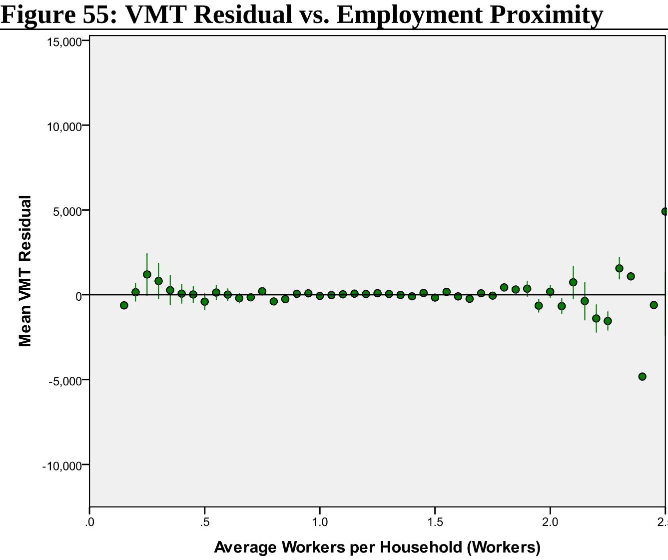


Figure 57: VMT Residual vs. Workers per Household

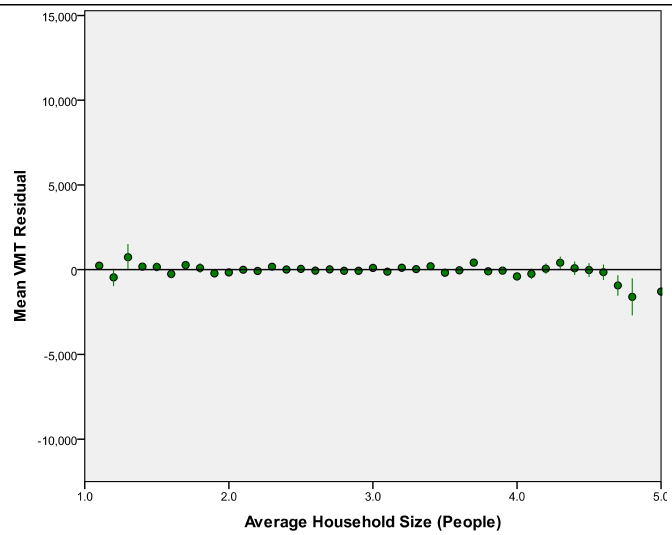


Figure 58: VMT Residual vs. People per Household

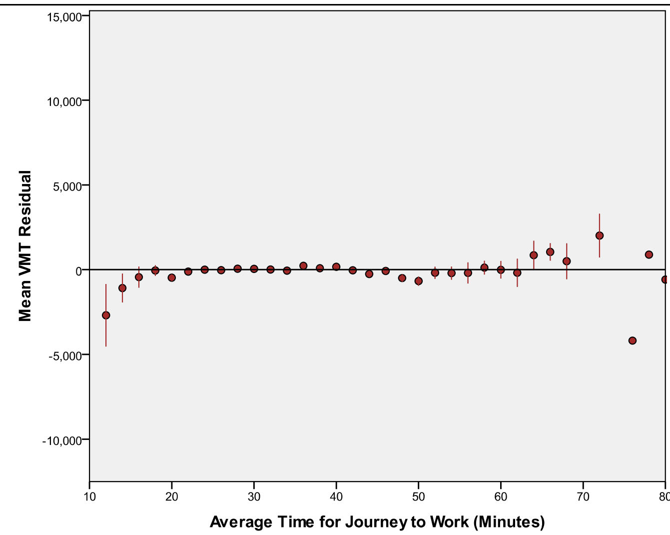


Figure 59: VMT Residual vs. Average Time Journey to Work

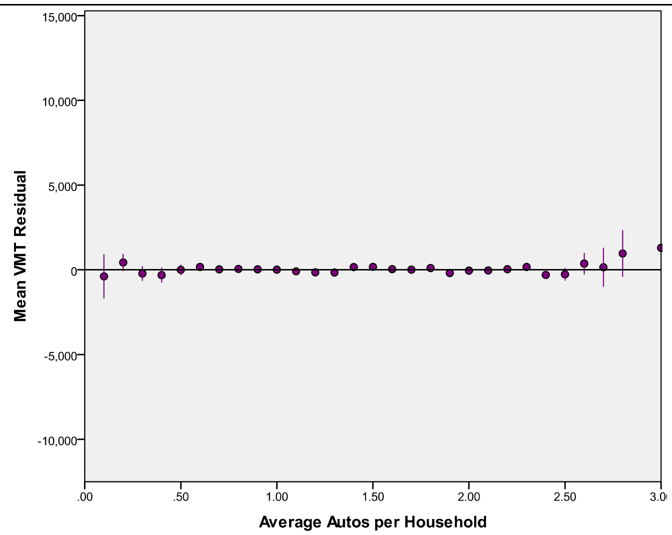


Figure 60 VMT Residual vs. Autos per Household

As a further check of any bias in the model we aggregated both the measured and modeled autos per household