Life cycle assessment of urban vs. suburban residential mobility in Chicago

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ABSTRACT: In the United States, metropolitan area population increased from 69 percent of the total population in 1970 to 80 percent in 2000, but the population has continued to suburbanize within the metropolitan areas. This phenomenon is especially highlighted in Chicago. The population of the City of Chicago peaked at 3.6 million in 1950, containing 70 percent of metropolitan area residents. By 2000, 2.9 million Chicagoans made up only 36 percent of the region's population. Also, vehicle miles traveled (VMT) on U.S. highways has been increasing at a much faster rate than either population or developed land for several decades.

It is widely accepted that dense or compact city should be more "sustainable" due to higher energy efficiency in higher residential density along with greater accessibility to city facilities, and shared infrastructure. A key question of interest is the extent to which developing more compactly would reduce VMT and make alternative modes of travel (i.e., walking, bicycling, public transit, etc.) more feasible. Yet, there are very few studies that conduct a comprehensive energy and environmental life-cycle measure of residential mobility in different urban patterns, in terms of location, travel behavior, accessibility, etc.

The research outlined in the paper conducts a life-cycle assessment (LCA) of residential mobility within three urban scenarios in Chicago: Chicago Loop as a high dense downtown district, Oak Park as a less dense suburb close to the downtown, and Aurora as a much less dense suburb far away from the downtown. In these three cases the research quantifies and compares the life-cycle energy in resident travel through different modes of transport such as automobile, bus, CTA train, and Metra, including such LCA components as vehicle manufacturing & maintenance, vehicle operation, infrastructure construction & operation, etc. The study proves the denser area with shorter commuter distance consumes less life-cycle energy of residential mobility.

Due to the complexity of residential mobility, the metropolitan region could be the best geographic scale for transportation LCA integration, and LCA can and should be used as a valuable guiding framework for novel mitigation strategies. Based on the case studies in Chicago Metropolitan area, the paper provides an alternative perspective for policy and decision makers to incorporate life-cycle thinking into planning.

KEYWORDS: LCA, Sustainability, Transportation, Infrastructure, Embodied Energy

INTRODUCTION

The United Nations forecasts that 70 percent of the world's projected nine billion populations will be urbanized by the year 2050, up from 51% of seven billion urbanized as of 2010[1]. The enormity of this total figure of 2.8 billion people moving into cities over the next 40 years is perhaps more clearly appreciated when converted into an annual rate of 70 million people per year, or a daily rate of nearly 200,000 people. That means that the human race needs to build a new or expanded city of more than one million people every week for the next 40 years to cope with this urban growth. The key question is: how are these new millions of urban inhabitants best accommodated – in the horizontal city, or the vertical city?

The U.S. population has continued to urbanize and suburbanize. As a share of total population, metropolitan population increased from 69 percent in 1970 to 80 percent in 2000 (Hobbs and Stoops 2002 in Giuliano et al. 2008, 11). Within metropolitan areas, however, the population has continued to suburbanize. From 1970 to 2000, the suburban population slightly more than doubled, from 52.7 million to 113 million[2].This phenomenon is especially highlighted in Chicago, where there has been a huge population shift from city to suburbs over the last half of 20thcentury. The population of the City of Chicago peaked at 3.6 million in 1950, containing 70 percent of metropolitan area residents. By 2000, 2.9 million Chicagoans made up only 36 percent of the region's population[3].

Yet, these dispersed, automobile-oriented suburbanized patterns have resulted in consuming vast quantities of undeveloped land, and increasing vehicle miles traveled (VMT), which contribute to increasing energy usage. Specifically, passenger vehicle travel on U.S. highways has been increasing at a much faster rate than either population or developed land for several decades (Transportation Research Board, 2009).

It is widely accepted that the concentration of people in denser cities – sharing space, infrastructure, and facilities – offers much greater energy efficiency than the expanded horizontal city, which requires more land usage as well as higher energy expenditure in infrastructure and mobility. A key question of interest is the extent to which developing more compactly would reduce VMT and make alternative modes of travel (i.e., walking, bicycling, public transit, etc.) more feasible. Yet, there are very few studies that conduct a comprehensive energy and environmental life-cycle measure of residential mobility in different urban patterns, in terms of travel behavior, shared infrastructure, etc. This research project could thus hardly be important, and looks to fill a massive research gap.

