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Exploring the link between urban form and work related transportation using combined satellite image and census information: Case of the Great lakes region

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ABSTRACT

Aspects of urban transportation have significant implications for resource consumption and environmental quality. The level of travel activity, the viability of various modes of transportation and hence the level of transportation-related emissions are influenced by the structure of cities, i.e., their urban forms. While it is widely recognized that satellite remote sensing can provide spatial information on urban land cover and land use, its effective use for understanding impacts of urban form on issues such as transportation requires that this information be integrated with relevant demographic information. A comprehensive bi-national urban database, the Great Lakes Urban Survey (GLUS), comprising all cities with populations in excess of 200,000 has been created from Landsat imagery and national census and transportation survey information from Canada and the United States. A suite of analysis tools are proposed to utilize information sets such as GLUS to investigate the link between urban form and work-related travel. A new indicator, the Employment Deficit Measure (EDM), is proposed to quantify the balance between employment and worker availability at different transit horizons and hence to assess the viability of alternate modes of transportation. It is argued that the high degree of residential and commercial/industrial land uses greatly impact travel to work mode options as well as commute distance. A spatial interaction model is developed and found to accurately predict travel distance aggregated at the census tract level. We argue that this model could also be used to explore the relative levels of travel activity associated with different urban forms.

1. Background

Urbanization is a global trend. According to United Nation's World Urbanization Prospects publications (United Nations, 2002, 2007), the percentage of the world's population living in urban areas increased from 29% in 1950 to 50% in 2008 and can be expected to reach 70% by 2050. Urbanization is generally associated with increasing affluence which is reflected in high automobile ownership and use. Therefore, urbanization can be expected to result in increased energy demand (Transport Canada, 2006; United Nations, 2007; Wang et al., 2012; Han et al., 2014). In the case of the United States and Canada, transportation accounted for 27.2% and 29.0% respectively of overall energy consumption in 2001 (TEDB, 2007; Cuddihy et al., 2005).

While the extent of urban areas and their intensity are fundamental land information items, an understanding of urban impacts on energy use and the environment requires a more comprehensive and integrated information base. A relevant characterization of urbanization is 'urban form'. We define urban form as the combined spatial distributions of land uses and demographic-related attributes (e.g., overall population, dwelling counts, employment, etc.). It has long been recognized that the structure of cities, i.e., their urban 'form', greatly influence intra-urban human activities and consequently levels of energy consumption (e.g., Kenworthy, 2003). In the case of transportation, the level of travel activity (i.e., distances traveled, accessibility and feasibility of public transit, etc.) are influenced in part by urban attributes such as land use mix, population density, etc. (Crane, 1999; Badoe and Miller, 2000; Ratner and Goetz, 2013). Effective use of urban form databases requires a suite of analysis tools to quantify relative transportation energy efficiencies of cities through a combination of sustainability indicators and travel modeling.

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Table 1
List of major urban areas included in the Great Lakes Urban Survey.

CMA/MSA	Population	CMA/MSA	Population
Chicago–Gary, IL/IN	9,157,540	Kalamazoo–Battle Creek, MI	452,851
Detroit-Ann Arbor-Flint, MI	5,456,428	Lansing–East Lansing, MI	447,728
the Greater Toronto Area, ON	4,682,897	London, ON	432,451
Cleveland–Akron, OH	2,945,831	Kitchener–Waterloo, ON	414,284
Milwaukee–Racine, WI	1,689,572	Saginaw–Bay City, MI	403,070
Buffalo–Niagara Falls, NY	1,170,111	St. Catharines–Niagara Falls, ON	377,094
Rochester, NY	1,098,201	Windsor, ON	307,877
Grand Rapids–Muskegon–Holland, MI	1,088,514	Oshawa, ON	296,298
Syracuse, NY	732,117	Erie, PA	280,843
Hamilton, ON	662,401	South Bend, IN	265,559
Toledo, OH	618,203	Green Bay, WI	226,778

Remote sensing has the potential to provide urban land surface information. There are two key challenges in effective use of satellite imagery for these urban applications. First, while there is a need to map temporal changes in overall urban extent (e.g., Koeln et al., 2000), energy applications require more detailed intra-urban land use information. For example, to address transportation energy use associated with work-related travel, 'residential' and 'commercial/industrial' land use categories provide spatially explicit locations of trip origins and destinations respectively. Satellite image classification suffers from spectral confusion between built areas and other non-vegetated surfaces such as fallow agricultural land. This problem is especially acute for large area mapping initiatives, for example the generation of the National Land Cover Datasets (NLCD) (Vogelmann et al., 2001; Homer et al., 2007) as opposed to studies that restrict mapping to only areas around cities (e.g., Lo and Choi, 2004; Lu and Weng, 2005; Yuan et al., 2005). In the former case, since urban land only contributes a small fraction of land cover, commission errors can be severe. To overcome this problem, hybrid processing involving satellite image classification, census and nighttime light data have been developed (e.g., Vogelmann et al., 1998).

