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Assessing the Potential for Reducing Life-Cycle Environmental Impacts through Transit-Oriented Development Infill along Existing Light Rail in Phoenix

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Abstract

There is significant interest in reducing urban growth impacts yet little information exists to comprehensively estimate the energy and air quality tradeoffs. An integrated transportation and land-use life-cycle assessment framework is developed to quantify the long-term impacts from residential infill, using the Phoenix light rail system as a case study. The results show that (1) significant reductions in life-cycle energy use, greenhouse gas emissions, respiratory, and smog impacts are possible; (2) building construction, vehicle manufacturing, and energy feedstock effects are significant; and (3) marginal benefits from reduced automobile use and potential household behavior changes exceed marginal costs from new rail service.

Keywords

air quality, energy, environment, greenhouse gases, growth management, housing, land use, life-cycle assessment, sustainability, transit-oriented development, transportation

As city and regional governments begin integrating sustainable practices into long-term planning, rigorous measures are needed to understand the comprehensive impacts of land use and transportation choices. One promising strategy, transit-oriented development (TOD), seeks to synchronize the densification of land with new or improved public transportation systems. Ideally, residents in TOD neighborhoods would have easy access to public transportation and would be colocated with public and private services that meet a majority of their social, physical, community, and economic needs (Calthorpe 1993; Churchman 1999; Loukaitou-Sideris 2010; Lund, Cervero, and Wilson 2004). Yet transportation policy and land use policy often remain unsynchronized and narrowly focused, such as those aimed at raising transit ridership or increasing property values, and historically fail to meet long-term expectations and goals (Bartholomew 2007; Cervero, Ferrell, and Murphy 2002; TRB 2009). Decision makers often use economic indicators to inform changes in urban planning and transportation systems, while published sustainability goals and regulatory compliance targets, like those in Phoenix, Arizona, focus on more holistic social and environmental goals (ADOT 2011; CCAG 2006; City of Phoenix 2008). This paper henceforth refers to the Phoenix metropolitan area as simply Phoenix, and distinguishes the individual city as the City of Phoenix. Phoenix, with twenty-six municipalities in Maricopa County, is one of the largest metropolitan areas in the United States, where close to five million people live in a region with few local natural resources, few public transportation alternatives, and high per capita energy footprints (City of Phoenix 2008; Gober 2005; Heim 2001; Rex 2000). As the global population shifts toward cities, frameworks for assessing the energy and environmental effects of interdependent building and transportation infrastructure systems should be developed so that the codependence and indirect effects are well understood. This is particularly important in Phoenix, an area that has incentivized auto-dominated travel and low-density sprawl (Gober 2005; Heim 2001).

Life-cycle assessment (LCA) can be used to provide comprehensive measures of the land use and transportation infrastructure interdependencies. However, LCA has historically

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assessed building and transportation systems independently. LCA is a framework for evaluating the raw material extraction, processing, use, maintenance, and end-of-life energy and environmental impacts of products, processes, services, activities, or the complex systems in which they reside. While several building and transportation LCA studies exist, they do not account for the full complexity of urban systems, such as how neighborhood design affects transportation mode choice and energy use in buildings. Phoenix has a fledgling light rail transit (LRT) system and is trying to promote the development of city centers, yet physical growth is largely unconstrained by geography and significant portions of urban land area are vacant. An obvious solution for growth that minimizes environmental impacts is placing TODs in vacant lots near LRT stations. Denser neighborhoods can have lower per-dwelling-unit energy and environmental footprints (Norman, MacLean, and Kennedy 2006; TRB 2009), and increased use of public transportation can reduce energy consumption and air pollutant emissions (Cervero, Ferrell, and Murphy 2002; Chester, Horvath, and Madanat 2010a; Parker et al. 2002). However, the energy and environmental interplay between public transit, TODs, and auto use has not been rigorously evaluated, and an LCA framework should be developed to assess the environmental outcomes of these interdependent systems.

This study assesses the interdependence of land use and transportation infrastructure to evaluate how more efficient and dense land use can accommodate population growth and help meet regional sustainability goals. Densification can reduce per-dwelling-unit energy consumption, improve human health, reduce congestion and traffic, increase land value, spur economic development, and grow local economies (Boarnet and Compin 1999; Cervero, Ferrell, and Murphy 2002; Heim 2001; Kittrell 2009; Norman, MacLean, and Kennedy 2006; TRB 2009). Densification and public transportation strategies are both fundamental to achieving urban sustainability goals (Churchman 1999; Lund, Cervero, and Wilson 2004), but rather than optimizing existing systems, sustainability policies often focus on reducing energy consumption and emissions through new growth initiatives (Cooper, Ryley, and Smyth 2001; Echenique et al. 2012; Norman, MacLean, and Kennedy 2006). If metropolitan areas like Phoenix are to improve urban sustainability by reducing energy use and air pollutant emissions while minimizing environmental tradeoffs, then policy makers, city planners, engineers, and environmental agencies should apply comprehensive assessment frameworks that evaluate the interdependency between transportation and land use. This study refers to this new approach as integrated transportation and land use LCA (ITLU-LCA).

LCA of Densification Strategies for Urban Sustainability Goals

Previous studies have used the LCA framework to evaluate the energy and environmental effects of buildings and transportation independently, but no LCA studies were identified that evaluate the future changes in energy and environmental impacts from codependent land use and transportation systems. There is an emerging body of LCA research that evaluates transportation systems and the associated infrastructure including roadway construction, vehicle manufacturing, and fuel supply (Chester and Horvath 2009; Chester, Horvath, and Madanat 2010a; Cooney 2011; Santero et al. 2011) and there are many LCAs of buildings (Adalberth, Almgren, and Petersen 2001; Gustavsson and Sathre 2006; Junnila and Horvath 2003; Masanet, Stadel, and Gursel 2012). Typically building studies focus on comparisons of specific classifications (e.g., commercial office building, multifamily residential building, or single-family home) and rarely are the results expanded to the metropolitan scale that would be necessary for assessing the benefits or costs of TODs.

Building LCA research to date has been limited in scope and does not consider the secondary benefits and costs (i.e., transportation) of integrating these buildings into large-scale urban systems. Building LCA studies evaluate either residential or commercial uses, and several focus on tradeoffs of materials (Ramesh, Prakash, and Shukla 2010; Sartori and Hestnes 2007). A small body of LCA literature considers how building design affects neighborhoods, with the goal of understanding densification effects (Adalberth, Almgren, and Petersen 2001; Duffy 2009; Frijia, Guhathakurta, and Williams 2012; Heinonen and Junnila 2011; Heinonen, Kyrö, and Junnila 2011), but does not rigorously integrate secondary impacts such as the travel behavior of those working or living in the buildings, particularly in response to the addition of transit service. Norman, MacLean, and Kennedy (2006) and Frijia, Guhathakurta, and Williams (2012) are two of the more comprehensive neighborhood LCAs to date, integrating transportation changes but extrapolating neighborhood impacts from data on individual buildings. In contrast, this study considers the energy and environmental consequences from combined land use and transportation changes, including upstream and nonlocal processes, when new growth occurs in TOD locations as opposed to business-as-usual (BAU) automobile-oriented growth.

Phoenix has a history of supporting urban sprawl through permissive residential zoning, agricultural land retirement, and real estate development incentives (Gober 2005), but the region is actively seeking solutions for sustainable growth in the future (Maricopa Association of Governments 2011). Sprawl has varied definitions but in this study refers to low-density, geographically dispersed development that separates residential from commercial land use (Bruegmann 2005; Galster et al. 2001). Since 1970, central Phoenix experienced periods of reduced density and sprawl while outlying land was developed (Rex 2000). City planners and policy makers recently initiated densification strategies; the region now has a widely used LRT and has received a $2.9-million Sustainable Communities Grant from the U.S. Department of Housing and Urban Development (HUD 2011) to explore smart growth. The Local Initiatives Support Coalition (LISC) has created a $20-million fund for development of near high-capacity transit (LISC 2013). The Cities of Phoenix, Tempe, and Mesa (connected by the new LRT) promote mixed land use by limiting residential and commercial growth (e.g., describing the intent of higher-density allowances in zoning regulations), and offering waivers and incentives for specific high-density construction near city centers. While successful urban densification requires multiple physical, economic, and social preconditions (Cervero 1984; Chatman 2013), this study evaluates the potential benefits and costs of development strategies around existing LRT to provide policy makers and planners with an understanding of those energy and environmental effects.

In 2009, the Environmental Protection Agency (EPA), in collaboration with the City of Phoenix, the City of Mesa, and Valley Metro (Phoenix's public transportation agency), developed a "Strategic Package of Tools: Transit Oriented Development in Metropolitan Phoenix" to chart a roadmap for improving land use planning (EPA 2009). With this roadmap and the newly deployed LRT system, Phoenix will consider infill strategies where development takes advantage of available land in urban areas rather than sprawling to the periphery (Bruegmann 2005; Ellman 1997; Heim 2001). Infill strategies use expedited permitting, permit fee waivers, urban growth boundaries, reduced financing for suburban infrastructure, and rezoning to dis-incentivize outward growth (Bruegmann 2005; Ellman 1997). Phoenix faces a projected 70–80 percent growth in population by 2040 (ADOT 2011; Morrison Institute for Public Policy 2011) and is already battling poor air quality and escalating long-run roadway costs. Infill strategies may hold potential for reducing future energy and environmental impacts.