1.0 LIFE CYCLE ASSESSMENT

Life cycle assessment (LCA) studies the environmental aspects and potential impacts throughout a product's life (i.e. cradle-to-grave) from raw material acquisition through production, use, and disposal (ISO, 1997). By including the impacts throughout the product life cycle, LCA provides a comprehensive view of the environmental aspects of the product or process and a more accurate picture of the true environmental trade-offs in product and process selection. Figure 1 illustrates the possible life cycle stages that can be considered in an LCA and typical inputs/outputs measured.

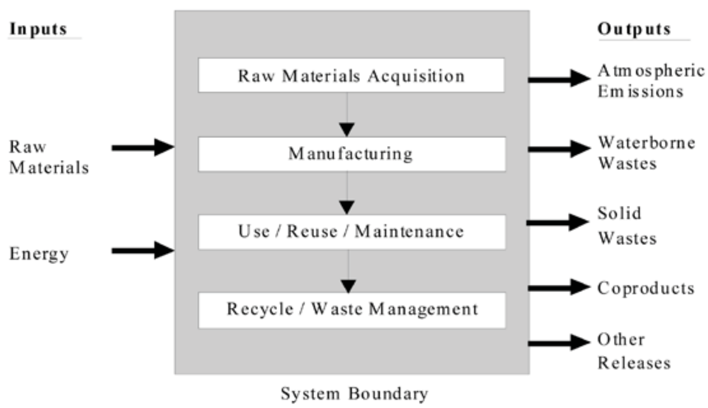


Figure 1: Life cycle stages. Source: (EPA, 1993)

Life cycle energy can also be expressed as a sum of Embodied Energy + Operating Energy. Embodiedenergytypicallyconsistsofthreemainelements:initialembodiedenergy,recurringembodiedenergy anddemolitionenergy.Comparedtoembodiedenergy,operatingenergyisanongoingandrecurrentexpenditur eofenergythatisconsumedtosatisfythedemandfor day-to-day operation process.

In transportation systems, LCA is a framework for assessing the energy use and resulting environmental impacts of mobility from well-to-wheels. Recent studies have developed a comprehensive environmental LCA for automobiles, buses, trains, and airplanes in the US, including vehicles, infrastructure, fuel production and supply chains (Chester 2008, Chester and Horvath 2009). Specifically, the components inventoried in vehicles include manufacturing, operation, maintenance, replacement and insurance, and the components inventoried in infrastructure include construction, operation, maintenance, parking insurance, etc.

Based on the methodological framework and database from Chester et al, the research outlined in the paper conducts a LCA of residential mobility within three urban scenarios in Chicago to specifically quantifies and compares the life-cycle energy in resident travel through different modes of transport such as automobile, bus, CTA train, and Metra, including vehicles manufacturing, maintenance &operation, and infrastructure construction, maintenance & operation, etc.