The second challenge involves integration of land surface information with demographics (e.g., population counts, employment statistics, etc.). A suitable level of census detail must be selected that is commensurate with the spatial mapping resolution of satellite data. Also, since census reporting areas are based on population count criteria, they are not of constant areal extent nor are they 'pure' in terms of land use. For our synoptic information creation and analysis goals, we have selected census information at the census tract level. Census tracts (CTs) tend to exhibit increasing areal size with distance from city cores, reflecting radial decline in population density with distance from the city center. In addition, while core CTs encompass only urban land uses, fringe CTs can include significant contributions from non-urban land uses.

The objectives of this paper are (a) to describe the design and creation of an urban information base that is tailored for analysis of the link between the urban form and transportation, (b) to identify issues related to the creation of equivalent information for urban areas of different countries thus supporting international comparisons and (c) to demonstrate the application of these information bases through the derivation and anlaysis of a relevant sustainability indicator and through travel activity modeling. In Section 2 we describe the creation of a bi-national database of urban form, the Great Lakes Urban Survey (GLUS). The following two sections illustrate the utilization of GLUS to study the urban form—transportation link. In Section 3 we propose a novel sustainability indicator that targets the feasibility of alternate modes of transportation. Section 4 presents a modeling scenario to illustrate how EO-based information can be exploited to quantify the impacts of urban form attributes on travel distance. Finally, Section 5 provides the conclusions resulted from this work.

2. Creation of the Great Lake Urban Survey

The Great Lakes are an important water resource, containing 84% of North America's and 18% of the world's fresh surface water resources. While the land in the northern part of its watershed remains largely forested, the southern portion is highly developed both in terms of urbanization and widespread agricultural use. The total urban population in this region is over 33 million, which includes roughly 10% of the US population and 30% of the Canadian population.

This paper builds upon earlier work involving the creation of a Canadian urban form information base, the Canadian Urban Land Use Survey (CUrLUS) (Zhang et al., 2010), and its use in analysis of the link between Canadian urban form and aspects of work-related travel (Zhang and Guindon, 2006; Guindon and Zhang, 2007). Based on encouragement from the Air Quality and Science Advisory Boards of the International Joint Commission, the CUrLUS concept was extended to create a bi-national (Canada–United States) information base, the Great Lakes Urban Survey (GLUS) that would provide consistent urban form and travel information on all 22 urban centers in the watershed with populations in excess of 200,000 in the year 2000 (Table 1). These urban areas are designated as Census Metropolitan Areas (CMAs) in Canada and Metropolitan Statistical Areas (MSAs) in the United States. Both CMAs and MSAs include CTs of a major city and surrounding rural land and satellite communities. Fig. 1 illustrates the extent of the overall watershed and the rectangular portion of the watershed (1173 × 577.8 km in extent in the east and north directions respectively) that has been mapped using Landsat imagery for this study. Fig. 2 illustrates the outline of our information generation and integration strategies for the creation of GLUS and for subsequent transportation-related analysis.

2.1. Generation of land cover land use information

Land cover and land use (LCLU) information was extracted from summer Landsat Thematic Mapper images (summer acquisition dates in the interval June 8, 1999–August 22, 2001) using a semi-automated classification methodology proposed earlier (Guindon et al., 2004). The approach utilizes a rule-based approach to combine pixel-based and segment level classifications to (a) distinguish between non-built urban areas (e.g., parklands) and rural vegetated areas (b) to generalize urban land uses, such as residential suburbs and (c) to identify and compensate for large shadows in city cores. Classification was aided using 1:50,000 and 1:100,000 topographic maps and higher resolution satellite and aerial images as reference material. Forty-six Landsat TM scenes, geocoded in the Albers Equal Area projection, were procured, classified and composited (Guindon and Edmonds, 2002) to create a seamless land cover land use product of the southern portion of the Great Lakes watershed that included the 22 urban centers of interest (Fig. 2). The