



Carbonless footprints: Promoting health and climate stabilization through active transportation

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ARTICLE INFO

Available online 20 October 2009

Keywords:

Urban Form
Obesity
Transportation
CO₂ Emissions
Climate Stabilization
Energy Use

ABSTRACT

Objective. Our objective was to describe how active transportation can help meet health and greenhouse gas emissions goals, and the ability of urban form strategies to impact both issues. In addition, we wanted to assess if there is an inverse relationship between active and motorized forms of travel.

Methods. A cross-sectional analysis of travel diary data was used to measure relationships among energy (kcal) burned from walking, energy (kcal) burned from motorized transportation, and the ratio of the two (the transport energy index) with regional accessibility and local walkability when adjusting for demographic factors. Multiple linear regression and descriptive statistics were employed to estimate these relationships.

Results. Transit accessibility, residential density, and intersection density were positive predictors of walk energy and the energy index and inverse predictors of motorized energy. The land use mix variable was negatively and significantly associated with energy burned from walking and from motorized transportation, with no significant impact on the transport energy index. Because a mixed land use pattern places destinations closer together, it reduces distances and thus energy demands for both walking and driving.

Conclusions. The results support the concept, previously untested empirically, that similar urban form strategies can have cobenefits for both physical activity and climate change.

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Introduction

A policy framework for solving two societal challenges

Climate change and obesity have both emerged in the past decade as urgent policy mandates. Dire predictions about the environmental and human consequences of climate change are now widely accepted (IPCC, 2007), and obesity is an increasing global problem that already costs the United States health care system more than \$147 billion annually (Finkelstein et al., 2009). The two issues share some common sources and impact individuals and communities across the globe, but both have particular importance to the United States. Per capita greenhouse gas emissions are close to 20 tons per person per year (U.S. Department of Energy, 2009). That adds up to about one-fifth of the global CO₂ total (Energy Information Administration, 2008), which until recently was the highest on the planet. The United States also has a high prevalence of sedentary lifestyles, overweight,

and obesity (U.S. Department of Health and Human Services, 2001). Although the rapid increase in obesity seen in the past 25 years has recently leveled off, about one-third of the country's adults are estimated to be obese, and roughly two-thirds are overweight or obese (Ogden et al., 2006).

How we travel represents a means to promote or hinder achievement of both environmental and health goals—energy used for active forms of transportation has a health benefit, while energy used for motorized forms of travel contributes to climate change and generates other harmful air pollutants. Recently, climate change and public health policy agendas have begun to converge, with increasing focus on the built environment as a key part of any policy to address obesity and greenhouse gas emissions. Considerable evidence already exists documenting multiple impacts of climate change on human health (McMichael et al., 2006). Because the built environment is associated with how we travel (TRB/IOM, 2005; Boarnet and Crane, 2001; U.S. EPA, 2001; Kuzmyak and Pratt, 2003; Bento et al., 2003; Frank, 2000), planners and policymakers have an opportunity to use changes in the built environment to make progress toward healthier and more sustainable communities. This is particularly the case for cities, counties, and regions, where actions and policies that can be implemented at the local level are needed.

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Transportation, the built environment and climate change

The transportation sector¹ makes up the largest share of United States greenhouse gases (GHGs)—about one-third of the total (U.S. Department of Energy, 2009), with much of that amount generated by routine household travel (Federal Highway Administration, 2009). There is growing agreement that in order to meet the necessary targets for GHG reduction, changing travel behavior needs to be part of the solution (Yang et al., 2009; Greening, 2004; Silsbe, 2003).

