Comparing High and Low Residential Density: Life-Cycle Analysis of Energy Use and Greenhouse Gas Emissions

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Abstract: This study provides an empirical assessment of energy use and greenhouse gas (GHG) emissions associated with high and low residential development. Three major elements of urban development are considered: construction materials for infrastructure (including residential dwellings, utilities, and roads), building operations, and transportation (private automobiles and public transit). Two case studies from the City of Toronto are analyzed. An economic input–output life-cycle assessment (EIO-LCA) model is applied to estimate the energy use and GHG emissions associated with the manufacture of construction materials for infrastructure. Operational requirements for dwellings and transportation are estimated using nationally and/or regionally averaged data. The results indicate that the most targeted measures to reduce GHG emissions in an urban development context should be aimed at transportation emissions, while the most targeted measures to reduce energy usage should focus on building operations. The results also show that low-density suburban development is more energy and GHG intensive (by a factor of 2.0–2.5) than high-density urban core development on a per capita basis. When the functional unit is changed to a per unit of living space basis the factor decreases to 1.0–1.5, illustrating that the choice of functional unit is highly relevant to a full understanding of urban density effects.

DOI: 10.1061/(ASCE)0733-9488(2006)132:1(10)

CE Database subject headings: Residential location; Emissions; Energy consumption; Canada; Buildings, residential.

Introduction

As North America's cities continue to grow, it is important to plan urban communities with long-term sustainability objectives in mind. In particular, with recent concerns over global climate change and related greenhouse gas (GHG) emission reduction programs such as the Kyoto Protocol, policy makers and infrastructure planners are being increasingly pressured to ensure that overall energy use and associated GHG emissions are minimized when planning cities. Urban form is a crucial element of any municipal planning process, and a better understanding of the relationship between urban form, energy, and the environment is critical to the formulation of workable strategies to meet environmental targets (Anderson et al. 1996). Indeed, given the high profile of "urban sprawl" as a potentially significant contributing factor to GHG emissions and electricity/fuel use (Newman and Kenworthy 1999; Gurin 2003), residential density associated with new urban development is, in particular, emerging as a primary issue for rigorous energy and environmental analyses. A focus on residential density is useful since it is an element of urban development over which municipal planners often have direct legislative control, whether via zoning bylaws or development approvals.

However, any serious attempt at addressing such broadly based environmental issues must consider the direct and indirect implications of policy actions over the entire life cycle (Chertow and Esty 1997). The life cycle of a product or project includes the stages of raw materials extraction, construction/manufacture, product/project use, and end of life. Life-cycle assessment (LCA) takes a systems approach to evaluating the environmental consequences of a particular product or project by quantifiably accounting for impacts generated across the life cycle (Svoboda 1995). A life-cycle focus is particularly crucial for urban density, given the myriad interrelated effects that can ripple through the developed environment. In this sense, informed decisions on residential density must heed a number of direct and indirect environmental considerations, including the environmental and human health impacts of transportation, continuous building operation, and material requirements for infrastructure.

Over the years, the environmental effects of urban form and residential density have often been studied in qualitative terms for policy applications [see, for example, Burchell and Listokin (1982); Lang (1986); Breheny (1992); Squires(2002)]. Yet, the current level of understanding with respect to the specific influence of urban form on the generation of environmental emissions and use of energy remains relatively weak (Anderson et al. 1996). Indeed, despite its analytical advantages and quantitative insights, a rigorous LCA approach has yet to be fully applied to the urban density debate (Tarlo 2002).

Most detailed life-cycle studies examining urban development have to date been focused on building design issues. A number of recent studies have examined single dwellings or multistory

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Note. Discussion open until August 1, 2006. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on June 24, 2004; approved on January 7, 2005. This paper is part of the ***Journal of Urban Planning and Development***, Vol. 132, No. 1, March 1, 2006. ©ASCE, ISSN 0733-9488/2006/1-10–21/$25.00.

buildings from a life-cycle perspective, notably Junnila and Horvarth (2003), Zachariah (2003), Thormark (2002), Fay et al. (2000), and Cole (1998). A common finding of these studies is the significant contribution of annual operational energy/emissions to overall life-cycle impacts. Junnila and Horvarth (2003) also show the relative environmental importance of material usage (i.e., the energy and environmental emissions "embodied" in the materials from manufacturing) in high-rise structures.

Other quantitative urban development studies have specifically examined transportation energy use and emissions associated with urban density. An important example is the extensive analysis by Newman and Kenworthy (1989), who show a strong link internationally between transportation energy use and urban density. More generally, Lang (1986) identifies transportation as one of the most important contributing factors to environmental emissions and energy use in the context of different residential development densities, a finding generally corroborated by qualitative studies of urban sprawl (Squires 2002; Gurin 2003).

While the above studies have made substantial contributions to the field, there are few objective studies that quantifiably link environmental impacts to development density. There is a need for further studies which holistically analyze the various components of urban density (e.g., buildings, transportation, utility infrastructure), and focus on quantitative environmental metrics, such as energy use and GHG emissions. These metrics are becoming more relevant as our society grapples with energy supply shortfalls, energy security, and climate change.

Based on the foregoing, the overall purpose of this study is to move toward a more complete life-cycle based understanding of the energy use and GHG emissions associated with typical high- and low-density residential development in a North American context. The study provides an empirical assessment of these metrics for three major aspects of the urban density issue: construction materials for infrastructure (including residential dwellings, utilities, and roads), building operations, and transportation (private automobiles and public transit). It is relevant to the current urban density debate given its life-cycle consideration of these three factors, its specific focus on GHG emissions and energy use, and its detailed consideration of a wide array of infrastructure materials. Furthermore, by using recent data for urban development to examine "real-world" case studies, the study avoids simplified theoretical assumptions about regional land use or transportation patterns. It is instead a pragmatic, empirical assessment of energy use and GHG emissions associated with high-density residential development closer to a city's core employment areas versus lower density development at the suburban fringe.