and looked to see if these aggregate numbers were consist. For the unit of aggregation we used both counties and municipalities. The following scatter plots show that the model is consistent with the measurement for both levels of aggregation. The one outlying municipality is on the edge of the region and has a limited set of odometer readings.

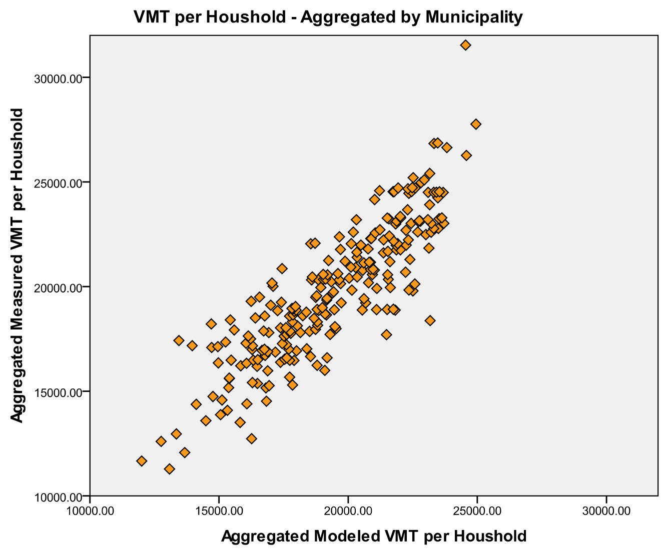


Figure 61 Aggregated VMT per Household Comparison for Municipalities of Measured vs. Modeled