Existing research has focused on the conditions that create healthy TODs (Cervero 1984; Cervero, Ferrell, and Murphy 2002; FTA 2004) and has established that economic, social, and physical variables directly influence the development potential and combined land use and transportation benefits from public transit. Unfavorable preconditions make future transit investments appear risky, such as a weak local economy, zoning impediments, ample free parking, and a low-density downtown (Cervero 1984). While the economic downturn since 2007 has significantly curbed Phoenix growth, the housing market is beginning to rebound. New companies are moving to Phoenix, and several cities offer density bonus programs. Chatman (2013) concludes that the automobile-related benefits of TOD are not from transit access alone but from a combination of travel changes that come with less parking availability and greater access to jobs, destinations, and services. The potential benefits from TOD infill in Phoenix are not just about density but the policies and improved access that are sometimes created with TOD. Parking fees and restrictions are now in place in downtown locations, and the region is actively encouraging TOD growth through grants, incentives, public–private partnerships, and planning initiatives (HUD 2011; Kittrell 2009; LISC 2013; Maricopa Association of Governments 2011).

Phoenix has significant unused urban land that can be considered for TOD development, and developing an ITLU-LCA framework to comprehensively assess transportation and land use coeffects can better inform decision makers of upfront costs and long-term impacts. Within 0.5 mile of LRT stations, there are 390 acres of vacant lots and another 340 acres of paved lots. These lots are zoned for both residential and commercial use and include neither historic preservation areas nor restricted zoning that would prevent residential infill. There is strong potential for Phoenix to capitalize on the economic, social, and environmental benefits of TOD infill by maximizing the use of this land in a form that minimizes future energy consumption and environmental impacts.

Methodology for Assessing TOD Strategies

An ITLU-LCA framework is developed to contrast densification around the existing LRT by utilizing vacant and parking lots against continued low-density automobile-centered outlying development. Energy consumption and the potential environmental and human health impacts are determined for increasing land use TOD commitment around the new 20-mile LRT system. For each TOD strategy, energy and environmental indicators are determined for an equivalent number of dwelling units (du) built in outlying areas that are inaccessible to LRT.

Application of the Environmental LCA Framework

The LCA framework is used to evaluate the cradle-to-use energy consumption and impact potentials of the combined land use and transportation changes. The analytical system boundary (see Figure 1) includes building construction, building energy feedstock (primary fuel extraction and processing combined with transmission and distribution for electricity and natural gas), building end-use energy (emissions and energy associated with electricity generation at the power plant as well as natural gas used within the household), vehicle manufacturing, gasoline feedstock (crude oil extraction and processing), and vehicle operation. For each life-cycle component in Figure 1, end-use energy (not primary energy) inputs are determined as well as emissions of greenhouse gases (CO_2, CH_4, and N_2O), nitrogen oxides (NO_x), sulfur oxides (SO_x), carbon monoxide (CO), particulate matter less than 10 microns (PM_{10}), particulate matter less than 2.5 microns ($PM_{2.5}$), and volatile organic compounds (VOCs). NO_X, SO_2, CO, PM_{10}, $PM_{2.5}$, and VOCs are either directly emitted or are precursors to the Criteria Air Pollutants regulated by the EPA's Clean Air Act and Amendments. Greenhouse gas (GHG) emissions are reported as CO_2 equivalence (CO_2e) using radiative forcing multipliers of 25 for CH_4 and 298 for N_2O for a hundred-year horizon (IPCC 2007). The Tool for the Reduction and Assessment

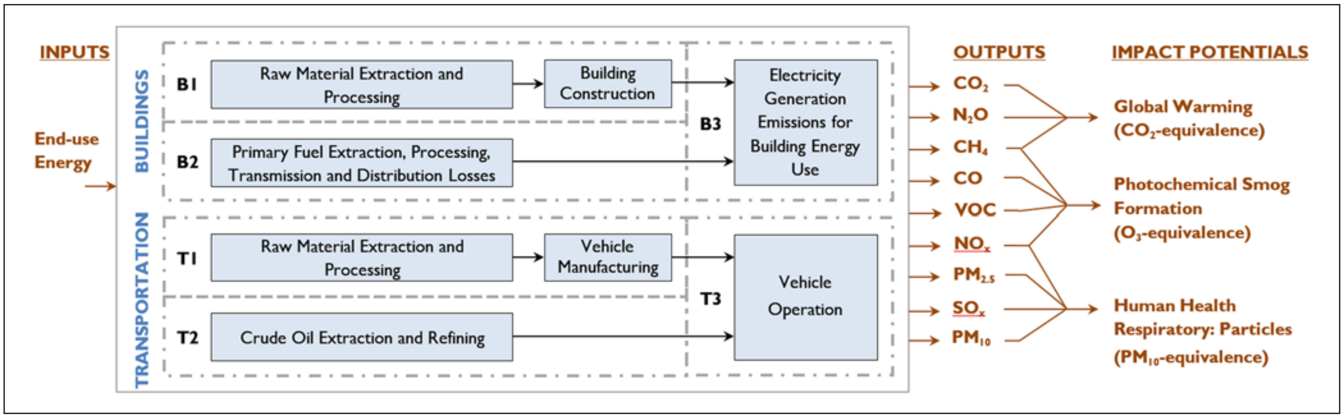

Figure 1. Life-cycle system boundary.
Note: Life-cycle groupings: B1: Building Construction (Athena Sustainable Materials Institute 2011); B2: Electricity Feedstock for Building Electricity Use (ANL 2012); B3: Building Energy Use (Electricity Generation Emissions) (Ochsendorf et al. 2011; ANL 2012); T1: Vehicle Manufacturing (Chester, Pincetl, et al. 2013; ANL 2012); T2: Gasoline Feedstock (Crude Oil Extraction and Processing) (ANL 2012); T3: Vehicle Operation Tailpipe (ANL 2012).

of Chemical and Other Environmental Impacts (TRACI) is used to determine midpoint characterization factors that quantify the potential for photochemical smog formation and human health respiratory impacts (inhalation of particle pollutants) from air emissions (Bare 2011), and the specific normalization factors used in this study are included in the Supplementary Information (SI; available online at http://jper.sagepub.com/supplemental). Phoenix experiences chronic smog and respiratory issues, and the inclusion of these measures, in addition to energy consumption and GHG emissions, will provide a broader understanding of the interdependent environmental effects. By evaluating a broad suite of environmental impacts in addition to GHG emissions (i.e., global warming potential), the potential for unintended tradeoffs (i.e., trading a reduction in one environmental impact for an increase in another) will be reduced and the cobenefits (e.g., decreasing GHG emissions and the potential for human health respiratory impacts) will be clearer.

The functional unit in this prospective LCA is the LRT corridor over the sixty-year building lifetime. The components included in the analysis are those that will change between BAU and TOD scenarios. While many behavioral changes may occur when people move to TOD neighborhoods, we focus on buildings and transportation effects exclusively (as shown in Figure 1).

The building and transportation effects modeled in this study are only a portion of the total changes that may occur from shifts to TOD. Existing research has quantified the housing and transportation fractions of an individual's total environmental footprint (Heinonen and Junnila 2011; Heinonen, Kyrö, and Junnila 2011; Weber and Matthews 2008). As residents move to TODs, there may be changes in their consumption of goods and services that are outside the scope of this analysis. The LCA framework developed here can serve as a foundation for future studies to assess these lifestyle changes.

Urban Infill Potential

Five TOD densification strategies are developed to evaluate the life-cycle footprint of varying levels of residential urban infill along the LRT corridor. For each TOD strategy, the number of dwelling units is used to compute the life-cycle footprint of a corresponding BAU strategy. The BAU strategies evaluate the same number of dwelling units built in outlying areas where residents commute only by automobile. Table 1 summarizes the development potential of the TOD and BAU strategies. In the results, each TOD strategy is directly compared to its BAU counterpart, and each strategy increases the aggressiveness of residential densification.

Commercial building changes are not included because of the dearth of data on the heterogeneous configurations of retail, leisure, and office space; however, changes in nonwork travel capture some of the nonresidential TOD life-cycle effects. Commercial properties exhibit many different configurations making assessment of TOD changes challenging. While this is also true for residential properties, there has been significant research of and tools developed for residential buildings (EIA 2008, 2012; Norman, MacLean, and Kennedy 2006; RSMeans 2009a). A survey of resources revealed significant challenges in assessing commercial building energy use and design changes for TODs and was therefore excluded from the study, ultimately producing a conservative assessment of TOD environmental benefits. Research results using the ITLU-LCA methodology that include commercial buildings and associated travel indicate that commercial-based energy consumption and travel generate significantly more benefits in TODs than residential-based benefits (Chester, Nahlik, et al. 2013).