A large and growing body of research has examined the connections between the built environment and travel. Although there is no research to date that documents a causal link, the evidence has consistently found associations among walkable, transit-oriented neighborhood design, decreases in vehicle travel, and increases in transit, bicycling, and walking (Ewing et al., 2007; TRB/IOM, 2005; Ewing and Cervero, 2001). Research on the connection between urban form and GHGs from transportation is still emerging (Ewing et al., 2007; Muñoz and Galindo, 2005; Rajan, 2006; Frank et al., 2007b, 2009; LFC, 2005). However, because CO₂ is largely a function of vehicle miles traveled, urban form relationships with VMT can be extended directly to greenhouse gas emissions (Frank et al., 2007b; Ewing et al., 2007). Regional scale development patterns—a region's size and how much it "sprawls"—have been found to play an important role in VMT (Ewing et al., 2002), fuel consumption and energy use (Goudie, 2002; Newman and Kenworthy, 1989), and CO₂ emissions from transport (VandeWeghe and Kennedy, 2007). At the neighborhood scale, design characteristics—an interconnected street network and a compactly developed mix of commercial and residential land uses—have consistently been found in the research to be associated with more walking, bicycling, and transit use and less driving (Cervero and Kockelman, 1997; Frank and Pivo, 1995; Handy, 1996; Holtzclaw et al., 2002). Neighborhood-scale walkability may also influence the decision to take transit for work trips because it can facilitate nondriving access to auxiliary destinations—for example, to the bank during the work day (Cervero, 1988, 1989, 1991; Frank et al., 2007a).

Transportation, the built environment and physical activity

Large amounts of time spent driving have been associated with higher body weights (Frank et al., 2004; Wen et al., 2006)—and in 2001, the average American spent 64 min daily in a vehicle (Hu and Reuscher, 2004). Walking and bicycling, on the other hand, are inherently active, and have been associated with a lower likelihood of obesity (Frank et al., 2004). Research also suggests that walking or cycling to transit contributes substantially to physical activity (Besser and Dannenberg, 2005; LaChapelle and Frank, 2009; Frank and Chapman, 2004; Weinstein and Schimek, 2005). A number of recent studies have documented that residents of walkable neighborhoods are more physically active and less likely to be overweight or obese (Black and Macinko, 2007; Gebel et al., 2007; Papas et al., 2007; Heath et al., 2006; Saelens and Handy, 2008; Saelens et al., 2003; Sallis et al., 2009; TRB/IOM 282, 2005; Frank et al., 2005, 2006), although, again, the links are not causal.

Policy agendas, interventions, and overlap

The respective health and climate policy goals are quite different—increasing physical activity requires a focus on increasing the demand for active travel, as opposed to reducing GHG emissions from vehicles, which entails decreasing the demand for driving (VMT). These two goals overlap where active travel substitutes for vehicle travel, as shown in Fig. 1. Although a number of researchers have observed that some degree of mode substitution can occur, there is little conclusive

¹ Typical sectors (sources) of GHG emissions in the United States include agriculture, industry, commercial, residential, and transportation.

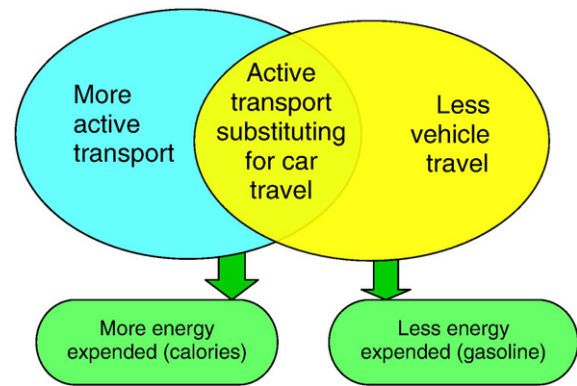


Fig. 1. Conceptual transport energy model.

evidence on how much (Handy and Clifton, 2001; Boarnet and Greenwald, 2000; Greenwald and Boarnet, 2001; Greenwald, 2003; Beiborn et al., 2003). The evidence suggests that the same basic set of neighborhood design strategies—compact development, a mix of land uses, and an interconnected street network—may have positive benefits for health and climate change goals. This paper tests this hypothesis. The analysis that follows explicitly documents the relationships between energy used for active and motorized forms of transportation, and empirically evaluates how modifiable features of the built environment (land use mix, compact development, street connectivity) are associated with the ratio between energy used for active vs motorized forms of travel.