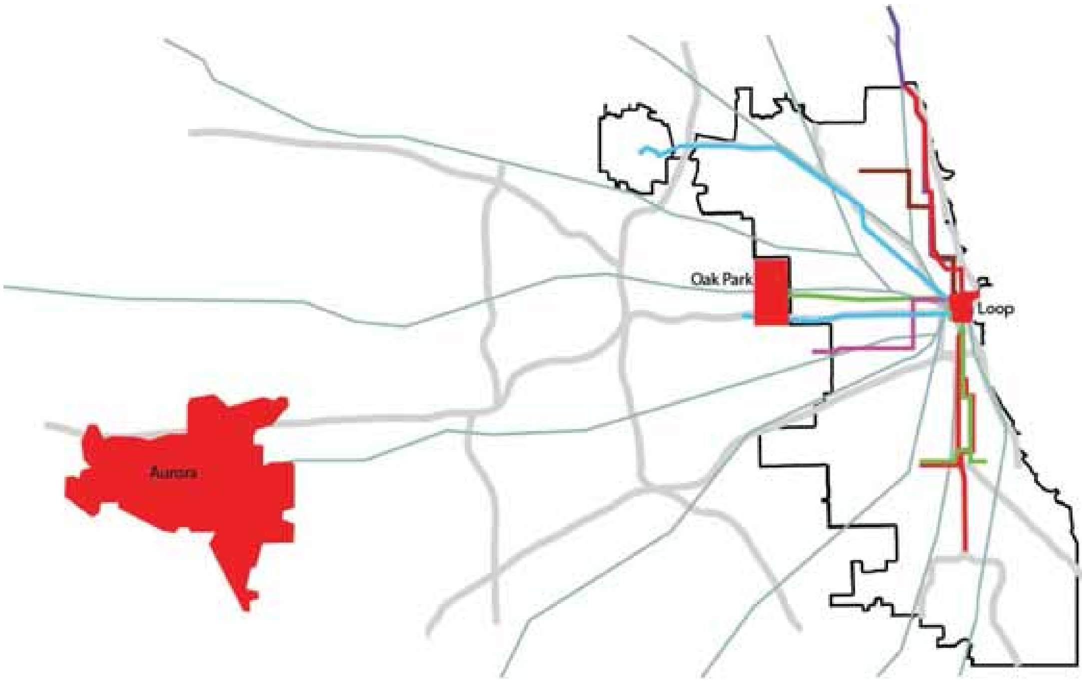


Figure 2: Site location and transportation systems (including CTA train lines, Metra lines and major highways) of the 3 case studies. Source: (Author 2014)

Chicago Loop, as the primary destination of commuter in Chicago metropolitan area, integrates all public transportation train lines and multiple buses. High dense residential community dominates the housing type in the Loop. Oak Park located about 8 miles from Chicago city center has easy access to downtown Chicago (the Chicago Loop) via public transportation, such as the Chicago 'L' Blue and Green lines, CTA buses and Metra commuter rail. Actually, Oak Park is a relatively dense mixed community of single-family homes and apartment blocks. Aurora located about 50 miles from Chicago city center has relatively limited public transportation system. Aurora is the final stop of the Metra BNSF Line connecting to Downtown Chicago, and also operates Pace suburban bus connecting to the surrounding cities. Single-family housing dominates the housing type in Aurora. Figure 3 shows the differences in the urban fabrics of the three study areas.

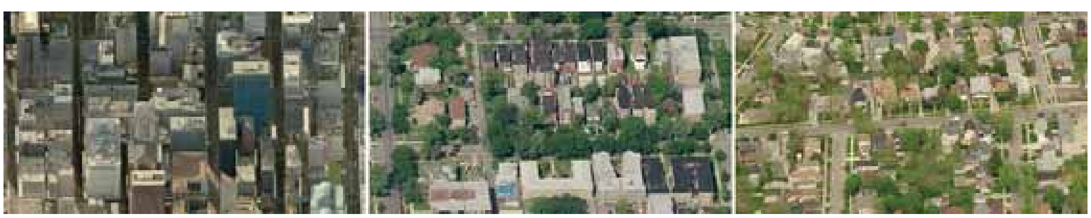


Figure 3: Urban Fabrics of Chicago Loop (Left), Oak Park (Middle) and Aurora (Right). Source: (Author 2014, images from Bing Maps)

Table 1 outlines the basic characteristics of the three study areas. Generally, it shows that the denser area has lower VMT as we all have already known. However, factors that affect VMT are various, including demographic characteristics, access to jobs, proximity to business and amenities, availability of public transportation, neighborhood walkability, etc. The research quantifies and compares the life-cycle energy in the residential mobility via different modes cross the three urban scenarios.

Table 1: Basic characteristics of the three study areas. Source: (Author 2014, data from 2010 and 2012 Census, 2011 American Community Survey five-year estimates, CMAP calculations of US Census Bureau, and Illinois Secretary of State)

Characteristics/Study Areas	Chicago Loop	Oak Park	Aurora
Urban Pattern	Downtown	Inner commuter suburb	Outer commuter suburb
Population	29,283	51,878	199,932
Density	7,200/km^2	4,262/km^2	1,433/km^2
Distance to Downtown	Walkable	Avg. 8 miles	Avg. 50 miles
Avg. Household Size	1.8	2.4	3.2
Median Number of Rooms	3.7	5.4	5.8
Avg. Vehicle Number per HH	0.67	1.61	1.8
Avg. Annual VMT per HH	6,949 miles	13412 miles	20,931 miles
Avg. Annual VMT per Person	3,860.6 miles	5588.3 miles	6540.9 miles
Public Transportation	All CTA Lines, All Metra Lines & Multiple Bus Lines	Green & Blue CTA lines, Metra UP-West Line & Pace Buses	Metra BNSF Line& Pace Buses

According to the 2008 Household Survey[4] Share of Total Mileage of Travel by Mode by Residents of each Zone, the total mileage traveled per person by public transportation modes can be calculated as shown in Table 2.Due to the limited open data about the travel behavior via public travel mode and the geographic characteristics, the study assumes that the share of total mileage of travel by mode in Loop is the same as Central Chicago zone, Oak Park is the same as West Cook zone, and Aurora is the same as Eastern Kane zone.