Data and Methodology

Urban Density Case Studies

Two case studies are developed and analyzed using LCA (described in more detail in the next section) to represent high-density and low-density development: a compact, multistory condominium project located near the inner core of the City of Toronto; and a low-density residential subdivision located within Toronto's suburban fringe. The locations of the high-density and low-density case studies are shown in Fig. 1. The case studies were chosen due to the availability of high quality public data describing building operational energy use, automobile use, and public transit use for different dwelling types and relative locations in the Toronto area. Furthermore, Toronto development trends and housing styles tend to be quite typical of the relatively compact central core and suburban sprawl patterns common to many major urban centers in North America. To provide a reasonable reflection of general urban density effects in other cities, each case study was carefully chosen to be widely representative of new residential development in many North American cities.

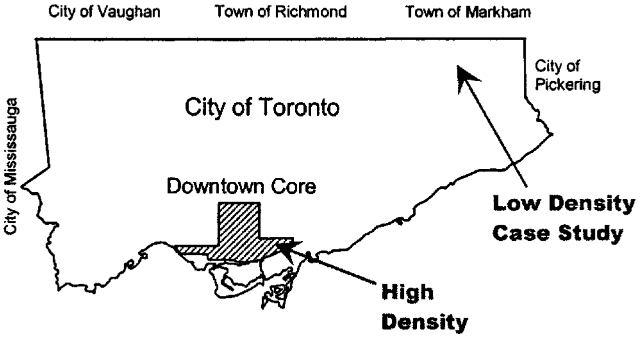
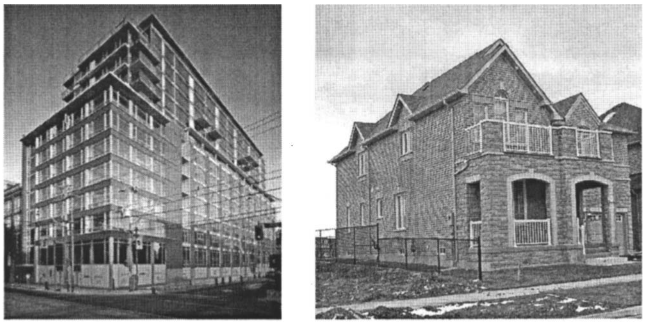


Fig. 1. Relative locations of low and high density case studies within city of Toronto

The high-density case study consists of a new construction 15 story residential condominium building located close to Toronto's downtown core, reflecting a development density of 150 dwellings/hectare of land used, which would be considered "high-density" by most municipal jurisdictions (Lang 1986). The low-density case study consists of a 161 unit residential subdivision of single-detached dwellings located near the border of the City of Toronto and the suburban Town of Markham. The subdivision has a development density of 19 dwellings/hectare, which would be considered "low-density" by most municipal jurisdictions (Lang 1986). All houses consist of a wooden structure and primarily brick façade. Based on correspondence with engineers and contractors experienced with new high-rise construction in North America, both case studies are considered to be quite typical of current and upcoming residential construction. Representative photographs of the high- and low-density case study buildings are shown in Fig. 2.

Life-Cycle Assessment

LCA is used to estimate the energy use and GHG emissions associated with each case study. The LCA boundary includes three major elements of urban development, chosen based on their


High Density Case-Study Building

Low Density Case-Study Typical Dwelling

Fig. 2. Representative photographs of low- and high-density case studies

overall relevance to urban energy use and GHG emissions and the availability of high-quality public data. These are: (1) all activities throughout the economy associated with resource extraction through material production for infrastructure (i.e., building, utility, and road materials); (2) the operational requirements (heating, cooling, and electricity) for dwellings; and (3) the operational requirements of vehicles for personal transportation and public transit. It is noted that building/infrastructure construction, maintenance, and end-of-life issues are not included in the study boundary due to a lack of available data and their relative insignificance to the overall life cycle, as reported by previous building LCA studies [see, for example, Junnila and Horvath (2003)]. A number of other contributing factors that may be relevant to energy use and GHG emissions associated with urban development have also been excluded from the LCA boundary, such as traffic congestion, infrastructure maintenance, and loss of arable/forest land. While these factors are excluded primarily due to lack of available data, the relevance of this study is undiminished since transportation, building operations, and material production are expected to play a significant (perhaps the most significant) role for overall GHG emissions and energy use in urban developments (see "Introduction").

One of the first steps in a LCA is the definition of the functional unit, which is related to the function that the product/project will deliver. Two functional units have been selected for this study. The high- and low-density case studies are each normalized with respect to: living area (on a per m^2 basis), and people housed (on a per capita basis). The use of living area as a functional unit allows the comparison of multifunctional residential development projects on a homogeneous basis (Peupoitier 2001). However, value judgments about an individual's living space requirements (as opposed to privileges) are implicit to this functional unit assumption. As such, a per capita (per person) basis is also included in the analysis to assess the relative importance of living space considerations when comparing urban density impacts. Per capita housing rates for each high- and low-density dwelling in the case study are estimated at 1.8 and 3.0 people housed per unit, respectively, based on data from the 1996 Statistics Canada census. The choice of functional unit is shown in the "Results" section to have a significant impact on the study results.

Environmental Metrics

This study quantifiably accounts for energy use and GHG emissions associated with residential development. These two metrics were chosen to indicate the overall energy intensiveness and climate change potential associated with different residential densities, which are highly relevant to urban planners given the current importance of energy supply issues and global climate change. Energy use described in this study corresponds to the total fuel and electrical energy required for material production, transportation, and building operation, measured in gigajoules (GJ) or megajoules (MJ). Primary GHGs [carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs)] emitted during the above activities are also considered. These emissions are normalized in terms of global warming potential (GWP), measured as total metric tons (tonnes) of CO_2 equivalents (eq.), which is calculated in accordance with the United Nations Framework Convention on Climate Change (GDI 2004).