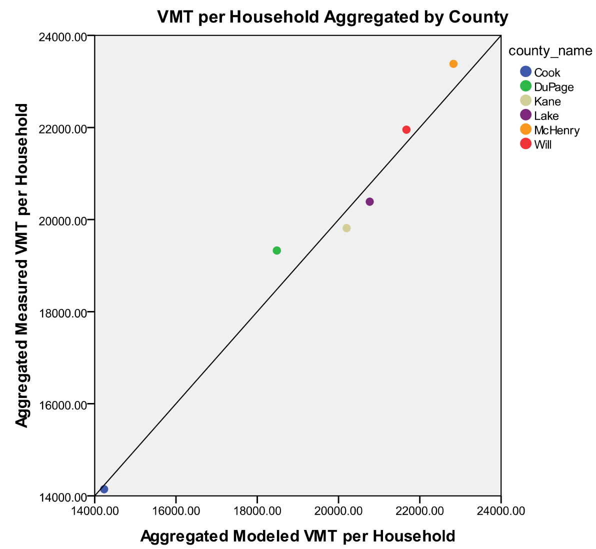
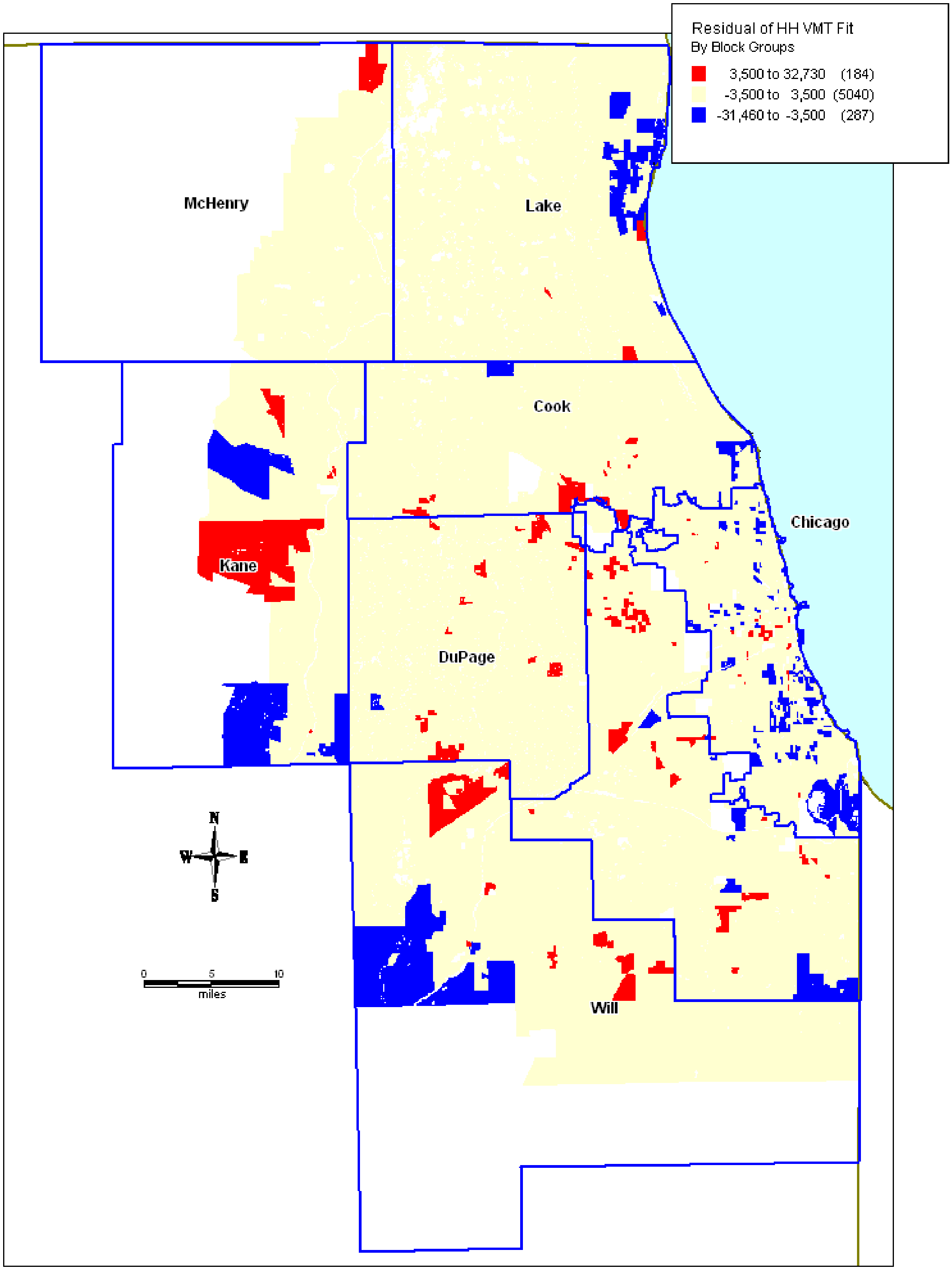


Figure 62 Aggregated VMT per Household Comparison for Counties of Measured vs. Modeled

The following table show the measured vs. modeled for the 4 sub areas.

Area	Measured VMT per Household	Modeled VMT per Household
In Chicago Near Transit	10909.65	11287.77
In Chicago Not Near Transit	12915.55	13206.14
Suburban Near Transit	18210.28	17617.35
Suburban Not Near Transit	19200.99	19120.45

Finally the following map show the residual for the fit, but only highlights the cases where that residual is rather large. There is not systemic location for extreme bad fits.