Table 2: Annual mileage traveled per person by different transportation modes in different study areas. Source: (Author 2014)

Study Areas/Mode	Automobile	CTA/Pace Bus	School Bus	CTA Train	Metra
Loop	3860.6	737.4	23.2	552.1	139
Oak Park	5588.3	145.3	117.4	424.7	357.7
Aurora	6540.9	6.5	91.6	0	510.2

2.1. Methodology

The study quantifies the energy inputs of annual mobility per person via different transportation modes, including automobile, CTA/Pace/school bus, CTA train, and Metra, associated with the life cycles of vehicles and infrastructure in Chicago Loop, Oak Park and Aurora.

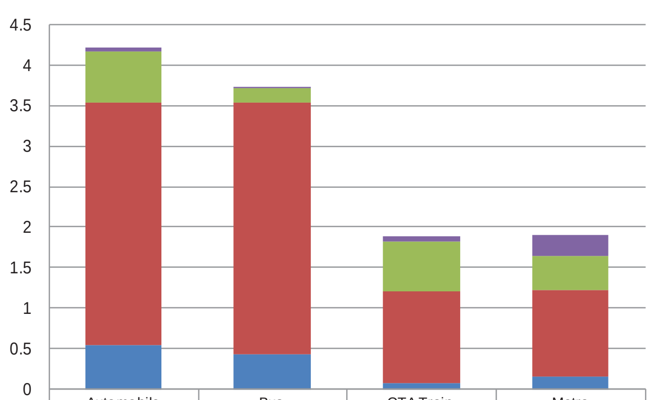
System boundary selection is a critical first step in LCA to establish a consistent scope for comparing alternatives. Based on the system boundary selected in the study, the embodied energy of vehicle includes the energy consumed in vehicle manufacturing and maintenance process, and the embodied energy of infrastructure includes the energy consumed in the construction and maintenance process for he the infrastructure. Table 3 outlines the system boundary of analysis with life cycle groupings and generalized life cycle components for each of the transportation modes.

Table 3: Life cycle assessment of the system boundary. Source: (Author 2014)

Life Cycle Grouping/Mode	Automobile	CTA/Pace/School Bus	CTA Train/Metra
Vehicle			
Manufacturing	Manufacturing	Manufacturing	Manufacturing
Maintenance	Typical Maintenance Tire Replacement	Typical Maintenance Tire Replacement	Routine Maintenance Flooring Replacement
Operation	Propulsion	Propulsion Idling	Propulsion Idling HVAC
Infrastructure			
Construction	Roadway Parking	Roadway	Station Station Parking Track
Maintenance	Parking	Roadway	Station Station Parking Track
Operation	Roadway Lighting	Roadway Lighting	Station Lighting Station Parking Lighting Station Escalators Station Train Control Station miscellaneous

For each component in the transportation mode's life cycle, environmental performance is calculated and then normalized per Passenger-Mile-Traveled (PMT).The travel modes have different life-cycle energy profiles as shown in Table 4, which outlines the energy per PMT of four different transportation modes including automobile, bus, CTA train and Metra. It shows the vehicle of each mode consumes more operating energy than its embodied energy per PMT, but the infrastructure of each mode requires more embodied energy than operating energy per PMT. It also demonstrates the energy in vehicle operation shares the largest portion in each mode, especially in automobile and bus.

Table 4: Energy data per PMT of multiple transportation modes. Source: (Author 2014, data from: Transportation LCA Database)[5]



	Automobile	Bus	CTA Train	Metra
Infrastructure Operating Energy	0.04	0.0022	0.05739	0.2624
Infrastructure Embodied Energy	0.624	0.186	0.6238	0.4201
Vehicle Operating Energy	3	3.1	1.136	1.068
Vehicle Embodied Energy	0.553	0.445	0.07479	0.16532

3.0. RESULTS AND COMPONENT COMPARISONS

Based on the data in Table 2 and Table 4, the life-cycle energy associated with annual mileage traveled per person via different transportation modes across different urban patterns can be calculated. All energy inputs showed in the paper are converted to Megajoules (MJ) for an equivalent comparison.