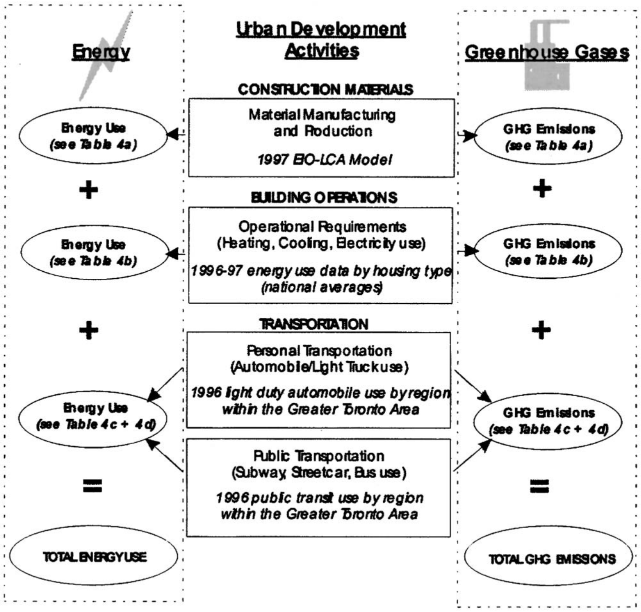


Fig. 3. Conceptual diagram of LCA methodology

Data Analysis

The general analytical framework and data analysis methods are summarized in Fig. 3. Due to three diverse elements of urban development being included in the LCA boundary, three distinct analytical approaches are employed for estimating energy use and GHG emissions associated with the elements: (1) for the construction materials an economic input–output life-cycle assessment (EIO-LCA) model is applied; (2) for building operations, nationally averaged public datasets are utilized; and (3) for public and private transportation, detailed location-specific data for the Greater Toronto Area are utilized. As a final step, the results from each study component are summed and compared to provide an overall assessment of the energy use and GHG emissions associated with high- and low-density development. The data analysis methods for each study component shown in Fig. 3 are detailed in the following sections. Where practical, all data were taken for the 1996–1997 time period to ensure consistency with the 1997 EIO-LCA model output.

Modeling of Construction Material Impacts

EIO-LCA is used to estimate the environmental impacts of material manufacturing required for the construction of infrastructure (buildings, roads, and utilities) in both the low- and high-density case studies. EIO-LCA was developed by researchers at Carnegie Mellon Univ. (Hendrickson et al. 1998) and a model for the United States is currently maintained by the Green Design Initiative (GDI 2004). The model couples national economic input–output accounts with environmental data for major industrial sectors to determine the total supply-chain effects of material purchases. As such, one of its primary advantages is that it considers economywide impacts and is not constrained by an arbitrary system boundary, a common limitation of conventional LCA methodologies (Hendrickson et al. 1998). Given this advantage, EIO-LCA has been effectively used for many development-related LCA applications, including a recent analysis of residential buildings (Ochoa et al. 2002).

EIO-LCA incorporates a number of simplifying assumptions. The primary assumptions relevant to this analysis are: (1) the

Table 1. Urban Infrastructure Materials: Producing Industries Analyzed and Data Sources

Material category	Producing industry classification	Data sources
Building materials		
Concrete	Ready-mix concrete manufacturing	(1) (3)
Reinforcing bar	Fabricated structural metal manufacturing	(1) (3)
Structural steel	Iron and steel mills	(1) (2) (3)
Structural lumber	Engineered wood member and truss manufacturing	(3)
Plywood	Veneer and plywood manufacturing	(3)
Brick	Brick and structural clay tile manufacturing	(1) (3)
Asphalt shingles	Asphalt shingle and coating materials manufacturing	(3)
Window panes	Glass and glass products	(1) (2)
Window/Door systems	Metal window and door manufacturing	(3)
Drywall	Gypsum product manufacturing	(1) (3)
Aluminum siding/Railings	Other aluminum rolling and drawing	(1) (2)
Elevators	Elevator and moving stairway manufacturing	(1)
Flooring (wood)	Other millwork, including flooring	(1) (2)
Flooring (ceramic/tile)	Ceramic wall and floor tile manufacturing	(1) (2)
Stairs (hardwood)	Other millwork, including flooring	(1) (3)
Insulation (fiberglass)	Mineral wool manufacturing	(1) (3)
Insulation (polystyrene)	Foam product manufacturing	(1) (3)
Vapor barrier (HDPE)	Plastics packaging materials, film and sheet manufacturing	(1) (3)
Subfoundation aggregate	Sand gravel, clay, and refractory mining	(1) (2) (3)
Roads and Utilities		
Plastic pipe	Plastics pipe, fittings, and profile shapes	(4) (5) (8)
Concrete pipe	Concrete pipe manufacturing	(6) (8)
Concrete manholes/basins	Other concrete product manufacturing	(6) (8)
Poured concrete curb	Ready-mix concrete manufacturing	(7) (8)
Steel valves/hydrants	Metal valve manufacturing	(7) (8)
Asphalt road surface	Asphalt paving mixture and block manufacturing	(7) (8)
Aggregate road base	Sand, gravel, clay, and refractory mining	(2) (8)

Note: Sources: (1) Bird Construction Canada Ltd. (correspondence); (2) Department of Civil Engineering, Univ. of Toronto (correspondence); (3) Zachariah (2003); (4) Diamond Plastics Corporation (price lists); (5) IPEX Corporation (price lists); (6) Co-Pipe Concrete Products (price lists); (7) Orlando Construction Company (correspondence); and (8) Schaeffers Engineering Consultants (utility drawings).

impact model is linear, so that environmental impacts are proportional to economic output; (2) only production is considered (e.g., transportation of materials to the project site is not considered); and (3) industrial sectors are often aggregated, so some construction materials analyzed may be grouped with other less related products that skew the environmental impacts reported. Despite these assumptions, EIO-LCA remains a widely used and relevant preliminary guide to emissions and resource use associated with the production of building/infrastructure materials (Environment Australia/RMIT 2004). In particular, EIO-LCA is well suited to this study since it is able to comprehensively assess material/product manufacture energy use and GHG emissions associated with a wide variety of urban infrastructure materials. An assessment of this scope would have been difficult with conventional LCA techniques without limiting the system boundaries considered for individual materials, which would have resulted in significant output errors and missed impacts along the supply chain.