Methodology

Data sources

The analysis relied on data collected from the Atlanta-based SMARTRAQ travel survey, as described in Frank et al. (2004). The current study used 10,148 participants who completed a 2-day travel diary as part of this 13-county Atlanta regional study. Participants were screened and selected based on household income, household size, and residential density of the household location. Because the Atlanta region has so few compact, walkable environments, oversampling in higher density areas was necessary to ensure a statistically significant sample of participants in walkable environments. For the analysis, we eliminated observations with dependent variable values more than three standard deviations from the mean, and persons under age 16.

Sociodemographics

To estimate the independent effect of urban form, we controlled for sociodemographic and household characteristics known to be associated with travel (Murakami and Young, 1997; Stead, 2001; Pucher and Renne, 2007; Badoe and Miller, 2000): Age, gender, ethnicity (white/nonwhite), drivers' license status, ordinal categories of household income, and total number of household members and vehicles in the household. Household characteristics were self-reported from SMARTRAQ travel survey data.

Neighborhood design

Neighborhood-level built environment variables were calculated around each participant's home location in GIS using parcel, road network, and census data. These variables were measured based on a 200-m grid system that covered the 13-county region, used by the Atlanta Regional Commission (ARC). The built environment values assigned to each are based on an enlarged or "buffered" area in order to measure each household's surrounding neighborhood. Fig. 2 shows this buffered area. Each grid cell was assigned the average value of the built environment measures for the set of grid cells making up its buffered area.

The neighborhood design measures included land use mix, net residential density, and intersection density. Each is described below. Measures were calculated using version 1.5 of the 13 county parcel file based on tax assessor data.

Net residential density (NRD)

Net residential density was the total number of housing units divided by residential land area. The number of housing units came from census block data and was aggregated or disaggregated (as needed) to the 200-m grid. Residential acreage was derived from the ARC 2000 LandPro land cover data (from aerial photography).

Intersection density

The number of intersections per kilometer was determined using GIS, based on the regional street network for the region. An intersection was defined as where three or more roads meet, and excluded controlled access interchanges and on/off ramps.

Land use mix

The land use mix factor took into account the number of different land uses among three categories (single and multifamily residential, commercial, and office) as well as their relative amounts in terms of building floor areas. Building floor area data by use type from the parcel level land use database were aggregated to the desired grid cell level. The mixed use value was between zero and one. A value closer to one means a more even distribution of the relative amount of floor area for the land uses present, indicating that residential dwellings and everyday destinations are in close proximity to one another and therefore more walkable. The formula used was

$$\text{Mixed use} = - \sum [P_n * \ln(P_n)] / \ln(N),$$

where N is the number of different land uses and (P_n) is the proportion of inhabited space in the n th land use, which is the following ratio:

$$\frac{\text{total estimated square footage of building floor area of a certain land use type}}{\text{total estimated square footage of building floor area of for all three uses}}$$

Proximity to transit

The distance along the road network to the nearest rail and bus stops was calculated from the centroid of each participant's 200-m grid cell. Rail and bus stop data layers were provided by the ARC.

*Measuring regional accessibility**Auto travel time*

To control for regional accessibility, the average travel time to five major population and employment centers in the Atlanta region (Atlanta CBD, Hartsfield-Jackson Airport, Perimeter Center, Cumberland Mall, Buckhead MARTA Station) was estimated for auto and transit modes, for each survey household, using Traffic Analysis Zone (TAZ) travel time matrices from the ARC's regional travel model. Centrally located households will have overall shorter auto travel times than those in outlying areas.

Transit accessibility

Transit accessibility was used to measure regional location as it specifically related to transit service quality. To measure transit accessibility, we used a dummy variable capturing whether or not a travel survey household could access all the region's five major activity centers by walking to transit. Again, this measure relied on transit travel time matrices from the ARC's regional travel model.