The scenarios demonstrate successively aggressive residential infill and the potential for increased land use around LRT stations. All scenarios evaluate some configuration of

TOD around every existing LRT station. It is possible that TOD deployment would occur at a subset of stations and the assessment is structured as a bounding analysis to show the maximum potential benefits that could be achieved. The first three scenarios (TOD1, TOD2, and TOD3) only consider infill of vacant lots while the more aggressive TOD4 and TOD5 consider vacant and dedicated surface parking lots. TOD1 evaluates a future where vacant lots have been replaced with single-family homes and avoid the equivalent development in outlying areas. TOD2 evaluates infilling multifamily apartments where current zoning and land area allows, and single-family homes in the remaining vacant lots. TOD3 evaluates rezoning all vacant lots for multifamily apartments, and only places single-family homes where parcels are too small for large buildings. TOD4 increases the available infill land area by including paved lots and applies the same approach as TOD2. TOD5 is the most aggressive strategy, evaluating the construction of multifamily apartment buildings at the highest allowable city densities (du/acre) on both vacant and parking lots. For each of the five TOD scenarios, the counter scenario (BAU) considers the equivalent number of dwelling units constructed in outlying areas as single-family homes. TOD strategies assume that policy mechanisms such as fee reductions, expedited permitting, and zoning waivers will incentivize residential infill around the LRT stations. The strategies use densities of 6 du/acre for single-family homes and 46, 30, and 43 du/acre for City of Phoenix, Tempe, and Mesa multifamily apartments respectively, consistent with the current zoning codes (City of Mesa 2011; City of Phoenix 2011; City of Tempe 2005). While many social, technical, political, community, and economic factors dictate how vacant and parking lots are used, the scenarios are designed to illustrate environmental benefits and costs that could be achieved at a confluence of these exogenous factors.

The land area and residential densities are determined from Phoenix assessor data. A generally accepted walking distance of one-half mile (FTA 2004; Guerra, Cervero, and Tischler 2012) is used for determining the number of potential TOD locations with access to the twenty-eight Phoenix LRT stations. Potential land areas are tallied from zoning maps and satellite imagery (City of Mesa 2011; City of Phoenix 2004; City of Tempe 2005; Google Earth 2012) as shown in Figure 2 for the 12th/Washington and 24th/Washington stations. The assessment of available land across the system is detailed and illustrated in the SI.

The conservative scenarios (TOD1, TOD2, and TOD3) evaluate 390 acres of undeveloped vacant lots and the aggressive scenarios (TOD4 and TOD5) increase the available land area to 730 acres by including paved dedicated surface parking lots. Each city's zoning codes specify residential density by du/acre. Observed densities for existing single-family residences around light rail stations range from 1 to 9 du/acre for City of Phoenix, Tempe, and Mesa, and the multifamily densities range from 10 to 46 du/acre for City of Phoenix, 10 to 30 du/acre for Tempe, and 14 to 43 du/acre for Mesa (City of Mesa 2011; City of Phoenix 2004; City of Tempe 2005; Google Earth 2012).

Automobile and Light Rail Transportation

Automobile and LRT use, vehicle manufacturing, and energy feedstock production are inventoried. In TOD strategies, it is assumed that households will reduce, but not eliminate, automobile travel and switch to LRT (Cervero, Ferrell, and Murphy 2002; Hankey and Marshall 2010; TRB 2009). Work and nonwork travel distances are inventoried, assuming that one worker in each TOD household will use the LRT for commuting (by biking or walking to the station) while all other work and nonwork travel will occur by automobile. Phoenix averages 1.8 workers per household (DOT 2011). The BAU strategies assume that all workers will drive an automobile for both work and nonwork travel, since new outlying developments are unlikely to have access to bus, biking, or walking routes.

Automobile commute distances vary within the scenarios, generally with shorter work trips for those living in TOD neighborhoods (see Table 1). In TOD strategies, an 11-mile one-way work distance is used and is based on current commute distances for the highest density neighborhoods in Phoenix (DOT 2011). According to the National Household Travel Survey data, average annual mileage per Phoenix household is 32,000 miles. This value is used as a baseline for BAU1 and TOD1 travel, and the nonwork travel is subtracted from the total. The nonwork automobile travel is kept constant in all BAU strategies, while the TOD strategies assume that higher-density living will generate less nonwork automobile travel. Because the BAU strategies evaluate more single-family homes constructed in outlying areas, successive BAU strategies incrementally increase the work commute distance. Most auto transportation is assumed to occur in BAU5, where 22,000 dwelling units would generate nearly 860 million miles of auto travel per year. A summary of the calculations is provided in the SI.

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model (ANL 2012) is used to evaluate energy consumption and emissions of a typical future automobile through its life-cycle phases: crude oil extraction and processing; vehicle manufacturing including raw material extraction and processing; and vehicle operation. Changes in automobile travel are evaluated over the sixty-year building lifetime. New fuel economy standards require that cars achieve 55 miles per gallon (mpg) by 2025 (NHTSA 2012). Assuming a ten-year fleet turnover, a weighted average future gasoline automobile is developed for the next sixty years with a resulting fuel economy of 50 mpg. A higher-fuel-economy future vehicle (e.g., a gasoline or hybrid vehicle with a fuel economy greater than 50 mpg) is considered conservative in that it reduces the benefits of TODs because shifting auto trips will have less energy and

Figure 2. Land development assessment for the 12th and Washington and 24th and Washington stations.
Note: The light rail line is shown as bold black lines (note that there is a separated right-of-way for each direction of travel) and stations are dark shaded (purple in the online version of this article, available at http://jper.sagepub.com) square icons. Around stations are heavy one-quarter mile and light one-half mile circle boundaries. Vacant lots (conservative) are light shaded (orange in the online version) and surface lots (aggressive) are dark shaded (purple in the online version).

air emissions benefits than a lower fuel economy vehicle. This would also be true of electric vehicles being charged in a greening electricity mix. The GREET 2 model (ANL 2012) was used to develop energy and emissions inventories for vehicle manufacturing based on the number of vehicles a household would need over the sixty-year time span (given a 160,000-mile vehicle lifetime). It is assumed that light-weighting must occur (decreasing vehicle weight to 1,800 lbs) to achieve the 50-mpg fuel economy.

Additional light rail service is needed to meet the new demand generated by TOD households in strategies 4 and 5. In TOD1–3 it is estimated that the system already has the capacity for the additional riders (National Transit Database 2011). The existing Valley Metro LRT system has an average capacity of slightly more than 66,000 passengers per day and a maximum capacity of 91,800 passengers per day based on train seats (Kinkisharyo International LLC 2008; National Transit Database 2011). In TOD4 and TOD5, the new TOD riders will exceed the available seats and standing room so new trains must be put into service. In addition to the energy consumption, manufacturing of the vehicles will also occur. Train manufacturing was modeled with SimaPro and is consistent with the results of Chester, Nahlik, et al. (2013) (PRé Consultants 2008).

It is anticipated that TOD residents will be more likely to travel by bus in addition to rail; however, changes in bus service are not obvious. As residents shift from fringe areas to TODs, it is unclear if existing bus service will be reduced. It is also unclear if an influx of new residents near light rail will be large enough to justify increases in bus service that hubs at LRT stations. However, if TOD residents commute by bus to light rail stations and these trips are met by new bus service then additional impacts will be produced.

Low- and High-Density Residential Buildings

The assessment of TOD infill around light rail stations is based on a single-family home and a multifamily apartment building model. The single-family home is 1,600 ft^2, the average house size in the light rail corridor (Maricopa County Assessor's Office 2012), and the multifamily apartment building is 34,000 ft^2 (approximately 1,100 ft^2 each for 32 du), typical to the designs that are currently being used by developers near light rail (DOE 2012; Michael J. Lafferty, personal communication, September 19, 2012). Many different building designs could be used in the development of this land, and the design chosen in this study is intended to serve as a reasonable middle estimate, between a high-rise and low-rise apartment building. As building designs change, the per-dwelling-unit energy use may change and this is considered in the uncertainty assessment in the SI. The life span of these buildings is assumed to be sixty years, consistent with building LCA literature (Aktas and Bilec 2011; Athena Sustainable Materials Institute 2011; Ochsendorf et al. 2011), and the results are normalized to this time period.

A materials-based life-cycle inventory (LCI) of energy consumption and air emissions is developed for the construction of each building type. RSMeans (2009b) is used to

Table 1. BAU and TOD Strategy Summary.

Strategy		Characteristics	Dwelling Units (*n*)	Single-Family (%)	Multifamily (%)	Land Area Demand (acres)	Land Savings Ratio (acres saved per acre used)	One-way Commute Distance (miles)
1	TOD	Single-family homes, mixed LRT/automobile commute	2,200	100	–	390	0.94	11
	BAU	Single-family homes, automobile commute		100	–	370		13
2	TOD	Multifamily apartments, limited single-family homes, mixed LRT/automobile commute	11,000	6	94	390	3.6	11
	BAU	Single-family homes, automobile commute		100	–	1,800		15
3	TOD	Rezoning, multifamily apartments, single-family homes where lot is too small, mixed LRT/automobile commute	12,000	4	96	390	4.0	11
	BAU	Single-family homes, automobile commute		100	–	2,000		17
4	TOD	Include paved lots, multifamily apartments, limited single-family, mixed LRT/automobile commute	21,000	5	95	730	3.7	11
	BAU	Single-family homes, automobile commute		100	–	3,500		19
5	TOD	Rezoning, include paved lots, multifamily apartments, single-family homes where lot is too small, mixed LRT/automobile commute	22,000	4	96	730	4.0	11
	BAU	Single-family homes, automobile commute		100	–	3,600		21

Note: Summary of BAU and TOD strategies with number of dwelling units (du), proportion of housing structure type (single-family vs. multifamily), and commute distance. Each TOD strategy fills the vacant lots within a half-mile of LRT stations, whereas each BAU strategy builds new homes that are automobile-centric and inaccessible to LRT. The land savings ratio is the acres of development avoided (i.e., BAU minus TOD) per acre of land consumed in the TOD scenario. TOD = transit-oriented development; BAU = business-as-usual; LRT = light rail transit.

determine the material profile of an average one-story home and four-story apartment building, assuming typical assemblies for Phoenix (e.g., foundation, roof, framing). The buildings are then modeled in the Athena building LCA tool to develop estimates of construction energy use and impacts (Athena 2012). Materials listings for each building type as well as the impact estimator results are reported in the SI. Parking effects are also considered. For the single-family home, a two-car garage is included, and for the apartment building it is assumed that a parking garage is built with 1.5 spaces/du using existing parking garage LCA results to model the structure (Chester, Horvath, and Madanat 2010b).