This study employs the 1997 (most recent year available) EIO-LCA model for the United States. The United States model's structure and data sources are described in detail by GDI (2004). The key drawback of employing the United States-based EIO-LCA model to the Toronto case study is that it assumes identical production structures and industrial emissions/energy use for both Canada and the United States. This assumption could be construed as unrealistic given some inherent differences between the countries, such as dissimilar electricity generation mixes. However, the use of United States EIO-LCA for generalized North American analysis is seen as justifiable given the growing integration of the North American economy and typically comparable manufacturing technologies used in both countries. Furthermore, the intent of this study is to assess urban density in a general North American context; therefore, employing the U.S. EIO-LCA model to assess construction material impacts likely results in the most robust generalized findings.

Construction Material Data

This study considers a large array of construction materials relevant to urban development, including all major building, road, and utility materials. Table 1 summarizes the materials considered along with the respective producing industries analyzed in the EIO-LCA model, as well as all sources used to determine quantities and purchase price data in Canadian dollars (all sources are 2003 dollars). Materials that do not form part of the dwelling/subdivision structure, such as the manufacturing of appliances or carpeting, are not considered in this analysis. Building material costs for the high-density case study condominium building are directly provided by industry project contacts, while material cost breakdowns for the low-density case dwellings are estimated based on a typical single-detached dwelling recently analyzed by researchers at the University of Toronto (Zachariah 2003). Utility and road infrastructure requirements for both case studies are determined from as-built municipal drawings and correspondence

Table 2. Building Operational Data for 1997 and Data Sources

Item	Data used for analysis	Source(s)
Total residential energy use	1,394 PJ/year	NRCan (2003)
Total residential GHG emissions	72.7 MT CO_2 eq./year	NRCan (2003)
Single-detached dwellings		
Total energy use	999 PJ/year	CREEDAC (2000)
Number of dwellings	6,120,380 units	Statistics Canada (1999)
Number of occupants per dwelling	3.0 people/unit	Statistics Canada (1999)
Apartments >5 stories		
Total energy use	48.4 PJ/year[a]	NRCan (2003)/ CREEDAC (2000)
Number of dwellings	979,470 units	Statistics Canada (1999)
Number of occupants per dwelling	1.8 people/unit	Statistics Canada (1999)

Note: PJ=petajoule (1 million gigajoules); and MT=megatonne (1 million t).

[a] Based on calculated average energy consumption for all apartments (including those less than five stories).

with municipal engineers from the projects (a 200 m municipal frontage was assumed to estimate road and utility requirements for the high-density case study).

The EIO-LCA model was accessed on-line (GDI 2004) to run the analysis. The on-line model requires material producer prices (in United States dollars 1997) as inputs. As such, the purchase prices estimated above were reduced by a typical percentage of transportation and wholesaling costs for each material category, deflated to 1997 dollars using Industry Producer Price Indices (IPPI) and Raw Material Price Indices (RMPI) available from Statistics Canada (2004), and factored by a purchasing power parity (PPP) for 1997 between the United States and Canada, published by the Organization for Economic Development and Cooperation [(OECD) 2004]. The resulting 1997 United States producer prices for each material category were then input into the EIO-LCA model. The output from the model includes the energy use and GHG emissions throughout the entire economy resulting from the production of the quantity of materials required for each of the developments. For each urban density case, the GHG emissions and energy totals from the model are then normalized to per capita and per square meter values, based on the total number of people housed and total living space for the entire project. To be comparable with the other components of the analysis, the material production impacts are annualized assuming a material lifespan of 50 years.

Building Operational Data Analysis

Building operational energy use and GHGs emissions were estimated for the high- and low-density cases by analyzing publicly available data, which are summarized in Table 2. To estimate total energy use per dwelling unit for 1997, the number of single-detached dwellings (low-density case) and apartment dwellings greater than 5 stories (high-density), as outlined in the 1996 Canadian census, was coupled with national energy use data for the residential sector in 1997 broken down by housing type, as supplied by the Canadian Residential Energy End-use Data Analysis Centre [(CREEDAC) 2000] and Natural Resources Canada (NRCan 2003).

Annual GHG emissions from low- and high-density building operations for 1997 are based on total GHG emissions for the residential sector (NRCan 2003). Unfortunately, GHG emissions data are not currently available in Canada that distinguish between housing type. Instead, the percentage of total residential energy use attributable to single-detached dwellings (72%) and apartments greater than 5 stories (3.5%) was applied directly to total residential GHG emissions. While this assumption is not insignificant, it is expected to be reasonable given that the large majority of residential GHG emissions result from the burning of fuel and use of electricity for heating/cooling, which are also the most significant factors in total energy use (NRCan 2003).

It is noted that all building operational data correspond to Canada wide averages for 1997. In the absence of more directly applicable data, these averages have been applied to the Toronto case studies to provide an overall indication of operational energy/emissions. Based on data available from NRCan (2003) and U.S. Department of Energy (1999), residential energy use per dwelling in Canada was 14% higher than in the United States for 1997. While it is possible that regional variation in residential housing energy across North America may be significant (whether due to climatic differences, differences in regional electricity supply sources, or different methods of heating/cooling), the use of national averages for this study is considered useful for generalizing these results to other cities.

Transportation Data Analysis

Transportation energy use and GHG emissions resulting from light-duty vehicle (automobiles and light trucks) and public transit use were estimated by analyzing data reported in a variety of recent studies and government reports. All sources of data are for 1996 and are shown in Table 3. Using these data, annual energy use values were estimated by dividing the combustion energy of gasoline by the weighted average fuel economy for all 1990–1999 light-duty vehicles in Canada, and multiplying the result by the yearly vehicle mileages per capita for "core" city drivers in the Greater Toronto Area (GTA), representing high-density development close to downtown, and "outer suburb" drivers, representing low-density development along the suburban fringe. The resulting annual vehicle operating energies were normalized to a per-person and per-unit living area basis for each case study.

Total GHG emissions for automotive transportation were estimated using CO_2 emissions data from gasoline consumption in the GTA from a recent study by Kennedy (2002). According to national GHG data published by Environment Canada (2003), CO_2 accounted for 96% of the total GWP weighted emissions from road transportation. Using this ratio and the NRTEE travel kilometer estimates, total GHG emissions per person resulting from automotive transportation were calculated. Per person values were then normalized to per unit living area values based on 1996 Census data from Statistics Canada (1999).