*Outcome variables**Average kilocalories spent walking*

For each individual with reported walking trips in the travel survey, we converted average distance walked into calories using the following formula based on Ainsworth (2002):

$$0.35 \text{ kcal per lb, per mile} * \text{reported weight} * \text{average daily walk distance.}$$

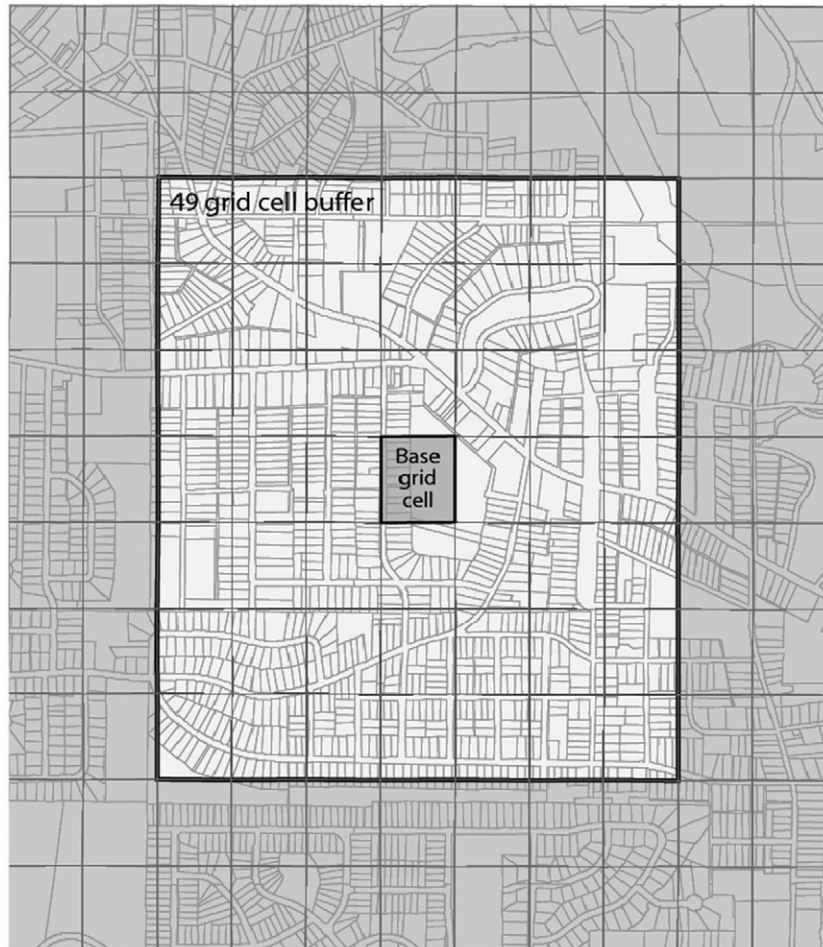


Fig. 2. A 200-m walkability surface.

The formula was adjusted based on each survey participant's reported weight. The actual path of each trip taken by the survey participant was not reported. Using GIS analysis, we created walking paths based on the shortest distance between the origin and the destination of the trip, along the road network.

Average per capita kilocalories from motorized transport

To estimate kilocalories expended from motorized transport, we first estimated average daily weekday vehicle CO₂ emissions for each travel survey participant based on their trips reported over the 2-day travel survey period. CO₂ emissions estimates were generated for the following motorized modes: single-occupant cars, carpools, bus (school buses and public transit), and motorcycles. Estimates were calculated using data on CO₂ emissions from the Environmental Protection Agency's MOBILE 6.2 emissions model. Estimates were generated for each link of each trip, and accounted for vehicle occupancy, travel time, speed, facility type and "cold starts" (CO₂ emissions rates are slightly higher when an engine is cold as opposed to after it has warmed up). Links were summed together to produce total CO₂ estimates for each motorized trip, as well as person-level totals. The details of the trip level emissions methodology can be found in Frank et al. (2000) and Bachman et al. (2003).