Building energy use and resulting emissions are determined from existing databases for each building type. Multifamily structures tend to have lower per-dwelling unit energy footprints than single-family homes because of a confluence of factors (including smaller dwelling unit sizes) that may be affected by the demographics of inhabitants and efficiency gains in shared walls and HVAC systems (TRB 2009). Phoenix-specific estimates from the American Housing Survey (U.S. Census Bureau 2012) are adopted for both single- and multifamily building types and are validated against results from other literature (see SI). Utility bills from homes built in the last decade are used with average electricity prices (EIA 2011) to estimate energy consumption. A Phoenix single-family home consumes 58 TJ/year in combined electricity and natural gas, and a multifamily apartment dwelling unit consumes 45 TJ/year of energy in electricity only (EIA 2011; U.S. Census Bureau 2012). A typical Arizona home consumes roughly 63 percent of their total energy as electricity with the remainder natural gas (EIA 2008, 2012, 2013), but the American Housing Survey data suggest that multifamily apartments built in the last two decades are transitioning away from natural gas use (U.S. Census Bureau 2012). Given the uncertainty in the final design of apartment buildings, the energy consumption associated with public spaces (e.g., elevators, common area lighting, and HVAC) is not included. Since construction of these BAU or TOD strategies is likely to happen over decades, energy consumption is evaluated with a forecasted 2025 region-specific electricity mix that incorporates renewable portfolio standards (DSIRE 2012), and energy delivery is assumed to be electric in apartments and electric and gas in single-family homes. Electricity feedstock and generation emissions are determined with the GREET Fuel Cycle Model (ANL 2012). Natural gas use feedstock effects are also determined using laboratory-tested combustion values (EPA 1998) and GREET modeling (ANL 2012; EPA 2011; Traynor, Apte, and Chang 1996). The SI validates residential energy consumption estimates against several other sources and also lists electricity generation mixes for 2009 and projected to 2025.

Energy and Environmental Effects of TOD Strategies

The results show that the energy and environmental footprints associated with land use and transportation are heavily interdependent and reveal the potential for significant human health and environmental savings from smart growth strategies (Figure 3). There are increasing GHG emissions, respiratory, and ozone impact reductions from the building and transportation life cycles with each increasing densification strategy. TODs lower the life-cycle footprint in all five strategies, largely the result of reduced automobile use. Building life-cycle energy consumption and GHG emissions decrease by 9–25 percent while the potential respiratory impacts increase by up to 21 percent and smog up to 10 percent. In the case of respiratory and smog impact potentials, the transition to larger shares of electricity use (replacing natural gas use in households for electricity from a heavy coal mix) combined with heavier material in multifamily buildings produces increases in impacts that are offset by transportation reductions. Buildings and transportation combined decrease the total effects by as much as 36 percent for GHG emissions, 8.4 percent for respiratory impacts, and 25 percent for smog formation potential. This is the result of lower building energy demands paired with access to LRT, reducing work and nonwork automobile use for the households. Should residents access and egress light rail stations through new linked bus service then transportation emissions in TOD scenarios will increase. Using natural gas bus emission profiles from Chester, Pincetl, et al. (2013) and assuming that all light rail commuters from the TODs connect to/from light rail by bus, then over the sixty years GHG emissions would increase between 0.15 and 0.18 percent for TOD scenarios and would have negligible impacts on the results. The smaller TOD footprints would not be possible without the existing LRT infrastructure, and the results show that by utilizing the excess infrastructure capacity there is a significant opportunity to lower the corridor’s GHG emissions footprint through infill strategies.

The energy consumption and environmental impacts from expanding LRT operations will enable the reduction in automobile use that over sixty years decreases impacts from residents by as much as 44 percent, as seen in the energy consumption results for scenario TOD5. In TOD4 and TOD5, LRT capacity is exceeded and new trains must be put into operation. However, the additional life-cycle impacts are negligible when joined with the avoided effects from denser living and reduced automobile demands. Small marginal costs that utilize the existing transportation infrastructure (in this case adding LRT trains) can lead to as much as hundredfold marginal benefits in avoided automobile travel and building energy. Figure 3 shows a blowout of the LRT effects (green sidebar) since they are nearly invisible when graphed together with the building and automobile phases. The reduced automobile effects seen in the TOD strategies would not be possible without residents using the 26,000 trips per weekday excess capacity of light rail (National Transit Database 2011).

The results suggest that previous studies, by only considering use phases (e.g., building energy use or tailpipe emissions), fail to account for as much as 25 percent of total energy consumption savings and up to 30 percent of GHG emissions savings. Building end-use energy and vehicle operation life-cycle components together account for 70–76 percent of energy consumption and GHG emissions in all BAU and TOD strategies. The reductions seen in the TOD strategies are largely the result of reduced automobile travel. Previous TOD studies have typically considered building energy use (the darkest red in Figure 3) and auto operation (the darkest blue) exclusively (Adalberth, Almgren, and Petersen 2001; Echenique et al. 2012; Norman, MacLean, and Kennedy 2006). While these two components do account for the majority of the life-cycle footprint of every strategy, there are significant contributions from building construction and energy (electricity and natural gas) feedstock (accounting for 7–11 percent of the total energy consumption and 11–18 percent of the total GHG emissions), and from vehicle manufacturing and gasoline feedstock (accounting for 13–18 percent of the total energy consumption and GHG emissions). This reveals the importance of expanding analytical system boundaries beyond operational (use) phases. Policy makers and planners who only consider use phase effects will underestimate the benefits and costs of their strategies (see SI for a comparison of use-only phases vs. all LCA phases). Even in the most conservative TOD1 strategy, Phoenix can place the next two thousand homes near stations and achieve 6.8–13 percent life-cycle impact reductions. By rezoning all vacant lots and maximizing the use of multifamily apartments in TOD3, twelve thousand new dwelling units

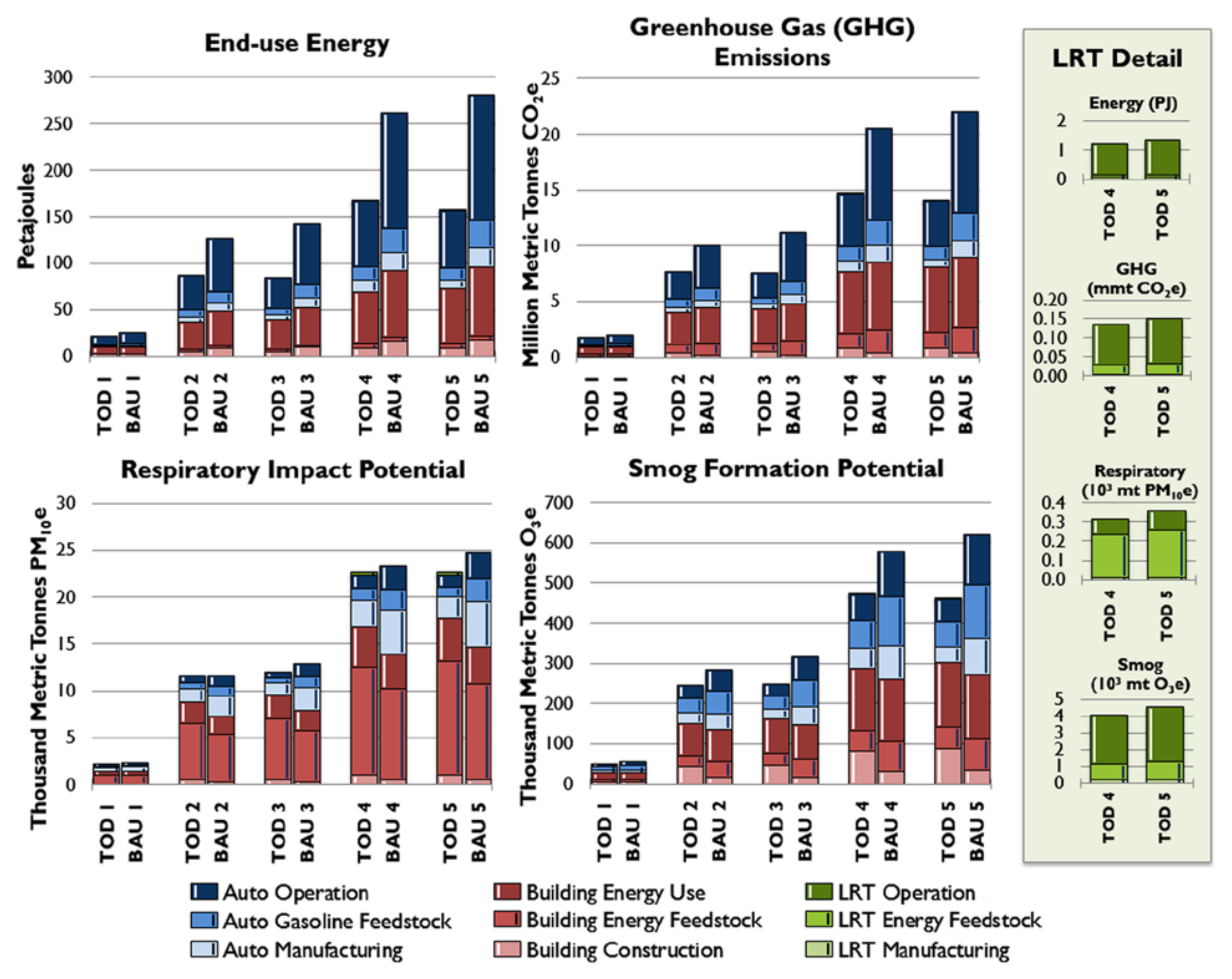

Figure 3. Net impact potentials over sixty years.