Public transportation energy use and GHG emissions for each case study were estimated using similar data sources. Total transit usage per capita and median travel distances were determined for each case study from the 1996 Transportation Tomorrow Survey (TTS) (University of Toronto 2003), which provides detailed data about regional transportation patterns for different travel modes across the Greater Toronto Area. For this analysis, the high-density case was represented by transit data for the Toronto Core area, while the low-density case was represented by transit data

Table 3. Transportation Operational Data for 1996 and Data Sources

Item	Data used for analysis	Source(s)
Low density case		
Light-duty vehicle usage	22 vehicle km/person/day	NRTEE (2003)
Transit usage	0.15 trips/person/day	University of Toronto (2003)
Modal split[a] / Trip length	Bus: 85%/16.0 km	University of Toronto (2003)
	Train: 15%/24.5 km	University of Toronto (2003)
High density case		
Light-duty vehicle usage	6 vehicle km/person/day	NRTEE (2003)
Transit usage	0.62 trips/person/day	University of Toronto (2003)
Modal split[a] / Trip length	Bus: 10%/2.5 km	University of Toronto (2003)
	Streetcar: 40%/2.5 km	University of Toronto (2003)
	Subway: 50%/2.5 km	University of Toronto (2003)
Light-duty vehicles		
Fuel efficiency (1990–1999 fleet)	10.32 L/100 km	DesRosiers Automotive (Personal communication 2004)[b]
Combustion energy of gasoline	35.4 MJ/L	MacLean and Lave (1998)
Average GHG emissions (GTA)	620 g CO_2/person km	Kennedy (2002)
Average vehicle occupancy (GTA)	1.17 person/vehicle	City of Toronto (1999)
Transit vehicles		
Energy use (GTA)		
Bus	1.66 MJ/passenger km	Kennedy (2002)[c]
Streetcar	0.77 MJ/passenger km	Kennedy (2002)[c]
Subway	0.42 MJ/passenger km	Kennedy (2002)[c]
Commuter train	0.35 MJ/passenger km	Kennedy (2002)[c]
GHG Emissions (GTA)		
Bus	161 g CO_2/passenger km	Kennedy (2002)[c]
Streetcar	37 g CO_2/passenger km	Kennedy (2002)[c]
Subway	20 g CO_2/passenger km	Kennedy (2002)[c]
Commuter train	28 g CO_2/passenger km	Kennedy (2002)[c]

Notes: All GHG emissions are given here in grams of CO_2, which are converted to total GWP (g CO_2 eq.) by the writers for analysis.

[a] Modal splits for transit types other than commuter train were not available. Instead they are assumed based on relative levels of route coverage for each mode in the case study area.

[b] 1990–1999 Fuel Economy Chart for Canadian Automobiles, provided in personal correspondence, dated June 4, 2004.

[c] Transit vehicle energy use and GHG emissions for each mode are averaged from typical ranges reported by Kennedy (2002).

Table 4. Annual Energy Use and Greenhouse Gas Emissions Associated with Low- and High-Density Case Studies

	Annual GHG emissions (kilograms CO_2eq./year)		Annual energy use (magajoules/year)	
Component	(per person)	(per m^2)	(per person)	(per m^2)
(a) Construction materials (50 year lifespan)				
Low density	597	7.4	7,365	91.5
High density	391	9.1	4,678	109.3
(b) Building operations				
Low density	2,730	33.9	49,800	619
High density	1,510	35.1	27,500	643
(c) Automotive transportation				
Low density	5,180	64.4	27,500	341
High density	1,420	33.0	7,490	175
(d) Public transit				
Low density	130	1.6	1,300	16.5
High density	20	0.5	390	9.1

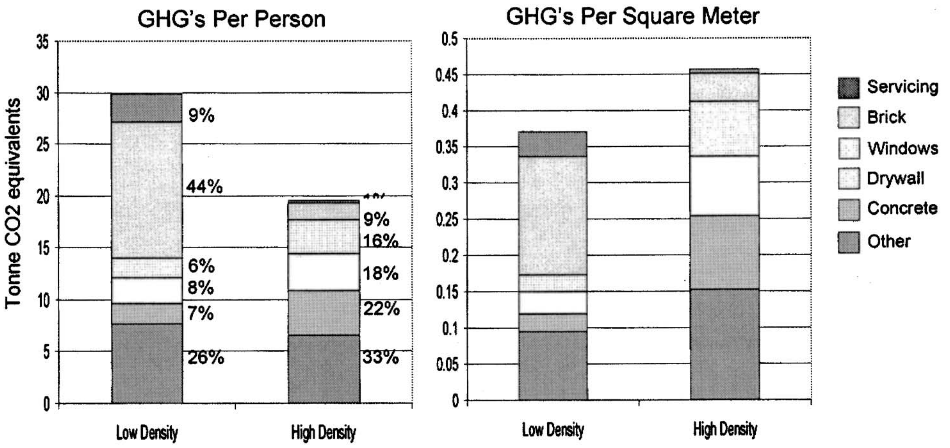


Fig. 4. Total greenhouse gas emissions from production of materials for low- and high-density development

for the Town of Markham (due to the low-density case study's suburban location adjacent to Markham). Energy use and GHG emission estimates per person-kilometer for different transit modes (diesel bus, streetcar, subway, and commuter train) were taken from the previously cited report by Kennedy (2002). Total transit energy use and GHG emissions for each case study were subsequently normalized to per capita and per unit living area bases for comparison.

Results

Construction Materials Results from EIO-LCA Model

The annual GHGs emitted and energy used during manufacture of the construction materials in the low- and high-density case studies are summarized in Table 4(a). All EIO-LCA results reported are for 1997, and the materials considered include those required for construction of the buildings, roads, and utilities. The results of this analysis show that embodied energy and GHG emissions resulting from material production across the supply chain are approximately 1.5 times higher for the low-density case study than the high-density case study on a per capita basis. However, changing the functional unit from per capita to per living area (m^2) alters these findings significantly. When considered on a unit living area basis, the high-density development scenario becomes 1.25 times more energy and GHG emissions intensive in terms of material production than the low-density case. It is clear, therefore, that the choice of functional unit is critical when assessing relative embodied energy and GHG emissions in the context of different urban densities. However, the overall significance of this finding in the wider context of urban density issues requires consideration of additional factors (for instance, building operational and transportation impacts). These issues are discussed later in the paper.