We converted CO₂ emissions to gallons of gasoline and gallons of gasoline to kilocalories using the following formula:

$$\begin{aligned} \text{Average per capita CO}_2 \text{ per day} &\times 1 \text{ lb.} / 453.539237 \text{ g} \\ &\times / \text{gal} / 19.564 \text{ lb} \times 31250 \text{ kcal} / \text{gal} \approx \text{average total CO}_2 * 3.5219 \\ &= \text{daily per capita kilocalories from motorized transport.} \end{aligned}$$

Transport energy index

The energy index expressed the ratio of calories burned by walking to calories burned by gasoline: kcal burned by walking/kcal burned by gasoline. The more walking and less driving a person does, the closer the index gets to 1. For someone who engaged a high amount of walking distance and very little driving distance, the index could be well above 1. Conceivably, for someone who did no driving trips at all during the survey period, the denominator in this index would be zero, resulting in an infinitely large value.

Statistical analyses

We used multiple linear regression analysis to model the relationships between urban form and energy from walking, energy from motorized

transport, and the energy ratio. We also grouped the sample into four quadrants of walking and motorized energy, in order to evaluate how regional accessibility and local walkability characteristics can conspire to create a high walk–low drive land use pattern that is a win–win for health and climate change.

Due to skewed distributions, the dependent variables were natural log transformed for the regression analysis. A value of 1 was added to all of the observations for kcal from walking and kcal from motorized transport in order to retain the many observations for which kcal from walking equaled zero. The "+1" adjustment was a mathematical necessity to account for those persons who did not have any energy expenditures by either motorized or nonmotorized modes; the natural log of zero is undefined, as would be the natural log of any whole number divided by zero. The +1 adjustment creates a nonzero value in the dependent variable with only minimal distortion to the original energy measurements, and no change to the underlying distribution of observations. To log-transform the energy index, we calculated the natural log of the index of the non-natural log transformed variables (retaining the +1): LN energy index = LN(average daily kcal spent walking +1/average daily kcal burned from motorized transport +1).

Results

Summary statistics

Table 1 illustrates the summary statistics for the sample population. Seventy-two percent of the sample was white, 28% nonwhite. Ninety four percent of the sample had drivers' licenses. Only 10% reported any walking, with a mean distance of 1/20 of a mile, with only three additional kcal per day, per person, on average from walking. Conversely, respondents generated an average of 40,000 kcal per day driving. This resulted in a very low energy index.

Atlanta is quite skewed toward low-density, auto-dependent urban form, as the values for residential density, intersection density, and land use mix demonstrate. Average distance to transit is quite high in particular—over 9 miles for rail and over 4 miles for bus, with only 14% able to access all 5 CBDs on transit. Forty-one percent of the sample was able to walk to transit which accesses between 1 and 4 of the region's 5 major activity centers. The remaining 45% were not able to access any of the major activity centers via transit.

Regression models are shown in Table 2. All demographic variables emerged with largely expected relationships for all outcomes, with

Table 1
Sample characteristics.

N = 10184	Mean	Median	Minimum	Maximum
Age	44.61	44	16	102
Gender (1 = Male, 0 = Female, Otherwise = Blank)	0.5	1	0	1
Ethnicity (1 = White, 0 = Non-White, Don't Know/Refuse = Blank)	0.72	1	0	1
Drivers' License Status (1 = Yes, 0 = No, Otherwise = Blank)	0.94	1	0	1
Household Income \$20,000 - \$39,999 (1 = Yes, 0 = No)	0.17	0	0	1
Household Income \$40,000 - \$59,999 (1 = Yes, 0 = No)	0.24	0	0	1
Household Income \$60,000 - \$74,999 (1 = Yes, 0 = No)	0.14	0	0	1
Household Income \$75,000 - \$99,999 (1 = Yes, 0 = No)	0.19	0	0	1
Household Income Over or Equal to \$100,000 (1 = Yes, 0 = No)	0.18	0	0	1
Number of People in Household	2.61	2	1	8
Number of Vehicles in Household	2.11	2	0	8
Shortest distance to nearest rail station	9.55	7.931	0.04	43.76
Shortest distance to nearest bus station	4.32	1.32	0.01	32.55
Net residential density	3.76	2.54	0	38.54
Land use mix (office, commercial, residential)	0.23	0.15	0	1
Intersections per square kilometer	25.35	22.80	0	88.66
Avg. auto travel time (Mins.) to 5 major activity centers	61.98	58.78	23.67	138.43
Can access all 5 regional CBD TAZs by transit (1 = Yes, 0 = No)	14%	0	0	1
Average Walk Distance per day	0.05	0	0	2.54
Average Additional Kcal burned per capita+1	4.03	0	1	236.60
Average per capita Kcal from Motorized Modes+1	37069.33	30716.16	1	132220.10
Energy Index	0.45	3.48x10-5	7.56x10-6	160.65
LN (Average Additional Kcal burned per capita+1)	0.26	0	0	5.47
LN (Average per capita Kcal from Motorized Modes+1)	10.03	10.33	0	11.79
LN (Energy Index)	-9.77	-10.27	-11.79	5.08