Residual of HH VMT Fit
By Block Groups
3,500 to 32,730 (184)
-3,500 to 3,500 (5040)
-31,460 to -3,500 (287)
McHenry
Lake
Cook
Chicago
Kane
DuPage
Will
N
W
E
S
0
5
10
miles

Appendix 1.04 Conclusions

This model of household auto ownership and use works very well in the Chicago metropolitan area. It has also been shown to work well in other places, but for the scope of this paper this model can be used to project forward what overall auto use and therefore, greenhouse gas emissions will be under different growth scenarios. More research on this model will be useful. This should include examining other regions for similar behavior on auto ownership, collect more odometer readings from other regions and make sure the same or similar behavior can be observed, and look at other variables that might correlate with auto ownership and driving, for example, examining stage of life issues of household by examining the average age of the population in a block group, or the number of school age children and seniors in the block groups, and other measures of transit connectivity and walkability. However we will leave this for future research and for now use this model to examine Chicago Metropolitan area growth strategies, to examine the GHG emissions under different assumptions.

Appendix 2. Finding Transit Zone Types

The following six scatter plots show how the environment variables correlate for all of the US transit zones. Note that there is some clustering in some of these plots. We have used the K-Clustering statistical technique to look for type of transit zones, to see if there are examples of areas that can be a model for what is achievable for TOD.