Figs. 4 and 5 depict the relative contributions of specific building materials and residential servicing infrastructure (i.e., roads and utilities) to total material manufacturing related GHG emissions and energy use. Based on the EIO-LCA analysis, the most important construction materials contributing to embodied manufacturing energy and GHGs for both density cases are brick, windows, drywall, and structural concrete used for dwellings. These four materials combined account for between 60 and 70% of the total embodied energy and production-related GHG impacts for both the high- and low-density case studies (in the figures, "Other" represents the combined contribution of materials used in the dwellings other than the top four materials noted above). These findings suggest that minimizing the use of the top four materials by employing more benign alternatives, such as differ-

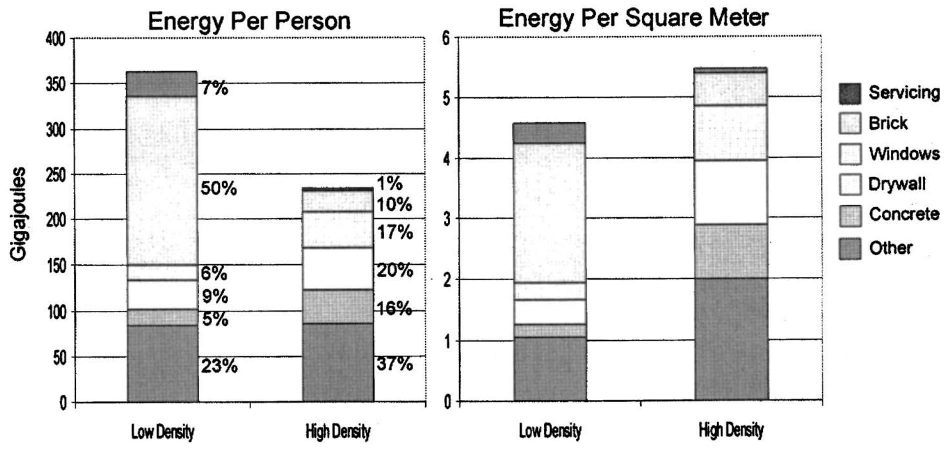


Fig. 5. Total energy use from production of materials for low- and high-density development

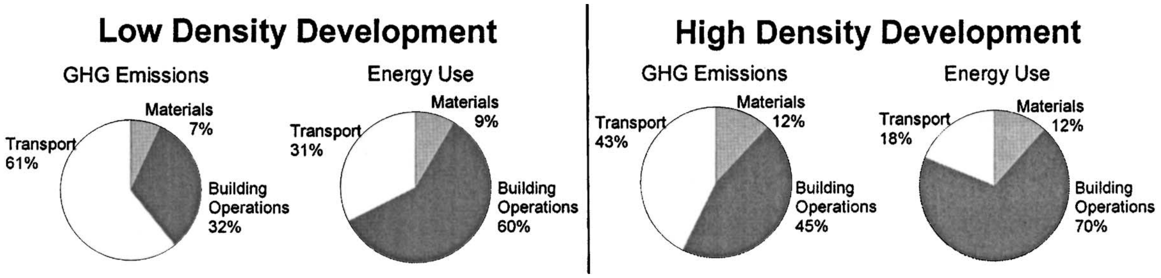


Fig. 6. Relative contributions of material production, building operations, and transportation to annual greenhouse gas emissions and energy use for low- and high-density development

ent forms of siding to replace brick usage, may result in the most significant reductions in overall embodied energy and GHGs for residential development projects. Brick alone accounts for 44% of total production-related GHGs and 50% of total embodied energy in the low-density case study. While this may be expected due to the primarily brick façade of the houses, it is notable that brick also contributed significantly to embodied energy and GHGs in the high-density case (10% for energy and 9% for GHGs) despite a comparatively low usage quantity. Furthermore, it appears that drywall may have contributed to the overall embodied energy and production-related GHG emissions beyond what would be expected based on its level of material usage, particularly in the low-density case study. These findings suggest that further assessment of the use of brick and drywall compared to other materials for residential development may be a worthwhile area of study. However, the effects of material substitution on operational energy requirements would need to be considered, in addition to other factors such as durability.

It is noted that residential servicing (utilities and roads) is significant only in the low-density case, where it contributes moderately to the overall embodied energy and GHG emissions associated with the subdivision (contributing 7 and 9%, respectively). Overall, servicing materials do not appear to be a significant factor for total embodied energy and production-related GHG emissions in residential developments relative to the building materials used for house/apartment construction.

Building Operational Impacts

The overall results of the building operational impact analysis normalized to per person and per unit living area bases are presented in Table 4(b). On a per capita basis, low-density developments comprising single-detached dwellings in Canada used 1.8 times more energy for building operation in 1997 than did high-density apartment developments (note that the low-density to high-density ratio for GHG emissions is equivalent due to the assumptions described previously). In general, this finding is consistent with other studies that have shown single-family houses use approximately twice as much energy as multiunit buildings (Diamond 1995). The trend is also expected due to the increased exterior wall surface area that increases the required heating and cooling loads in low-density (single-detached) dwellings (McMullan 2002).

Nonetheless, switching the functional unit to living area significantly alters these findings. When normalized on the basis of energy use per square meter of livable space, single-detached dwellings and high-density apartment buildings are essentially equal in annual energy use. Therefore, as with construction material impacts, the choice of functional unit is a critical factor when comparing operational energy use (and, by extension, GHG emissions) in the context of different urban densities.

Transportation Impacts

The overall results of the automobile and public transit analyses, normalized to per person and per unit living area bases, are presented in Table 4(c and d). It is notable that, despite a comparatively low transit ridership for the low-density case (see Table 3), normalized transit energy use/GHG emissions are higher in the low-density context, which is likely due to the greater travel distances required and heavy reliance on diesel buses instead of streetcars and subways. However, the overall contribution of public transit to overall transportation energy use and GHG emissions is minor. Public transit accounts for only between 2 and 5% of total transportation energy use and GHG emissions in both the high- and low-density scenarios. Therefore, automobile use is clearly the most significant contributing factor to transportation impacts for both high-density and low-density development. In this context, and because of the much higher car dependence and vehicle-kilometers traveled by residents of the outer suburbs relative to the city core, per capita transportation-related GHG emissions and energy use associated with low-density development are found to be 3.7 times higher than those associated with high-density development.