Table 2

Model results: Built environment impacts on energy from walking and motorized transport.

Variable	LN(Avg. Daily Kcal Spent Walking)			LN(Avg. Daily Kcal Burned From Motorized Transport)			LN(Energy Index)		
	β	SR2	p	β	SR2	p	β	SR2	p
Age of Individual	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.22
Gender (1 = Male, 0 = Female, Otherwise = Blank)	0.01	0.00	0.64	0.00	0.00	0.97	0.01	0.00	0.80
Ethnicity (1 = White, 0 = Non-White, Don't Know / Refuse = Blank)	0.15	0.00	0.00	0.03	0.00	0.31	0.11	0.00	0.01
Drivers' License Status (1 = Yes, 0 = No, Otherwise = Blank)	-0.38	0.01	0.00	1.65	0.05	0.00	-2.03	0.05	0.00
Household Income between \$20,000 and \$39,999 (1 = Yes, 0 = No)	-0.18	0.00	0.00	0.43	0.00	0.00	-0.61	0.01	0.00
Household Income between \$40,000 and \$59,999 (1 = Yes, 0 = No)	-0.08	0.00	0.03	0.53	0.01	0.00	-0.61	0.01	0.00
Household Income between \$60,000 and \$74,999 (1 = Yes, 0 = No)	-0.09	0.00	0.03	0.61	0.01	0.00	-0.70	0.01	0.00
Household Income between \$75,000 and \$99,999 (1 = Yes, 0 = No)	-0.09	0.00	0.02	0.70	0.01	0.00	-0.79	0.01	0.00
Household Income more than or equal to \$100,000 (1 = Yes, 0 = No)	-0.11	0.00	0.01	0.65	0.01	0.00	-0.76	0.01	0.00
Total number of people in household	0.01	0.00	0.37	-0.09	0.00	0.00	0.10	0.00	0.00
Total number of vehicles in household	-0.06	0.00	0.00	0.05	0.00	0.00	-0.11	0.00	0.00
Shortest distance to nearest rail station	-0.01	0.00	0.01	0.01	0.00	0.14	-0.02	0.00	0.01
Shortest distance to nearest bus stop	0.01	0.00	0.01	0.00	0.00	0.64	0.01	0.00	0.11
Net residential density	0.03	0.01	0.00	-0.04	0.00	0.00	0.07	0.01	0.00
Land use mix (office, commercial, residential)	-0.11	0.00	0.01	-0.24	0.00	0.00	0.13	0.00	0.13
Intersection density (per km)	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.00	0.00
Avg. auto travel time (min) to 5 major activity centers	0.00	0.00	0.16	0.00	0.00	0.32	0.00	0.00	0.14
Can access all 5 major activity centers via transit (1 = Yes, 0 = No)	0.19	0.00	0.00	-0.15	0.00	0.00	0.34	0.00	0.00
Constant	0.77		0.00	8.41		0.00	-7.64		0.00
R2	0.09			0.16			0.18		
Adj. R2	0.08			0.16			0.18		
N	10184			10184			10184		

Coefficients significant at 0.05 level are in bold text.

Untransformed dependent variables with zero values had 1 added to them before doing the natural log transformation.

LN is natural log.

SR2 is the squared semipartial correlation coefficient (i.e., the square of the correlation between the dependent variable and an independent variable when the linear effects of the other independent variables in the model have been removed from the independent variable (SPSS Inc., 2008)).

age, ethnicity, and income all playing a significant role. A drivers' license and more vehicles in the household were both associated with significantly less energy expended from walking, more energy expended from motorized travel, and a significantly lower energy index. Increased household size was associated with less kcal from motorized travel and higher vehicle occupancy rates, resulting in a higher energy index.