Note: The figure shows the sixty-year life-cycle energy consumption, greenhouse gas emissions, respiratory impact potential, and smog formation potential for the decision to infill vacant lots with transit-oriented development (TOD) vs. low-density single-family home construction (business-as-usual [BAU] growth) on the fringe. The building (shades of red in the online version of this article, available at http://jper.sagepub.com), automobile (shades of blue in the online version), and light rail transit (LRT; shades of green in the online version) life-cycle effects are shown together. The LRT effects are not visible against auto and building effects and as such are blown out separately on the sidebar. For each system (i.e., automobile, building, and LRT), operation, feedstock, and manufacturing/construction results are shown in the vertical order that appears in the legend. Local impacts are indicated by white vertical lines on the left side of the bar and remote impacts are indicated by dark vertical lines on the right side.

can be moved near stations and achieve 3.5 and 3.1 times the reduction over TOD1 for life-cycle energy and GHG emissions. By including paved surface lots in TOD5, nearly 22,000 dwelling units can be infilled and achieve 4.0 and 3.6 times the reductions of TOD1.

Respiratory and smog impact potentials are dominated by building energy use and feedstock production, as well as auto manufacturing and gasoline feedstock production. The inclusion of life-cycle components increases the respiratory footprint calculations by as much as 290 percent and smog potential as much as 119 percent. Respiratory impacts are largely the result of surface mining operations that provide coal to Arizona power plants (ANL 2012). These mining operations generate significant PM$_{10}$ emissions that create the potential for respiratory impacts. Furthermore, the shifting of building energy use from a mixture of electricity and natural gas in single-family homes to only electricity in apartment buildings increases the feedstock impacts for TODs. Production of steel for building materials and vehicle components also contributes to building construction and vehicle manufacturing components (ANL 2012; Athena 2012). The smog impact potentials primarily result from NO$_x$ emissions from ocean tanker transport of crude oil to U.S. refineries and from coal electricity used in the supply chain for concrete and steel building materials and vehicle parts (ANL 2012; Athena Sustainable Materials Institute 2011). The construction and electricity feedstock respiratory and smog impacts for apartment buildings are higher per dwelling unit than single-family homes. However, these upfront costs make possible significantly larger reductions in reduced automobile travel life-cycle effects. At the very least, Phoenix could add two thousand dwelling units in TOD1 and enable 6.8 percent respiratory and 10 percent smog impact reductions through reduced automobile use. With rezoning, TOD3 will achieve a 1.0 and 2.3 times reduction over TOD1 for respiratory and smog impacts, and in TOD5 a 1.3 and 2.8 times reduction.

LCA calls for the analysis of direct and supply chain effects and captures both local and remote impacts. The LCA framework transcends geopolitical boundaries in the assessment of large and complex systems, and urban sustainability policies and decisions should develop accounting protocols for assessing supply chain networks. For example, the building construction life-cycle component captures material production and its associated emissions outside of Phoenix, and gasoline refining also does not occur locally. Furthermore, impact potentials do not distinguish between upstream effects that may occur in remote low-risk areas versus those that may occur in heavily populated Phoenix neighborhoods. A majority of the energy consumption and GHG emissions occur locally (75 and 70 percent roughly for each strategy), whereas the majority of the respiratory and smog formation impact potentials occur outside of Phoenix (74 and 54 percent). The local and remote effects show that new methods are needed for urban sustainability policies and decisions that (1) include strategies for greening supply chains, (2) improve environmental inventorying and develop allocation models for upstream effects, and (3) identify upstream market and regulatory signals that incentivize local and remote actors to reduce the impacts that are ultimately realized in Phoenix.

The inclusion of commercial infrastructure changes would likely increase the benefits of TOD due to additional building energy efficiency gains (Chester, Nahlik, et al. 2013). Including commercial space would increase TOD building construction impacts but could offset current big box retail trends (FTA 2004). Mixed-use TODs are also likely to have lower building energy use and feedstock effects for commercial activities (Cervero, Ferrell, and Murphy 2002; Guggemos and Horvath 2006). The counter case would be if TODs induce new commercial infill but do not offset BAU growth. Regardless, these results demonstrate the significant benefits in transportation effects from reduced nonwork travel when TOD residents utilize more local and transit-oriented commercial infrastructure. Research in this area is ongoing and emerging methodologies will facilitate the assessment of the benefits and costs from retail and office infill with specific TOD typologies and both the building and transportation (shopping and work travel) effects (Chester, Nahlik, et al. 2013).

TOD Policy for Phoenix Environmental Goals

Planners and policy makers should incorporate the contribution of environmental effects to the total benefits and costs of urban infill strategies, including the interdependence of land use and transportation systems, when developing urban renewal and sustainability strategies. Currently, TOD and transit strategy decisions “get driven more by political and ideological considerations than by objective research” (FTA 2004, 133), and many of the assumed benefits are not rigorously quantified (TRB 2009). The results show that basic infill strategies have significant environmental benefits. Figure 4 shows the *per-dwelling-unit* avoidable energy consumption and environmental impacts from choosing TOD infill over BAU growth. The benefits of TOD infill increase with each strategy, with one exception, TOD4. TOD4 includes paved lots, and many of these parcels are too small for multifamily apartment buildings. As a result, TOD4 has a higher proportion of single-family homes than TOD3. This tradeoff suggests that planners might seek to deploy TODs to areas with sufficient land for higher density buildings to optimize the environmental benefits of infill.

The greatest environmental benefits occur when land-use policies trigger the greatest reduction in personal automobile travel, which are enabled by the use of the existing LRT system. The results are heavily influenced by the vehicle travel characteristics of the new residents, and Figure 4 shows the effect of an over- or underestimate of TOD household auto vehicle miles traveled (VMT). The upper bound of the uncertainty bars show the effect of more household travel by LRT (i.e., more than one worker per household commutes on LRT) and the lower bound shows less (i.e., people move to TODs but continue driving autos for the majority of their travel). The upper bound is one standard deviation from the average and the lower bound is 100 percent of TOD travel by automobile. Where previous studies have only calculated the use phases, or have not linked land use with transportation, the interdependent results show that transportation changes from land use policy should be considered if the decision maker aims to more accurately assess the benefits of TOD strategies. Phoenix already has some TOD initiatives and mixed-use land development in progress and has even rezoned parcels for densification. Prior to TOD project selection, planners can use the ITLU-LCA framework and results to understand how utilization of existing sunk transit infrastructure can position projects to achieve enhanced public health and mobility benefits.

Planners and policy makers should recognize that TOD deployment will produce upfront environmental impacts during construction that will enable long-term environmental benefits that are 1.1 to 130 times greater than the initial environmental investment. In TOD2 through TOD5, the majority of upfront impacts are the result of heavier building construction materials (specifically, concrete and steel). In TOD4 and TOD5, new trains must be manufactured. Over time, however, strategies that favor land reuse at maximum density (TOD3 and TOD5) have the potential for benefits that are three to four times greater than single-family home infill (TOD1). The upfront impacts should not be viewed as an uncontrollable outcome of TOD development but should instead be targeted for mitigation. LCA provides policy makers and planners