As has been discussed in previous sections, switching the functional unit from a per capita basis to a living area basis dampens the relative difference in transportation energy use and GHG emissions between low- and high-density developments to a factor of 2. However in the case of automotive transportation, it does not reverse or cancel the trend as was observed with building operational and material production-related energy use/GHG emissions. This indicates the overall importance of the high car dependence in low-density urban developments relative to high-density development areas.

Relative Contributions of Material Production, Building Operation, and Transportation

Based on the results presented in the previous sections, an overall assessment of the relative contributions to overall GHG emissions and energy use by the three urban development factors considered in this study (material production impacts, building operational impacts, and transportation impacts) has been conducted. Using the annual values for each factor considered, the relative percentage contributions to GHG emissions and energy use are depicted in Fig. 6, which shows the results for both high- and low-density development.

Some interesting trends can be seen in Fig. 6. For instance, it

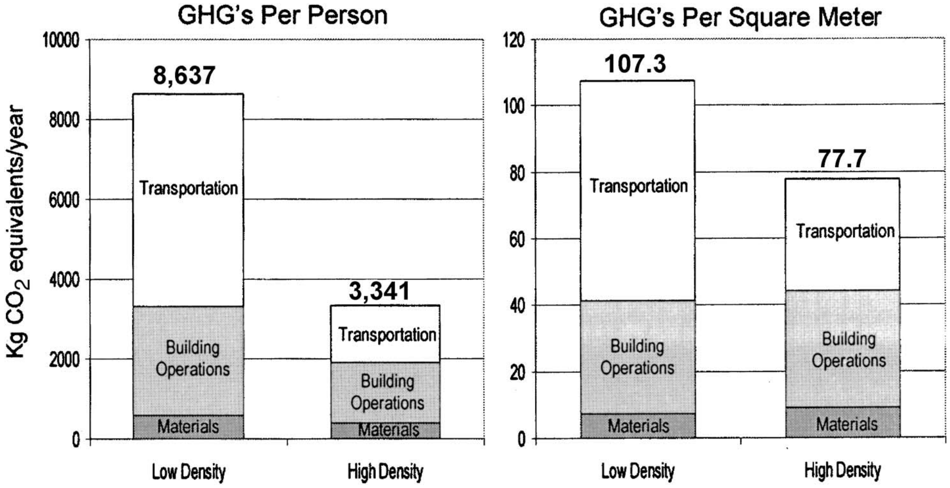


Fig. 7. Annual greenhouse gas emissions associated with low- and high-density development

is clear that transportation contributes far more significantly to overall energy use and GHG emissions in a low-density development context than in a high-density development context. Relatedly, it is apparent that building operational impacts are more significant in the high-density case. These results are not unexpected given the high automobile dependence and travel distances associated with suburban development, which tend to dwarf the contributions of building operations in the low-density case. In both cases, however, it is noted that material production accounts for only approximately 1/10 of total energy use and GHG emissions.

The majority of GHG emissions in both case studies result from transportation impacts, while the majority of energy use results from building operations. This finding is consistent with nationwide data for Canada aggregated by sector (NRCan 2003), which shows that the transportation sector as a whole contributes more significantly to GHG emissions than to energy use. This trend is partly explained by the fact that most of the energy used to power transportation vehicles is derived from fossil fuels with high carbon contents (NRTEE 2003), i.e., gasoline/diesel which are GHG emission intensive. Some of the nontransport energy contributions (e.g., electricity, natural gas) are less carbon intensive due to contributions of nuclear and hydropower and the lower carbon to hydrogen ratio of natural gas (compared to gasoline/diesel).

Overall Comparison of High- and Low-Density Development

A comparison of the overall impacts of high- and low-density development was conducted by summing the results of the three elements of urban development considered (material production, building operations, and transportation). The summed annual GHG emissions and energy use for the high- and low-density scenarios were then normalized to the two functional units. The results of the comparison are shown graphically in Figs. 7 and 8.

As can be seen in Fig. 7, the low-density development scenario results in roughly 2.5 times the annual GHG emissions on a per capita basis compared to the high-density scenario. Similarly, as shown in Fig. 8, the low-density case exhibits approximately twice the amount of annual energy use as the high-density development on a per capita basis. However, switching the functional unit to living area significantly dampens the relative difference

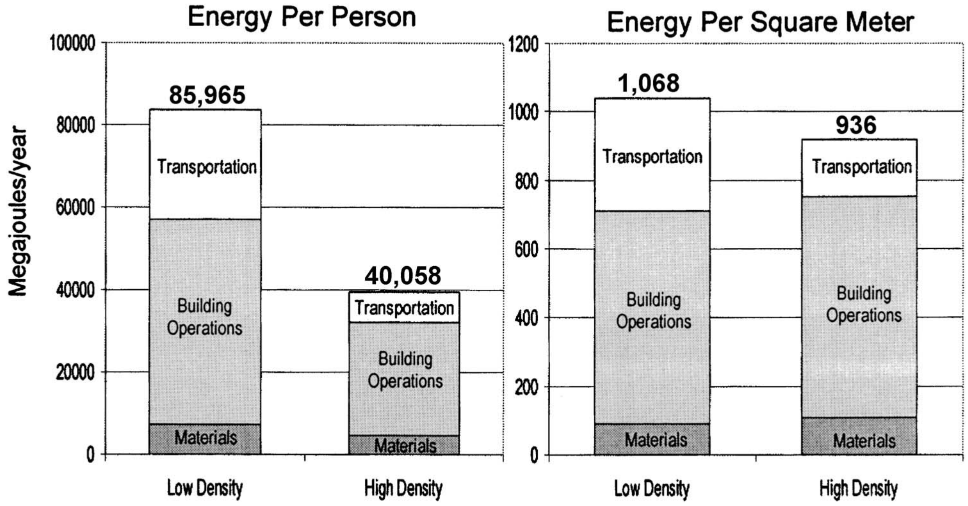


Fig. 8. Annual energy use associated with low- and high-density development

Table 5. Summary of Key Findings Pertaining to Low- and High-Density Development Case Studies Considered