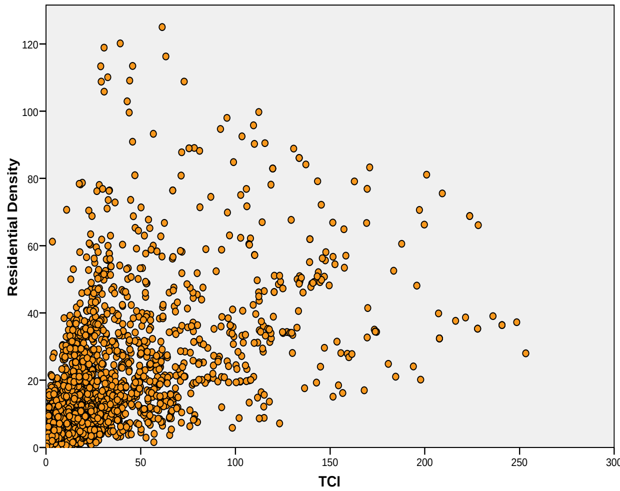


Figure 63: Residential Density vs. TCI

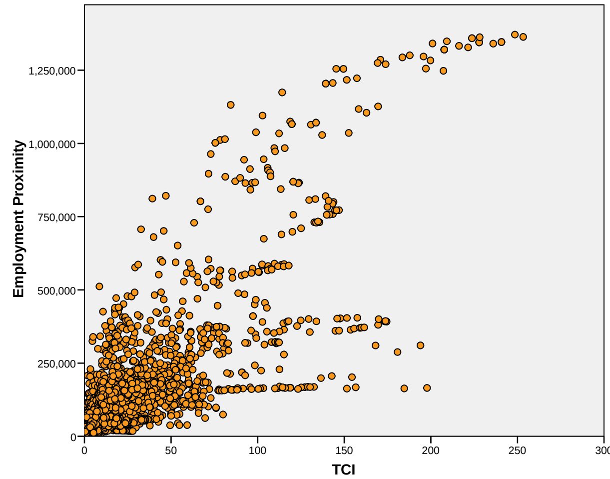


Figure 64: Employment Proximity vs. TCI

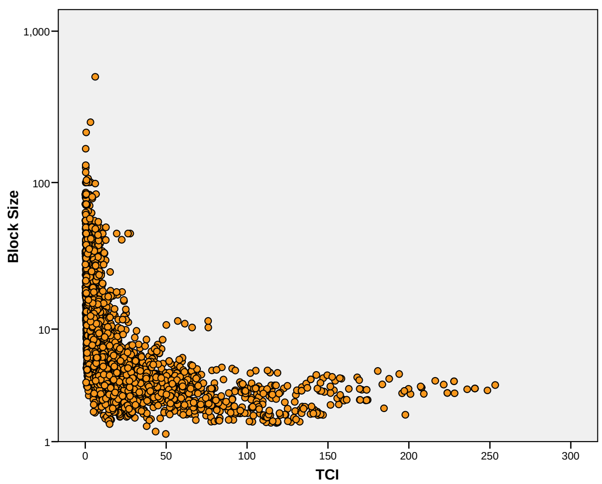


Figure 65: Block Size vs. TCI

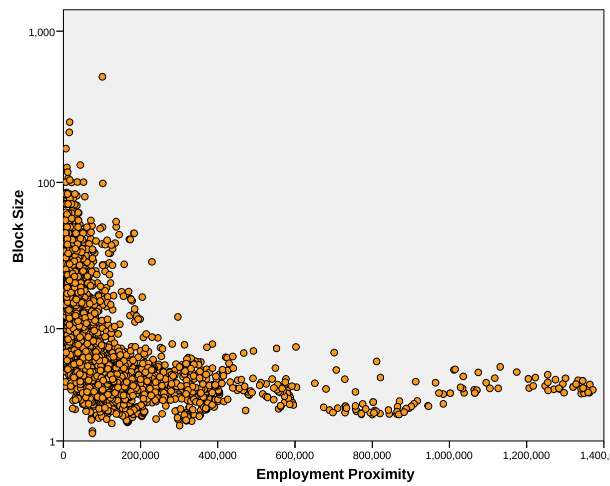


Figure 66: Block Size vs. Employment Proximity

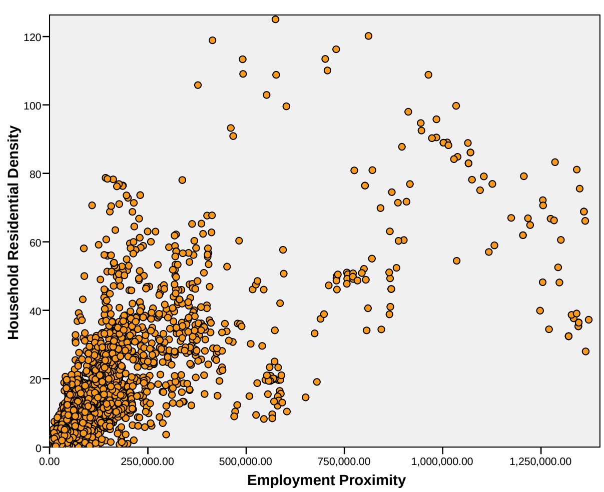


Figure 67: Residential Density vs. Employment Proximity

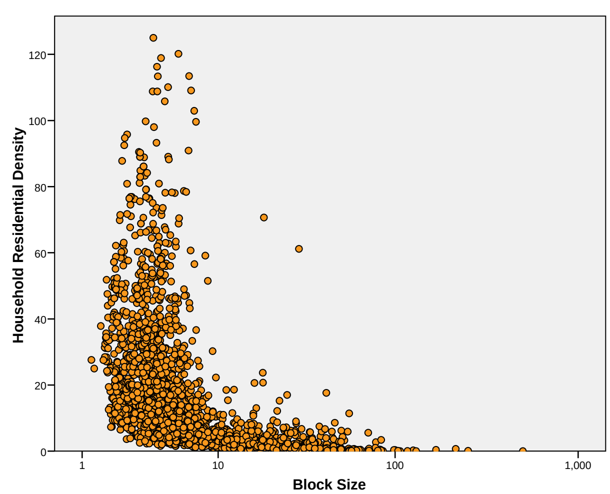


Figure 68: Residential Density vs. Block Size

The following are the same plots as in Figure 63 through Figure 68 but the types have been shown in color.