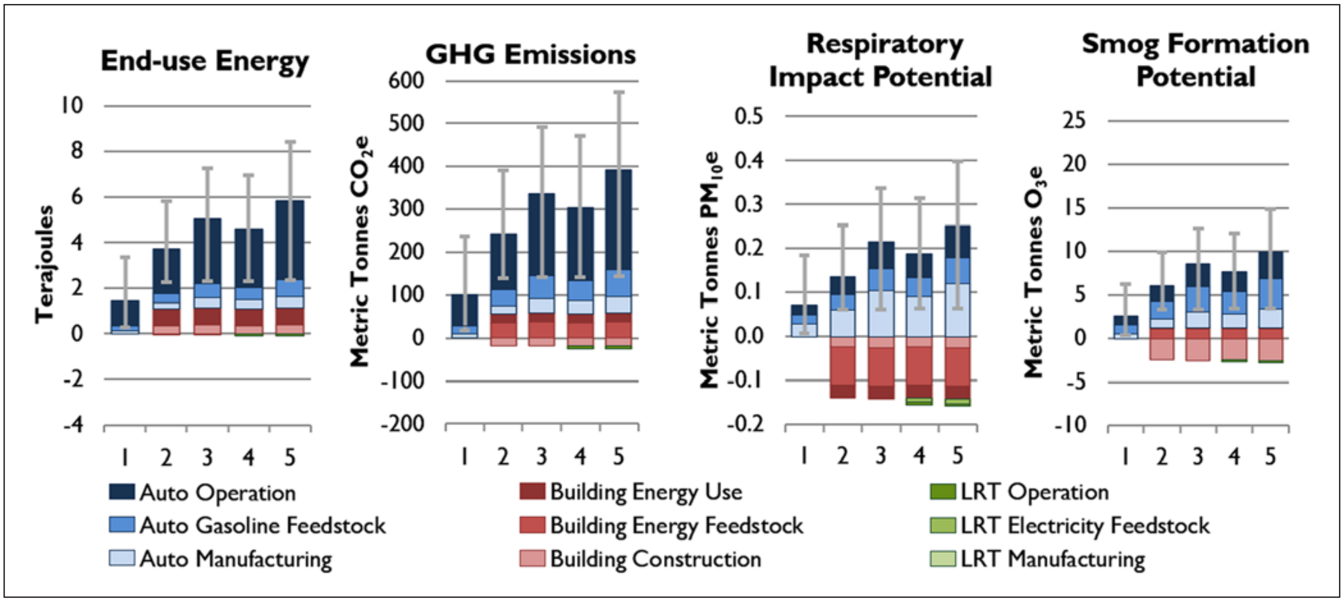

Figure 4. Impact potential savings per dwelling unit (BAU minus TOD).
Note: The figure shows the difference, per dwelling unit, between business-as-usual (BAU) growth and transit-oriented development (TOD) infill in each strategy when considering the life-cycle energy consumption, greenhouse gas emissions, respiratory impact potentials, and smog formation potentials sixty years after new dwelling units have been constructed. In the online version of this article (available at http://jper.sagepub.com), the red bars are building life-cycle effects, the blue bars are automobile effects, and the green bars are new light rail transit (LRT) effects. The life-cycle processes that are below zero are phases where the TOD strategy has a greater impact than the BAU strategy. The negative bar segments in greenhouse gas emissions and smog potential are building construction and LRT operation (the other LRT phases are not visible at this scale and are detailed in the Supplementary Information [SI]). The negative bar segments in respiratory potential are all three building phases, with LRT feedstock and operation below (see SI for detailed results). The uncertainty bars are the difference in automobile life-cycle savings if all new TOD households still commute by automobile (lower bound) and multiple TOD household workers shift to transit (upper bound).

insight into the outcomes of their decisions and provides opportunity for mitigating those impacts through intelligent planning and project incentives. Strategies for deploying TOD should include mitigation requirements to minimize life-cycle impacts. This could include requirements to use low-impact or recycled materials, the use of Tier 4 construction equipment to minimize air pollution, or the production of materials in locations that will have minimal human health or environmental exposures. Furthermore, any incentives to shift TOD buildings off of coal electricity (e.g., through rooftop solar incentives) will have large air emissions benefits.

Future behavior is a critical element in the environmental outcomes of TOD strategies and incentives can be offered to ensure that maximum benefits are achieved. Residential sorting and self-selection might attract new TOD residents who are already LRT riders and/or previous high-density dwellers; therefore, the smaller TOD home energy or automobile footprints may be overestimated (Cervero, Ferrell, and Murphy 2002). However, regional policies and incentives might be tailored to recognize the potential for long-term benefits, such as modifying employer trip reduction programs or behavior-based electricity rates, both of which are already active in Phoenix. Furthermore, LRT ridership may depend on job prospects near rail stations, so attracting employers to TODs is likely to be an important component of urban growth initiatives. It is possible that the people who live in Phoenix TODs are self-selected, that is, younger, willing to make longer commute trips by transit to avoid auto travel, and likely to live in higher-density buildings for short periods of time (Gober 2005; Cervero, Ferrell, and Murphy 2002). In deploying TODs, Phoenix should consider developing long-term programs to assess the characteristics of inhabitants and develop intelligent and adaptive incentive systems to ensure environmental benefits are maximized.

Regional planners and policy makers can prioritize direct and indirect residential impacts from sustainability initiatives by identifying the benefits and costs of environmental mitigation efforts. Several impacts occur in similar quantities regardless of the BAU or TOD scenario. For example, electricity generation emissions for building end-use energy make up 23–31 percent of the total life-cycle footprint for smog formation in all TOD and BAU scenarios, yet the building energy savings in smog formation emissions from deploying TOD5 instead of BAU5 represent only 0.59 percent of the total smog reductions. In this case, more significant reductions can be achieved in the building energy use phase by reducing high-emitting electricity sources in conjunction with the TOD initiatives. Similarly, technological improvements that reduce automobile particle emissions could be promoted based on the fact that the automobile operation phase is 76 percent of the TOD5 respiratory savings but only 6–12 percent of the total life-cycle respiratory impact footprint. Efforts to reduce smog and respiratory impacts will produce the largest benefits by focusing on power plant or vehicle technology, and those efforts will require nonlocal industry partnerships. Since these effects may be outside of the influence of city government, local resources might focus on enabling and incentivizing TOD infill whereas state and federal funding, or possibly national lobbying and advocacy, could aim to produce technologic solutions that reduce impacts from life-cycle processes.

By structuring the environmental assessment around the decision to deploy TODs, the benefits of policies that utilize existing infrastructure are shown. The impacts from expanding LRT service in TOD4 and TOD5 are dwarfed by the land use benefits and automobile reductions that are enabled, highlighting the advantages of synchronizing land use with existing transportation infrastructure, as well as the massive marginal benefits from small marginal LRT expansion costs. While infill benefits have been discussed for some time (Boarnet and Compin 1999; Calthorpe 1993; Churchman 1999; Ellman 1997), the results in this study show a distinct advantage of TOD strategies for reducing environmental impacts and only a small subset of interdependent infrastructure services have been considered. It is possible that TOD will achieve environmental impact reduction cobenefits through processes not included in these results such as reduced water use, wastewater generation, greater impervious surfaces, and heat island creation. However, there is also the question of how changes in lifestyle affect a household's consumption of goods and service (Heinonen and Junnila 2011). Given Phoenix's historic path dependence toward automobile-oriented sprawl, policies and initiatives that capitalize on existing infrastructure may promise enough benefits to break the automobile lock-in and low-density behavior. Had it not been for Phoenix's history of leapfrogging and sprawl, this infill opportunity would not exist.

Energy and environmental benefits are just two dimensions of the total potential benefits of land-use densification policies, and may increase as additional factors are included. Technology advancements in manufacturing, construction, and operation of cars, trains, and buildings are likely to alter the benefits achieved from TOD infill, but not likely to change the relative comparison between TOD infill and BAU growth (i.e. advancements in housing construction will be joined with advancements in apartment building construction). Uncertainty in electricity generation, building energy use efficiency, and automobile fuel efficiency are assessed in the SI, and the combined worst-case uncertainty still demonstrates significant savings from TOD infill. As more city residents live closer to public transportation options or their place of work, multimodal travel becomes more attractive (Cervero, Ferrell, and Murphy 2002; Parker et al. 2002). Walking, biking, and public transit use may increase, leading to greater reductions in energy use and emissions. Rezoning is both time and cost intensive because of bureaucratic rezoning practices and regulatory procedures within cities. However, if underutilized parking lots and vacant commercial lots become less valuable than land occupied with TOD, the energy and environmental benefits could be enlarged significantly. Furthermore, economic and social benefits may be realized, making a stronger case for TOD infill. Economic benefits include increased economic activity, increased land values, more efficient use of existing infrastructure, increased employment, and increased transit ridership (Cervero, Ferrell, and Murphy 2002; Ellman 1997; Golub, Guhathakurta, and Sollapuram 2012; Parker et al. 2002). Social benefits include increased accessibility to transit and public services, clean air, greater conservation of open lands, increased social interaction, and better accommodation of projected population increases (Cervero, Ferrell, and Murphy 2002; Ellman 1997; Parker et al. 2002). The environmental results combined with existing research on the economic and social benefits of TOD produce a strong justification for Phoenix to maximize the use of the light rail infrastructure that has already been deployed.

Conclusion

The ITLU-LCA framework can be used to inform city leadership as they develop strategies to meet environmental and sustainability goals. Furthermore, the cobenefits of land use and transportation activity can be calculated with consistent methods that satisfy the critical eyes of stakeholders at all levels. TOD densification produces benefits across a broad suite of environmental indicators, and the few short-term negative impacts are far outweighed by long-term benefits. In Phoenix, GHG emissions can be reduced by as much as 370 mt CO_2e/du and energy consumption can be reduced by nearly 5.7 TJ/du (the equivalent of 1.2 million households each driving 460 fewer annual miles, or turning off all BAU households for 3 days of the year). By transitioning the next residential developments from outlying areas to TODs, the potential for human health respiratory effects will be reduced by 8.4 percent and photochemical smog formation by 25 percent. The Arizona Climate Change Advisory Group (CCAG) projects that the state's GHG emissions footprint will reach 147 mmt CO_2e (148 percent increase from 1990 levels) by the year 2020 (CCAG 2006). TOD densification provides one solution, and at most (in TOD5 with 22,000 dwelling units) accounts for only 0.17 percent of this future footprint. The 22,000 new dwelling units are 1.8 percent of the current 1.2 million residential properties in Maricopa County (Maricopa County Assessor's Office 2012). By expanding the opportunity for high-density walk, bike, and transit-oriented neighborhoods to other regions of the city (assuming non-automobile travel options exist and are competitive), Phoenix could meet 7 percent of the Arizona GHG emissions reduction goals by targeting 200,000 dwelling units for TODs instead of allowing continued low-density auto-oriented construction of outlying regions.

This study is specific to Phoenix and shows that planners can consider and justify land use strategies that require capacity expansion of the existing transit infrastructure to enable long-term impact reductions. During this research, and subsequent expansion of this work (Chester, Nahlik, et al. 2013), local stakeholders both contributed to the design of the study and showed enthusiasm for learning about the results (see SI for a discussion of these interactions). Replicating this study may not result in the same conclusions for a city with less vacant space or without an existing light rail or other transit system. Nevertheless, the ITLU-LCA framework can be applied to other cities to assess the environmental benefits and costs of urban revitalization strategies.