Figure 4 proves that the denser area with shorter commuter distance consumes less life-cycle energy of residential mobility. Specifically, the left diagram shows the operating energy dominates the life-cycle energy (on average, the operating energy counts for almost 99% in total life-cycle energy in the all three cases), which again emphasizes on the importance of reducing the actual VMT, and developing alternative modes of travel without operating energy, e.g., walking and bicycling. The right diagram demonstrates the total energy consumption by vehicle itself is far more than its supporting infrastructure, which means we can either reduce the usage (i.e. less travel) or the amount of vehicles (i.e. carpool).Also, the Chicago Loop has the most complicated and densest transportation system, but the energy consumption of infrastructure is the least at a per-capital basis, which confirms the benefits of the shared transportation infrastructure in the dense areas of the city. On the contrary, Aurora, a typical American suburb with limited public transportation support (one Metra line and a few Pace Bus lines only) consumes the greatest energy of the infrastructure, which demonstrates the highway network is a major contributor to the energy consumption of the infrastructure from a life-cycle perspective.

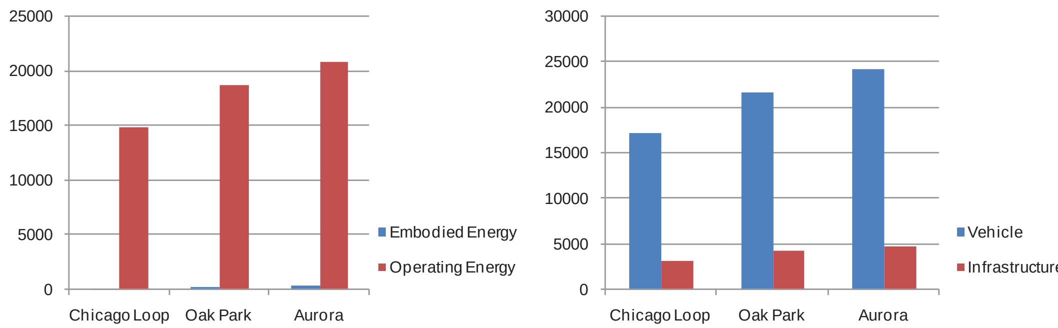


Figure 4: Total embodied energy and operating energy (left), and total energy consumption by vehicle and supporting infrastructure (right) cross the three urban scenarios. Source: (Author 2014)

Figure 5 provides more findings about the embodied energy and operating energy by both vehicle and infrastructure for each transportation mode across the three different study areas. It shows the less dense area with longer commuter distance consumes more energy via automobile and Metra, and less energy via bus and CTA trains. Specifically, the embodied energy by vehicle for automobile shares greater percentage in the total energy than any other vehicle types, which further demonstrates the significance to reduce the amount of cars, i.e. the car number per household. Thus, it is critical to provide alternatives to car ownership, including support car-sharing (i.e., Zipcar), facilitate carpooling and build bicycle infrastructure and facilities (i.e., Chicago Divvy Bikes).Also, the embodied energy and operating energy by infrastructure for bus share less portion in the total energy than either CTA train or