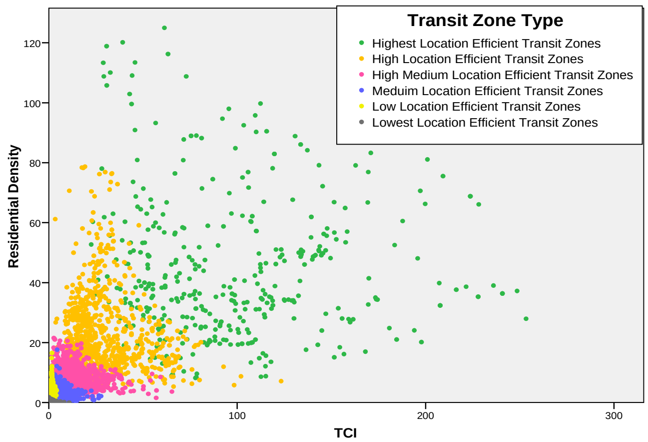


Figure 69: Residential Density vs. TCI - Displaying Transit Zone Type

Figure 70: Employment Proximity vs. TCI- Displaying Transit Zone Type

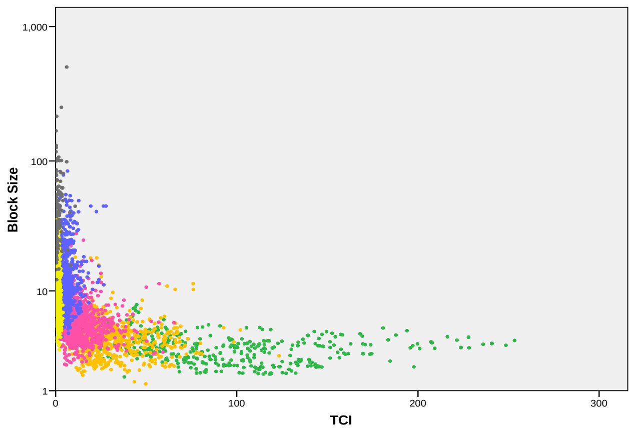


Figure 71: Block Size vs. TCI- Displaying Transit Zone Type

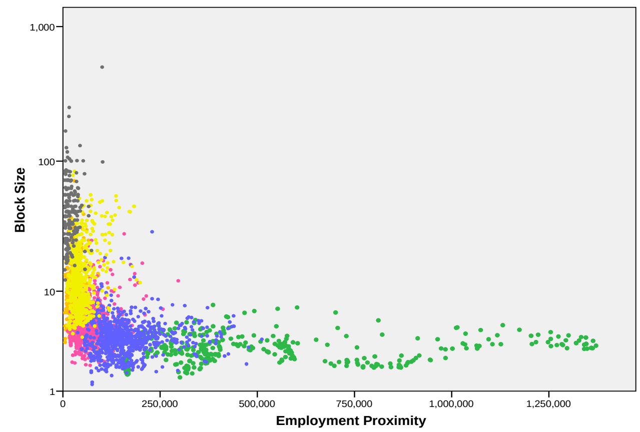


Figure 72: Block Size vs. Employment Proximity - Displaying Transit Zone Type

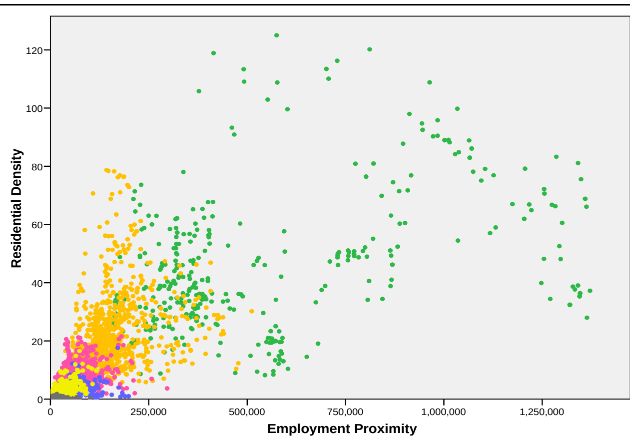


Figure 73: Residential Density vs. Employment Proximity - Displaying Transit Zone Type

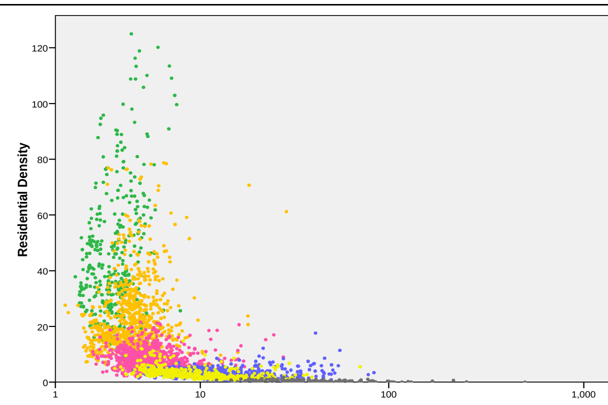


Figure 74: Residential Density vs. Block Size - Displaying Transit Zone Type

The following map shows five regions all at the same geographic scale. Note that the occurrence of the above transit zone differ from region to region but still have the same basic distribution.