In each of the five TOD strategies, the combined land use and transportation environmental benefits from densification are greater than the benefits gained through disjointed planning efforts. In land use planning literature, TODs appear to meet many of the demands for more affordable housing, economic growth, increased "livability," curbing sprawl, and the revitalization of aging downtown areas (Boarnet and Compin 1999; Cervero, Ferrell, and Murphy 2002; Golub, Guhathakurta, and Sollapuram 2012; Loukaitou-Sideris 2010). In transportation planning literature, TODs seem to be an antidote for congestion problems, low public transit ridership, and increasing gaps between infrastructure maintenance costs and revenue streams (Echenique et al. 2012; Hankey and Marshall 2010; Mashayekh, Hendrickson, and Matthews 2012; TRB 2009). Dense TOD districts can be successful without significant gains in transportation efficiency, while campaigns to increase transit ridership can be marginally successful without changes to building energy use at the rider's home. However, coupling land use and transportation policies by promoting residential infill near light rail stations would reduce the energy and environmental impacts of population growth, providing benefits to residents in the neighborhoods and across the city.

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References

Adalberth, Karin, Anders Almgren, and Ebbe Holleris Petersen. 2001. "Life Cycle Assessment of Four Multi-family Buildings." *International Journal of Low Energy and Sustainable Buildings* 2:21.

ADOT (Arizona Department of Transportation). 2011. *What Moves You Arizona: Long-range Transportation Plan 2010-2035*. Phoenix: Arizona Department of Transportation.

Aktas, Can B., and Melissa M. Bilec. 2011. "Impact of Lifetime on US Residential Building LCA Results." *International Journal of Life Cycle Assessment* 17 (3): 337–349.

ANL (Argonne National Laboratory). 2012. "The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) Fuel Cycle Model Version GREET 1.8d and Vehicle Cycle Model Version GREET 2.7a." Argonne, IL: Transportation Technology R&D Center, Argonne National Laboratory, US Department of Energy. Accessed May 5, 2012. http://greet.es.anl.gov.

Athena Sustainable Materials Institute. 2011. "Definitions and Assumptions: Athena Ecocalculator." Accessed May 10, 2012. http://calculatelca.com/software/ecocalculator/definitions-and-assumptions.

Athena Sustainable Materials Institute. 2012. "Impact Estimator for Buildings, Version 4.1.1412." Ottawa, Ontario, Canada: Athena Sustainable Materials Institute.

Bare, Jane. 2011. "TRACI 2.0: The Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts 2.0." *Clean Technologies and Environmental Policy* 13 (5): 687–96.

Bartholomew, K. 2007. "Land Use Transportation Scenario Planning: Promise and Reality." *Transportation* 34 (4): 397–412.

Boarnet, M. G., and N. S. Compin. 1999. "Transit-oriented Development in San Diego County: The Incremental Implementation of a Planning Idea." *Journal of the American Planning Association* 65 (1): 80–96.

Bruegmann, Robert. 2005. *Sprawl: A Compact History*. Chicago: University of Chicago Press.

Calthorpe, Peter. 1993. "Design Guidelines." In *The Next American Metropolis: Ecology, Community, and the American Dream*, 77–112. Princeton, NJ: Princeton Architectural Press.

CCAG. 2006. *Climate Change Action Plan*. Phoenix: Arizona Climate Change Advisory Group. Accessed July 8, 2012. http://www.azclimatechange.gov/docs.html.

Cervero, Robert. 1984. "Light Rail Transit and Urban Development." *Journal of the American Planning Association* 50 (2): 133–47.

Cervero, Robert, Christopher Ferrell, and Steven Murphy. 2002. "Transit-oriented Development and Joint Development in the United States: A Literature Review." *Research Results Digest* 52:1–144.

Chatman, D. "Does TOD Need the T?" *Journal of the American Planning Association* 79 (1): 17–31.

Chester, Mikhail, and Arpad Horvath. 2009. "Environmental Assessment of Passenger Transportation Should Include Infrastructure and Supply Chains." *Environmental Research Letters* 4 (2): 1–8.

Chester, Mikhail, Arpad Horvath, and Samer Madanat. 2010a. "Comparison of Life-Cycle Energy and Emissions Footprints of Passenger Transportation in Metropolitan Regions." *Atmospheric Environment* 44 (8): 1071–9.

Chester, Mikhail, Arpad Horvath, and Samer Madanat. 2010b. "Parking Infrastructure: Energy, Emissions, and Automobile Life-cycle Environmental Accounting." *Environmental Research Letters* 5 (3): 034001.

Chester, Mikhail, Matthew Nahlik, Andrew Fraser, Mindy Kimball, and Venu Garikapati. 2013. "Integrating Life-cycle Environmental and Economic Assessment with Transportation and Land Use Planning." *Environmental Science & Technology*. Published electronically September 20, 2013. doi:10.1021/es402985g.

Chester, Mikhail, Stephanie Pincetl, Zoe Elizabeth, William Eisenstein, and Juan Matute. 2013. "Infrastructure and Automobile Shifts: Positioning Transit to Reduce Life-Cycle Environmental Impacts for Urban Sustainability Goals." *Environmental Research Letters* 8 (1): 015041.

Churchman, A. 1999. "Disentangling the Concept of Density." *Journal of Planning Literature* 13 (4): 389–411.

City of Mesa. 2011. *Mesa Zoning Ordinance Chapter 5*. Accessed June 2012. http://www.mesaaz.gov/planning/PDF/ZoningOrd/Chapter05.pdf.

City of Phoenix. 2004. *Zoning Index Map*. City of Phoenix Planning Department. Accessed June 12, 2012. http://www.phoenix.gov/pdd/pz/pzmaps.

City of Phoenix. 2008. *Phoenix: Living Like It Matters*. Accessed July 2012. http://phoenix.gov/greenphoenix/sustainability/summary.

City of Phoenix. 2011. *Zoning Districts with Brief Descriptions*. Phoenix, AZ: City of Phoenix Planning and Development Department. Accessed June 12, 2012. http://www.phoenix.gov/planning.

City of Tempe. 2005. Zoning and Development Codes. In *Zoning Districts*. Accessed May 20, 2012. http://www.tempe.gov/index.aspx?page=900.

Cooney, Gregory A. 2011. "Life Cycle Assesment of Diesel and Electric Public Transportation Buses." MS thesis, University of Pittsburgh, Environmental Engineering.

Cooper, J., T. Ryley, and A. Smyth. 2001. "Energy Trade-offs and Market Responses in Transport and Residential Land-use Patterns: Promoting Sustainable Development Policy." *Urban Studies* 38 (9): 1573–88.

DOE (U.S. Department of Energy). 2012. *New Construction: Commercial Reference Buildings*. Accessed May 20, 2012. http://www1.eere.energy.gov/buildings/commercial/ref_new_construction.html.

DOT (U.S. Department of Transportation). 2011. *National Household Travel Survey*. Washington, DC: U.S. Department of Transportation, Federal Highway Administration.

DSIRE (Database of State Incentives for Renewables & Efficiency). 2012. *Arizona: Incentives/Policies for Renewables & Efficiency*. Accessed May 5, 2012. http://www.dsireusa.org/incentives/incentive.cfm?Incentive_Code=AZ03 R&re=1&ee=1.

Duffy, Aidan. 2009. "Land Use Planning in Ireland—A Life Cycle Energy Analysis of Recent Residential Development in the Greater Dublin Area." *International Journal of Life Cycle Assessment* 14 (3): 268–77.

Echenique, Marcial H., Anthony J. Hargreaves, Gordon Mitchell, and Anil Namdeo. 2012. "Growing Cities Sustainably: Does Urban form Really Matter?" *Journal of the American Planning Association* 78 (2): 121–37.

EIA (U.S. Energy Information Administration). 2008. *2005 Residential Energy Consumption Survey: Microdata*. Washington, DC: U.S. Energy Information Administration. Accessed May 5, 2012. http://205.254.135.7/consumption/%20residential/data/2005/#microdata.

EIA. 2011. "Monthly Electric Utility Sales and Revenue Report with State Distributions." *Form EIA-826*. Washington, DC: U.S. Energy Information Administration. Accessed March 15, 2013. http://www.eia.gov/electricity/data/eia826/.

EIA. 2012. *Residential Sector Key Indicators and Consumption*. Washington, DC: U.S. Energy Information Administration. Accessed May 5, 2012. http://www.eia.gov/oiaf/aeo/tablebrowser/#release=%20EARLY2012&subject=0-EARLY2012&table=4-EARLY2012&region=0-0&cases =full2011-d020911a,early2012-d121011b.

EIA. 2013. *Natural Gas*. Washington, DC: U.S. Energy Information Administration. Accessed March 15, 2013. http://www.eia.gov/naturalgas/.

Ellman, Tara. 1997. *Infill: The Cure for Sprawl?* Arizona Issue Analysis 146. Phoenix: Goldwater Institute.

EPA (U.S. Environmental Protection Agency). 1998. "External Combustion Sources: Natural Gas Combustion." In *Emissions Factors*. Washington, DC: U.S. Environmental Protection Agency, 1.4.1–1.4.10.

EPA. 2009. *Strategic Package of Tools: Transit Oriented Development in Metropolitan Phoenix*. Washington, DC: U.S. Environmental Protection Agency. Accessed May 20, 2012. http://www.epa.gov/smartgrowth/pdf/phoenix-sgia-package-tools.pdf.