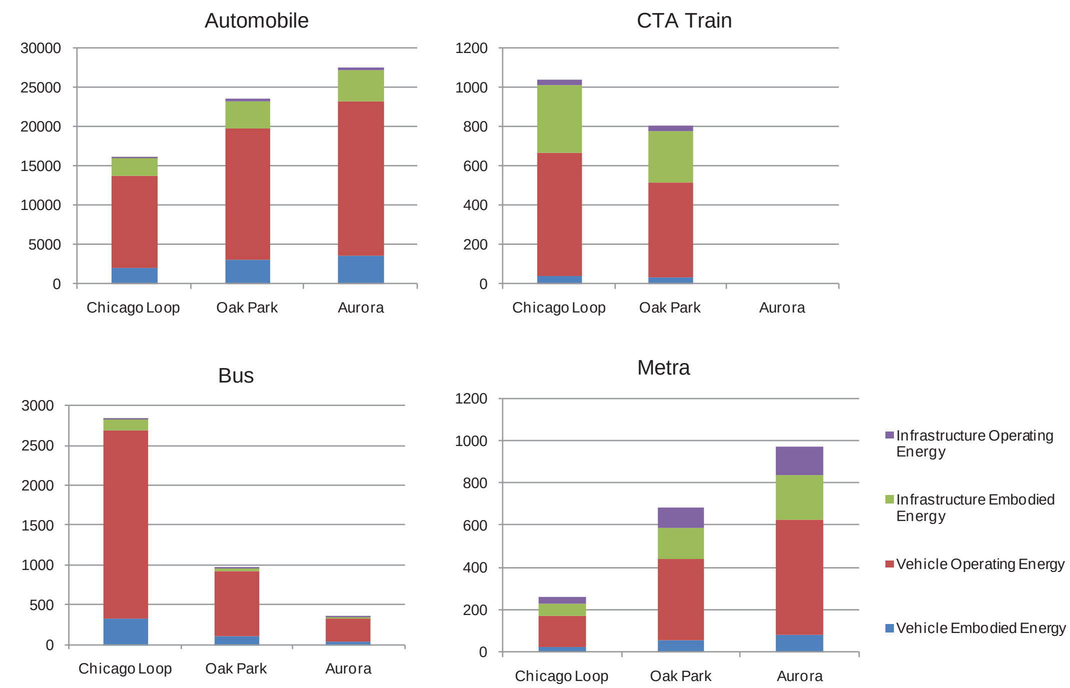


Figure 5: Life-cycle energy analysis in each transportation mode (automobile, bus, CTA train and Metra) cross the three different study areas. Source: (Author 2014)

CONCLUSION

The research shows either the embodied energy or the operating energy shared per person via automobile is far more than the sum of all other public transportation modes in the Chicago Loop, Oak Park and Aurora (see Figure 6). This confirms the benefits of transit-oriented development (TOD), and also demonstrates that reducing automobile usage and new roadway construction is a key point in lowering the energy consumption in the residential mobility. Thus, the policies that support more compact, mixed-use development and reinforce its ability to reduce VMT and energy use should be encouraged.

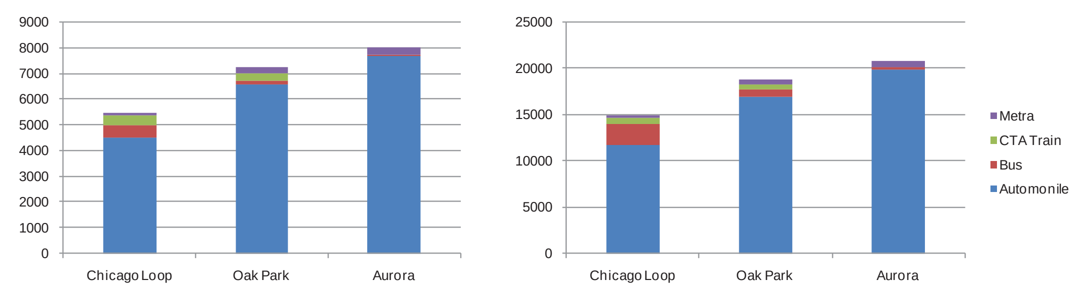


Figure 6: Annual total embodied energy (left) and operating energy (right) per person via different transportation modes cross the three urban scenarios. Source: (Author 2014)

Due to the complexity of residential mobility, the metropolitan region could be the best geographic scale for transportation LCA integration, and LCA can and should be used as a valuable guiding framework for novel mitigation strategies. Based on the case studies in Chicago Metropolitan area, the study incorporates life-cycle thinking into urban planning and transportation planning by conducting a LCA in residential mobility via multiple modes of transport in different urban locations, and analyzes the policy implications of life-cycle energy. Yet, to rely on transit and technology only to achieve sustainability in mobility is not realistic. Further work should also focus on the housing location selection and travel preferences in a more detailed level.

ACKNOWLEDGEMENTS

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ENDNOTES

[1] Source: Population Division of the Department of Economic and Social Affairs of the United Nations Secretariat, World Population Prospects: The 2006 Revision and World Urbanization Prospects: The 2007 Revision, http://esa.un.org/unup

[2] Source: U.S. Bureau. U.S. Bureau of the Census does not identify a location as “suburban.” Metropolitan areas are divided into two classifications: (a) inside central city and (b) outside central city. Many researchers treat the latter areas as suburban, and they are so treated in this paper (see Giuliano et al. 2008, Appendix B).

[3]Source: Metropolitan Decentralization of Chicago. College of Urban Planning and Public Affairs, University of Illinois at Chicago. July 2001.

[4] The Chicago Regional Household Travel Inventory (CRHTI) did a comprehensive study of the demographic and travel behavior characteristics of residents in the greater Chicago area.

[5] The transportation LCA database (tLCAdb) is a repository of greenhouse gas environmental results from research developed by Dr. Mikhail Chester, Dr. Arpad Horvath, and colleagues.www.transportationlca.org/. In this Chicago-based study, the automobile was assumed equivalent to a regular sedan, the CTA bus and school bus are equivalent to an average bus, the CTA train is equivalent to San Franciso’s BART, and Metra is equivalent to San Franciso’s Caltrain.