Of the neighborhood design variables, Net Residential and Intersection Density were significantly and positively associated with kcal from walking, negatively and significantly associated with kcal from motorized transport, and positively and significantly associated with the energy index. Land use mix was significantly and negatively associated with both kcal from walking and motorized transport, and had no significant impact on the energy index. This result likely demonstrates that the energy required to travel in a very mixed land use pattern is lower for both walking and driving—with no real impact on the relationship between the two modes.

As the shortest distance to the nearest rail stop increased, energy expended from walking decreased significantly, as did the energy index. As the shortest distance to the nearest bus stop increased, energy expended from walking and the energy index increased significantly. Those that could access all 5 of the major CBDs via transit burned significantly more kcal from walking, significantly fewer kcal from driving, and had significantly higher energy indexes. The connection between transit use and walking in this analysis was apparent, although it only emerged at a relatively high level of transit service. Average auto travel time to 5 regional CBDs was not significant in explaining any of the outcomes. It is possible that this variable is too highly correlated with the transit accessibility variables.

Table 3 provides results from an analysis where participants were assigned to quadrants of energy from walking vs energy from motorized transport using median values. Those who were at or below the daily per capita kilocalories from walking (0), and those who were 5% above or below the median daily per capita kilocalories from transport. Using the 5% threshold avoided a "boundary effect" eliminating cases with values close to the threshold with little

difference between quadrants. In the case of kcal from walking, the boundary effect could not be addressed because there is no value lower than zero. This situation was addressed by classifying observations with walking values as either zero or greater than zero.

Participants in quadrant 4 burned the most kcal from walking and the lowest from motorized modes, and they had the most supportive urban form values of all the quadrants. However, the urban form values were, on average, what would be considered moderately urban (or perhaps slightly less auto-oriented suburban). Travel time by car and transit was reflective of more centrally located households. Transit accessibility was also the best for quadrant 4. Participants in quadrant 4 expended 42% more kcal from walking than those in quadrant 2, the other quadrant with high amounts of kcal from walking. They also generated nearly 25% less kcal from motorized modes than persons in quadrant 3, the other quadrant with low kcal from motorized modes.

Discussion

The findings support the concept that the built environment strategies to reduce driving and increase walking are largely convergent. Increasing an area's residential density, street connectivity, and transit accessibility (both through service quality and proximity to transit service) are all significantly associated with both goals, as evidenced by their increasing the energy index. The only important distinction between the two goals is in the case of land use mix. The benefits of increasing land use mix to reduce greenhouse gas emissions from transport are quite significant, but are also associated with reduced energy required to travel between destinations on foot. The shorter distances between homes and common destinations that result from greater land use mix may mean less energy expended by active travel. Further investigation is required to fully understand this relationship. Previous published research using the same database documents increased levels of overall physical activity and frequency of walking in the most mixed use areas of the Atlanta region (Frank et al., 2004; Frank et al., 2005). However, these studies did not assess walk distance or convert walking into energy.

Table 3
Quadrants of kcal from walking and motorized modes.