EPA. 2011. *Appendix 15-A: Emissions Factors for Fuel Combustion from Natural Gas, LPG, and Oil-Fired Residential Appliances*. Washington, DC: U.S. Environmental Protection Agency. Accessed June 12, 2012. http://www1.eere.energy.gov/buildings/appliance_standards/residential/pdfs/aham2_dfr_app-15a_environmentalemissionfactors_2011-04-13.pdf.

Frijia, Stephane, Subhrajit Guhathakurta, and Eric Williams. 2012. "Functional Unit, Technological Dynamics, and Scaling Properties for the Life Cycle Energy of Residences." *Environmental Science & Technology* 46 (3): 1782–8.

FTA (Federal Transit Authority). 2004. *Transit-Oriented Development in the United States: Experiences, Challenges, and Prospects*. Washington, DC: Federal Transit Authority. Accessed June 4, 2012. http://onlinepubs.trb.org/onlinepubs/tcrp/tcrp_rpt_102.pdf.

Galster, George, Royce Hanson, Michael R. Ratcliffe, Harold Wolman, Stephen Coleman, and Jason Freihage. 2001. "Wrestling Sprawl to the Ground: Defining and Measuring an Elusive Concept." *Housing Policy Debate* 12 (4): 681–717.

Gober, Patricia. 2005. *Metropolitan Phoenix: Place Making and Community Building in the Desert*. Philadelphia: University of Pennsylvania Press.

Golub, A., S. Guhathakurta, and B. Sollapuram. 2012. "Spatial and Temporal Capitalization Effects of Light Rail in Phoenix: From Conception, Planning, and Construction to Operation." *Journal of Planning Education and Research* 32 (4): 415–29.

Google Earth. 2012. "Phoenix, Arizona." Accessed June 1–15, 2012. http://www.google.com/earth.

Guerra, E., R. Cervero, and D. Tischler. 2012. "Half-Mile Circle: Does It Best Represent Transit Station Catchments?" *Transportation Research Board: Journal of the Transportation Research Board* 2276:101–9.

Guggemos, A., and A. Horvath. 2006. "Decision-Support Tool for Assessing the Environmental Effects of Constructing Commercial Buildings." *Journal of Architectural Engineering* 12 (4): 187–95.

Gustavsson, L., and R. Sathre. 2006. "Variability in Energy and Carbon Dioxide Balances of Wood and Concrete Building Materials." *Building and Environment* 41 (7): 940–51.

Hankey, Steve, and Julian D. Marshall. 2010. "Impacts of Urban Form on Future US Passenger-Vehicle Greenhouse Gas Emissions." *Energy Policy* 38 (9): 4880–87.

Heim, Carol. 2001. "Leapfrogging, Urban Sprawl, and Growth Management; Phoenix, 1950-2000." *American Journal of Economics and Sociology* 60 (1): 39.

Heinonen, Jukka, and Seppo Junnila. 2011. "Case Study on the Carbon Consumption of Two Metropolitan Cities." *International Journal of Life Cycle Assessment* 16 (6): 569–79.

Heinonen, Jukka, Riikka Kyrö, and Seppo Junnila. 2011. "Dense Downtown Living More Carbon Intense due to Higher Consumption: A Case Study of Helsinki." *Environmental Research Letters* 6 (3): 1–9.

HUD (U.S. Department of Housing and Urban Development). 2011. *HUD FY2011 Sustainable Communities Grantees*. Washington, DC: U.S. Department of Housing and Urban Development. Accessed July 5, 2012. http://portal.hud.gov/hudportal/documents/huddoc?id=Sum_of_FY11ComChal_Reg.pdf.

IPCC (International Panel on Climate Change). 2007. *Climate Change 2007: The Physical Science Basis*, edited by S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller. Cambridge, UK: Cambridge University Press.

Junnila, Seppo, and Arpad Horvath. 2003. "Life-Cycle Environmental Effects of an Office Building." *Journal of Infrastructure Systems* 9 (4): 157–66.

Kinkisharyo International LLC. 2008. *Phoenix-Valley Metro Rail Technical Data*. Westwood, MA: Kinkisharyo International LLC.

Kittrell, Katherine. 2009. *Phoenix Metro Light Rail: Land Appreciation and Public Policy*. Tempe, AZ: Arizona State University.

LISC (Local Initiatives Support Corporation). 2013. What We Do: Transit Oriented Development (TOD). Phoenix: LISC. Accessed February 27, 2013. http://www.lisc.org/phoenix/what_we_do/transit_oriented_development/index.php.

Loukaitou-Sideris, Anastasia. 2010. "A New-Found Popularity for Transit-Oriented Developments? Lessons from Southern California." *Journal of Urban Design* 15 (1): 49–68.

Lund, Hollie M., Robert Cervero, and Richard Wilson. 2004. "Travel Characteristics of Transit-Oriented Development in California." Accessed August 2012. http://puff.lbl.gov/transportation/transportation/energy-aware/pdf/travel-of-tod.pdf.

Maricopa Association of Governments. 2011. "Sustainable Transportation & Land Use Integration Study: Working Paper One." Phoenix, AZ: Maricopa Association of Governments. Accessed August 17, 2012. http://www.bqaz.org/pdf/sustainable/BQAZ-STLU_2011-03-01_WorkingPaper-1_Regional-Transportation-Framework-and-Issues.pdf.

Maricopa County Assessor's Office. 2012. *Maricopa County Book 100 Parcel Data*. Phoenix, AZ: Maricopa County Assessor's Office.

Masanet, Eric, Alexander Stadel, and Petek Gursel. 2012. *Life-Cycle Evaluation of Concrete Building Construction as a Strategy for Sustainable Cities*. Skokie, IL: Portland Cement Association.

Mashayekh, Yeganeh, Chris Hendrickson, and H. Scott Matthews. 2012. "The Role of Brownfield Developments in Reducing Household Vehicle Travel." *Journal of Urban Planning and Development* 138 (3): 206–14.

Morrison Institute for Public Policy. 2011. *Watering the Sun Corridor: Managing Choices in Arizona's Megapolitan Area*. Tempe: Arizona State University.

National Transit Database. 2011. *Ridership 2011*. Phoenix: Valley Metro Rail Inc.

NHTSA. 2012. *NHTSA and EPA Propose to Extend the National Program to Improve Fuel Economy and Greenhouse Gases for Passenger Cars and Light Trucks Benefits to Consumers NHTSA's Proposed Standards*. Washington, DC: National Highway Transportation Safety Administration. Accessed August 17, 2012. http://www.epa.gov/otaq/climate/documents/420f11038.pdf.

Norman, Jonathan, Heather L. MacLean, and Christopher A. Kennedy. 2006. "Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions." *Journal of Urban Planning and Development* 132 (1): 10–21.

Ochsendorf, John, Leslie K. Norford, Dorothy Brown, Hannah Durschlag, Sophia Lisbeth Hsu, Andrea Love, Nicholas Santero, Omar Swei, Amanda Webb, and Margaret Wildnauer. 2011. *Methods, Impacts, and Opportunities in the Concrete Building Life Cycle*. Cambridge, MA: Massachusetts Institute of Technology.

Parker, T., Mike McKeever, G. B. Arrington, and Janet Smith-Heimer. 2002. *Statewide Transit-Oriented Development Study: Factors for Success in California*. Sacramento: California Department of Transportation.

PRé Consultants. 2008. "SimaPro LCA Software." Amersfoort, Netherlands: PRé Product Ecology Consultants.

Ramesh, T., Ravi Prakash, and K. K. Shukla. 2010. "Life Cycle Energy Analysis of Buildings: An Overview." *Energy and Buildings* 42 (10): 1592–600.

Rex, Tom R. 2000. *Population Density in Metropolitan Phoenix*. Phoenix: Morrison Institute for Public Policy.

RSMeans. 2009a. *Square Foot Costs: Residential, Commercial, Industrial, Institutional*. 15th ed. Kingston, MA: R. S. Means.

RSMeans. 2009b. *RSMeans Residential Cost Data*. 28th ed. Kingston, MA: R. S. Means.

Santero, Nicholas, Alexander Loijos, Mehdi Akbarian, and John Ochsendorf. 2011. *Methods, Impacts, and Opportunities in the Concrete Pavement Life Cycle*. Cambridge, MA: Massachusetts Institute of Technology.

Sartori, I., and A. G. Hestnes. 2007. "Energy Use in the Life Cycle of Conventional and Low-Energy Buildings: A Review Article." *Energy and Buildings* 39 (3): 249–57.

Traynor, Gregory W., Michael G. Apte, and Gee-Minn Chang. 1996. *Pollutant Emission Factors from Residential Natural Gas Appliances: A Literature Review*. Berkeley, CA: Lawrence Berkeley National Laboratory.

TRB (Transportation Research Board). 2009. *Driving and the Built Environment—The Effects of Compact Development on Motorized Travel, Energy Use, and CO_2 Emissions*. Washington, DC: Transportation Research Board, National Research Council.

U.S. Census Bureau. 2012. *2011 American Housing Survey*. Washington, DC: U.S. Department of Commerce. Accessed March 15, 2013. http://www.census.gov/housing/ahs/.

Weber, Christopher, and H. Scott Matthews. 2008. "Quantifying the Global and Distributional Aspects of American Household Carbon Footprint." *Ecological Economics* 66: 379–91.

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