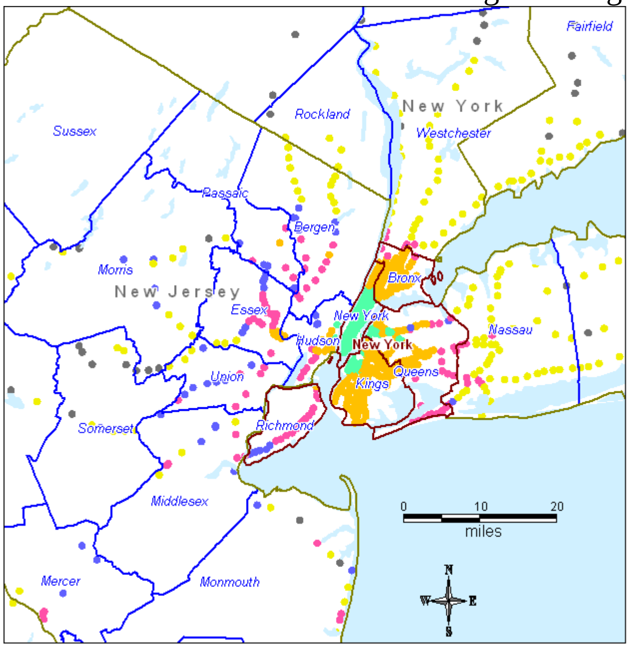


Figure 75: New York City Region Transit Zone Type

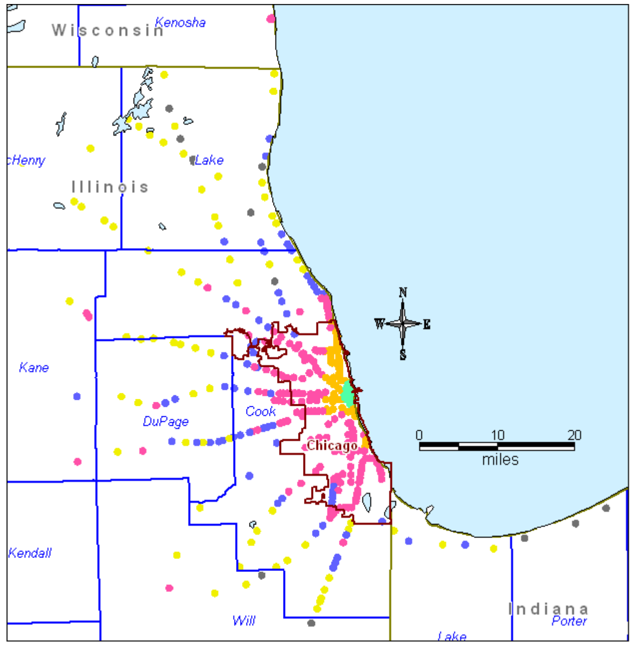


Figure 76: Chicago Region Transit Zone Type

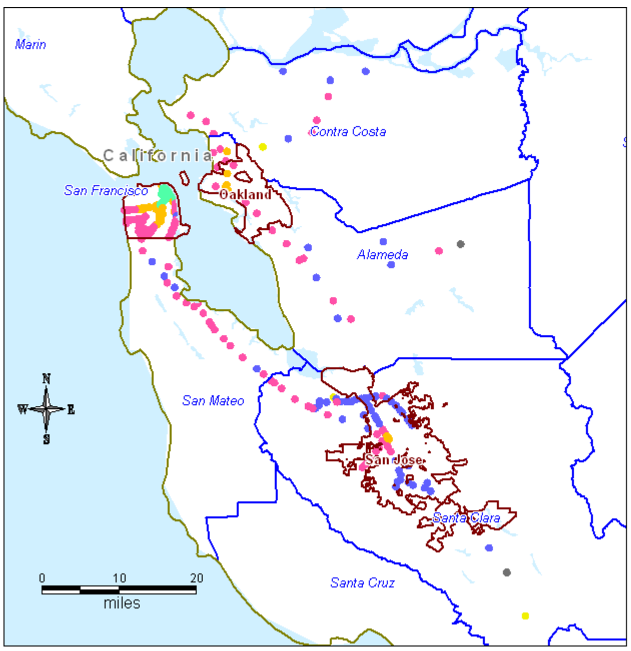


Figure 77: San Francisco Bay Region Transit Zone Types