Study element	Key conclusions
1. Building materials	a. Brick and Drywall in residential buildings contribute disproportionately to urban embodied energy/GHG emissions.
	b. Materials required for non-housing infrastructure do not contribute significantly.
	c. Material production overall accounts for about 10% of total life-cycle energy use/GHG emissions from residential development.
2. Building operations	a. Building operations account for 60–70% of life-cycle energy use in new residential development.
	b. Building operations for low-density development are 2× as energy and GHG emissions intensive as high-density development per capita.
	c. Building operations for low-density and high-density developments are about equal in energy and GHG emissions intensiveness per unit of living space.
3. Transportation	a. Transportation accounts for 40–60% of life-cycle GHG emissions in residential development.
	b. Public transit accounts for only 2–5% of total transportation energy use/GHG emissions.
	c. Transportation requirements for low density suburban development are nearly 4× as energy and GHG emissions intensive as high-density urban core development per capita.
	d. Transportation requirements for low density suburban development are 2× as energy and GHG emissions-intensive as high-density city core development per unit of living space.
4. Comparison of high and low urban density	a. Low density suburban development is 2.0–2.5× as energy and GHG emissions intensive as high-density urban core development per capita.
	b. Low density suburban development is 1.0–1.5× as energy and GHG emissions intensive as high-density urban core development per unit of living space.
	c. The choice of functional unit is highly relevant to understanding life-cycle density effects.

between high- and low-density development. On a per unit living area basis, low-density to high-density ratio drops to roughly 1.5 for GHG emissions, and is nearly 1.0 with respect to energy use.

It is notable that the overall trend between densities has not been fully reversed by changing the functional unit, which suggests a high level of overall energy and GHG emissions intensiveness for low-density development. This is largely due to the significantly higher level of automotive transportation emissions and energy use associated with low-density development compared with high-density development. However, it is important to note that energy use on a per unit living area basis is nearly equal between the densities. With consideration given to other factors, such as traffic congestion, it is possible that this trend would shift. Thus it is clear that, from an overall sustainability perspective, the choice of functional unit is highly relevant to the full understanding of urban density effects.

Discussion and Conclusions

This study provides a quantitative comparison of energy use and GHG emissions associated with high-density development close to a city core versus low-density development at the suburban periphery. Table 5 summarizes the key findings of the LCA conducted for the Toronto area case studies. It is important to remember that these conclusions are based on only a partial assessment of contributing factors to GHG emissions and energy use in residential development (i.e., infrastructure manufacturing, transportation, and building operations). Nonetheless, the findings of this study provide a reasonably complete understanding of urban density effects on overall GHG emissions and energy use, particularly given the overall life-cycle importance of infrastructure manufacturing, building operations, and transportation. It is noted, however, that the data reliability for the different components of this study may be variable given the disparate data sources relied on. Despite the assumptions implicit in the EIO-LCA analysis, the construction material production results are expected to be quite robust, particularly regarding the relative contribution of construction materials to the overall life-cycle impacts. The building operational and transportation results, on the other hand, are based on an analysis of currently available national/regional data which, while obtained from reliable sources, are somewhat limited in scope. Improvements to these components of the analysis could be made as better and more density-specific data sources become available. However, while the overall comparison of high and low urban density is limited by constraints in available public data, the general magnitude of differences in energy use and GHG emissions is believed to be quite representative of current development impacts.

The findings presented in Table 5 have clear implications for urban planners grappling with current critical environmental issues centered on climate change and energy supply. While it is clear that broad planning decisions about urban density need to consider a variety of other factors beyond simply GHGs and energy use (including other environmental, social, and economic considerations), this study empirically confirms that increasing residential density in urban form may comprise a significant component of broader energy conservation and GHG reduction policies. It is also noted that, while this study has given specific consideration to empirical evidence in the City of Toronto, it is quite probable that these findings are indicative of a more general relationship between urban density, GHG emissions, and energy use in many other North American cities. Nonetheless, similar empirical studies in other cities both within and outside North America would be helpful to move toward a better quantitative understanding of urban density effects.

It is also apparent that policy makers and urban planners should base their decisions about urban form on a greater quantitative understanding of the empirical effects of urban development policies. While this study provides a greater life-cycle understanding of the effects of urban density, additional insight can be gained by building upon its findings. For instance, a useful area of study from an overall urban development context would be an assessment of brick and drywall substitutes to reduce total embodied energy and GHG impacts associated with residential land use. Furthermore, an assessment of additional development factors that contribute to GHG emissions and energy use, such as traffic congestion, loss of green space, and other stages of dwelling life cycles, will assist in achieving a more complete understanding of urban density effects.

The findings of this study also emphasize the importance of functional unit assumptions when dealing with urban development considerations. Given the sensitivity of the relative findings to the choice of functional unit, it is apparent that implicit value judgments about an individual's "right to space" versus an individual's "right to comfortable shelter" are at question. Therefore, detailed consideration must be given to the broader implications of functional unit assumptions on urban land use policy. This can only be fully addressed from a wider context of societal value judgments about living space. However, ultimately, a greater life-cycle understanding of the true implications of urban density will enable more informed decision making and specific means of mitigating urban impacts.

Broadly speaking, this study shows that urban form and density considerations should be given a brighter spotlight within the overall energy conservation and climate change policy debate. The results clearly suggest that climate- and energy-oriented urban planning should give priority to policies that reduce automotive transportation in suburban settings (such as mixed-use policies reducing required travel distances), reduce operational energy associated with high-density high rise development (such as district heating/cooling projects), increase public transit use, and shift land use to higher density development closer to a city's core employment areas. Furthermore, a shift to alternative fuels and renewable energy sources can assist in reducing transportation and operational energy use and GHG emissions associated with residential development. In concept, these recommendations are not new to urban planners; however, the empirical nature of this analysis removes some of the inherent uncertainty about the "real-world" environmental effects of urban form, thus lending new weight to the adoption of these strategies in the wake of Kyoto.

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