	Quadrant 1: Low Walk/High Motorized		Quadrant 2: HighWalk/High Motorized	
	N = 4576		N = 298	
	Mean	Median	Mean	Median
Walk Distance per Day	0	0	0.48	0.32
Kcal Walking / Person / Day	0	0	27.35	17.65
Kcal motorized modes / person / day	60304.73	54159.50	58875.45	52995.89
Energy Index	-10.94	-10.90	-8.20	-7.99
Shortest Distance to Rail Stop	11.30	10.27	6.85	2.87
Shortest Distance to Bus Stop	5.35	2.69	2.79	0.57
Net Residential Density	3.11	2.04	4.42	3.38
Land Use Mix	0.20	0.08	0.25	0.19
Intersection Density	22.77	21.47	29.79	26.44
Travel Time by car to 5 major activity centers	67.43	67.86	54.08	46.64
Can access all 5 major activity centers via transit	0.1	0	0.21	0
	Quadrant 3: Low Walk/Low Motorized		Quadrant 4: High Walk/Low Motorized	
	N = 4292		N = 560	
	Mean	Median	Mean	Median
Average Walk Distance per Day	0	0	0.68	0.49
Kcal Walking / Person / Day	0	0	38.85	27.23
Kcal motorized modes / person / day	14835.33	14974.52	11238.91	10045.69
Energy Index	-9.26	-9.61	-4.66	-5.77
Shortest Distance to Rail Stop	8.78	6.58	3.25	1.39
Shortest Distance to Bus Stop	3.80	1.01	1.10	0.30
Net Residential Density	3.93	2.79	7.43	5.00
Land Use Mix	0.26	0.18	0.35	0.27
Intersection Density	26.19	23.41	36.83	37.23
Travel Time by car to 5 major activity centers	59.48	53.80	42.34	38.36
Can access all 5 major activity centers via transit	0.16	0	0.38	0

The total amount of variance explained by the model in each outcome was rather low, but not atypical for research investigating outcomes such as these that are influenced by many factors such as personal preferences and social conditions. It is important to note that the log transformation of the variables prohibits direct comparisons to linear regression research results. The transport energy index appears to have potential as a metric for defining the relative amount of energy consumed from walking vs motorized transport. The amount of variance explained in the energy index model was the highest of the three; indicating that the single energy use measure may have more informative value in evaluating the total impact of different urban form strategies than trying to examine either outcome (energy from walking and energy from motorized transport) in isolation. Further, the energy index can give some insight of how much substitution is going on from one mode to another, and why, for the various urban form measures. For example, the impact of the distance to a rail stop on the energy ratio is seen primarily through its effect on LN(kcal from walking), which is significant and negative, as opposed to its insignificant effect on LN(kcal from motorized transport).

Study limitations and strengths

The Atlanta region is relatively skewed in terms of walkability, with a low proportion of survey participants actually walking and limited variation in urban form. While this presented some difficulty, the large sample size and oversampling of residents of walkable neighborhoods allowed for reasonable estimates of association. The fact that these results emerged in the auto-oriented Atlanta region is an indication that relationships are robust; associations are expected to be stronger in regions with higher overall variations in walkability and/or transit access.

The Atlanta dataset we had also lacked reliable parks and open space and sidewalk data. The presence or absence of sidewalks needs to be captured in future research, since it would logically help to predict whether or not one chooses to walk. Access to recreational facilities has been documented in other research to influence physical

activity (Saelens and Handy, 2008; Frank et al., 2007c) so this is an important shortcoming to address in future studies. Lastly, the estimates of CO₂ from transport included the CO₂ generated from all motorized modes of transportation, including transit. Although this was perhaps the fairest approach to account for all CO₂ emissions generated from household transportation, the inclusion of transit CO₂ emissions in with the “pure” driving modes (i.e., car, carpool, motorcycle) could potentially confound the results.

Conclusion

In this cross-sectional analysis, we found clear evidence that urban form strategies can have converging benefits for public health and climate change. Increasing transit accessibility, residential density, and street connectivity were all significantly associated with more energy expended from walking and less energy generated from motorized transport, and significantly increased the index of energy from walking to energy from motorized transport.

The creation of a single metric, the energy index, increases the ability for policy makers and researchers to conceptualize the integration of health and climate change dimensions of transportation. Translating walking and motorized travel into energy metrics provides the ability to compare directly the utilization of healthy versus unhealthy or perhaps health neutral energy for travel. Results from this study make it clear that increased investment in transit and regional accessibility without the car coupled with increased walkability of local neighborhoods can collectively lead to a more active, healthier, and sustainable future.

Conflict of interest statement

All authors declare that there is no conflict of interest.

Acknowledgments

This study was funded by Active Living Research, a program of the Robert Wood Johnson Foundation. The data used for this study were

funded by the Georgia Department of Transportation and the Georgia Regional Transportation Authority.

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