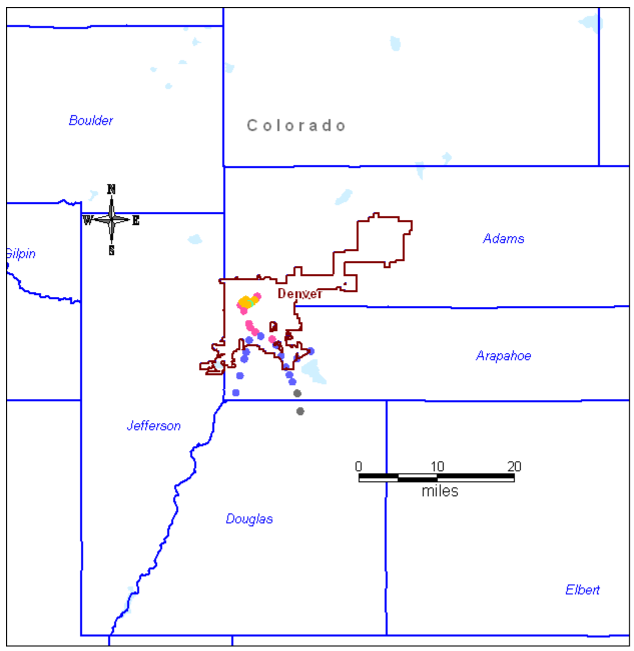


Figure 78: Denver Region Transit Zone Types

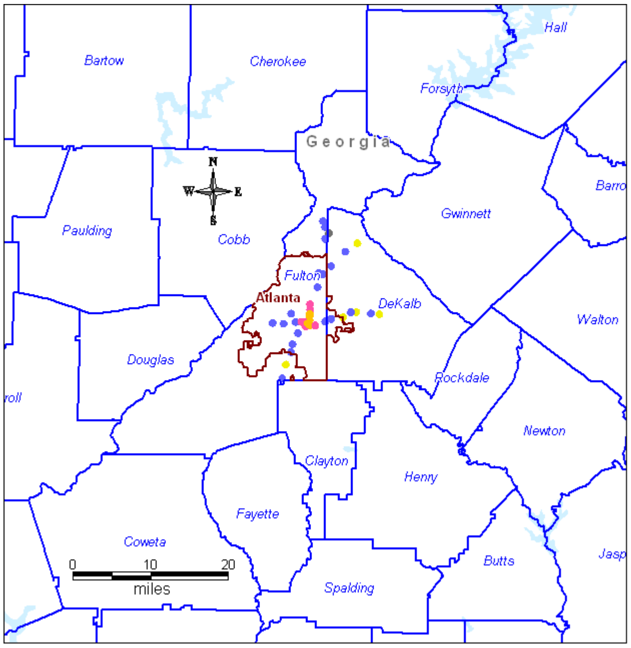


Figure 79: Atlanta Region Transit Zone Types

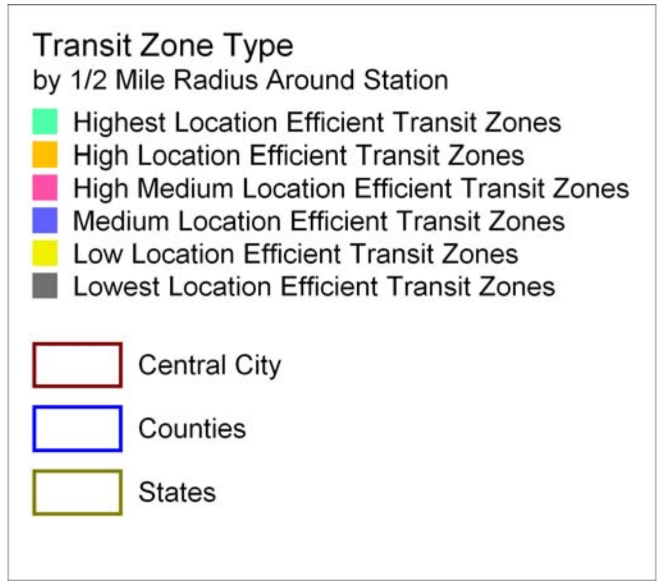


Figure 80: Transit Zone Type Legend