Journal of the American Planning Association

ISSN: 0194-4363 (Print) 1939-0130 (Online) Journal homepage: https://www.tandfonline.com/loi/rjpa20

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ABSTRACT

Problem, research strategy, and findings: The monocentric development pattern in the Alonso–Mills–Muth model underpinned theoretical discussions of urban form in the 1960s and 1970s and truly dominated theory up to the point when Joel Garreau published *Edge City: Life on the New Frontier* in the early 1990s. Monocentric development patterns remain dominant to this day among smaller metropolitan areas in the United States. However, for larger metropolitan areas in the United States, regional transportation plans suggest a paradigm shift to a polycentric structure. We review 126 regional transportation plans in the United States and find that a hierarchy of centers connected by high-quality transit has become the dominant vision for most of them. The plan for Salt Lake City (UT), for example, strives for a multicentered region even though secondary centers are only beginning to emerge beyond a dominant downtown. Generally missing from regional transportation plans are quantitative criteria for designating and guiding centers: In no case are the quantitative criteria empirically based on proven transportation benefits. Here we investigate how the built environment characteristics of centers are associated with people's travel mode choices and vehicle use. We employ visual and exploratory approaches through a generalized additive model (GAM) to identify nonlinear relationships between travel outcomes and "D" variables (density, diversity, design, destination accessibility, and distance to transit) within centers. The model and plots help us recommend the built environment characteristics of centers.

Takeaway for practice: The built environment thresholds and relevant tools provided here can enable planners to make informed decisions about future growth patterns, set realistic—yet visionary—goals, and improve the overall health of its residents and communities. We provide strategies and tools that planning agencies, such as metropolitan planning organizations, transit agencies, and municipalities, can adopt to channel developments into centers.

Keywords: center, generalized additive model, polycentricity, regional transportation plan, travel mode choice

Since the early 20th century, the notion of *polycentricity* has been used to describe the urban landscape, but only recently have urban planners and policymakers turned to polycentricity as a possible solution for more sustainable development (Davoudi, 2003; Meeteren, Poorthuis, Derudder, & Witlox, 2016). The monocentric development pattern in the Alonso–Mills–Muth model underpinned theoretical discussions of urban form in the 1960s and 1970s (Alonso, 1964; Mills, 1972; Muth, 1969) and truly dominated theory up to the point when Joel Garreau published *Edge City: Life on the New Frontier* (1991). Monocentric development patterns remain dominant to this day among smaller metropolitan areas in the United States. However, for larger metropolitan areas in the United States, regional transportation plans suggest a paradigm shift to a polycentric structure.

Scholars agree that the incidences of polycentric urban structures are increasing (Anas, Arnott, & Small, 1998; Hall & Pain, 2009; Kloosterman & Musterd, 2001; Parr, 2004; Vasanen, 2012) and that this development form is likely here to stay (Garcia-López & Muñiz, 2010; Geppert, 2009). Yet as polycentricity has gained increasing recognition in both the literature and the field, the definition has become nebulous and vague (Davoudi, 2003; Hague & Kirk, 2003; Kloosterman & Musterd, 2001).

DOI: 10.1080/01944363.2019.1692690

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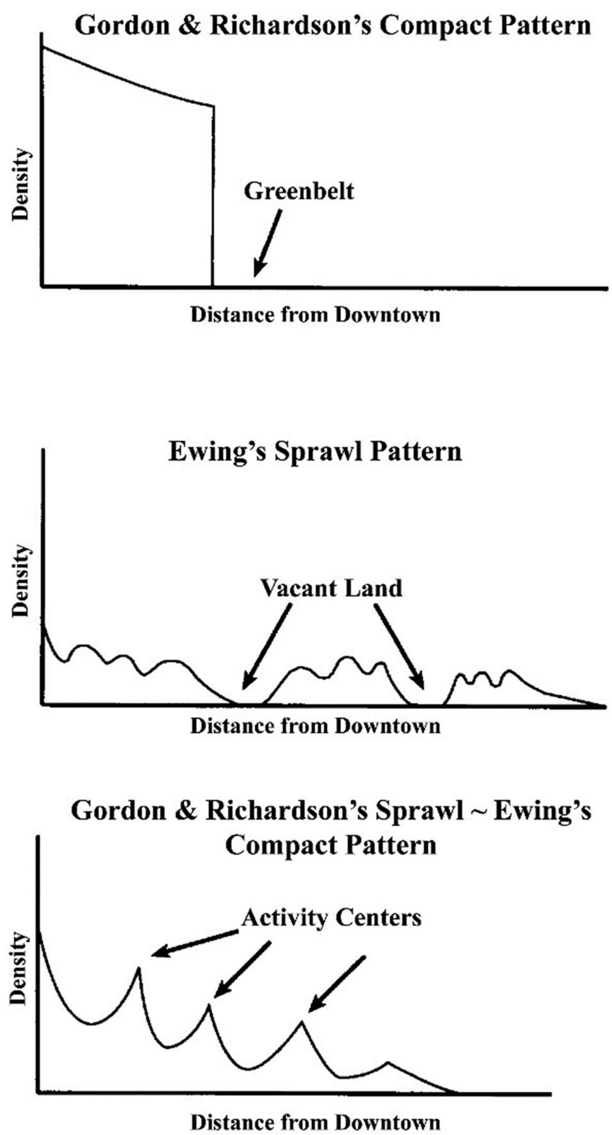

Figure 1. Three views of compact development and sprawl, in terms of urban density (adapted from Ewing, 1997).

The line between scattered development—a type of sprawl—and polycentric development may not be clear (Ewing, 1997; Figure 1). Typically and traditionally, the term has been applied to interurban spatial structure (i.e., a network of cities), but recently the concept has been applied to the intra-urban scale as well (multiple subcenters within an urban area; Davoudi, 2003). In 1997, in a point–counterpoint debate, Gordon and Richardson (1997) and Ewing (1997) continued to debate whether compact development was monocentric or polycentric and whether sprawl development was uncentered or polycentric (see Figure 1).

At the root of the intra-urban polycentric structure is compact development. If polycentric urban growth is going to be positive for cities, it must be anchored by compact centers that are dense, diverse, and accessible. Ewing (1997) made a case for polycentric development as the antidote to sprawling suburbs. Compact centers could encourage all of the things sprawl discourages: public health, environmental sustainability, and economic diversity (for a review of the literature on compact development and its impacts, see Ewing & Hamidi, 2015). Noting such benefits, cities and regions are strategically planning for and developing centers within their communities that would help them reach their goals of economic growth, community preservation, environmental sustainability, and connected transportation networks.

We refer to both the academic literature and regional transportation plans to extract a common definition of a center (see the next section). Generalizing, we define *centers* as the densest parts of a region, characterized by compact and mixed-use development, well-connected by a multimodal transportation network, and with more job opportunities than the areas around them. *Polycentric development* thus refers to a regional development pattern consisting of multiple centers that meet this definition.

Researchers often measure built environment characteristics of centers by "D" variables—density, diversity, design, destination accessibility, and distance to transit (Ewing & Cervero, 2010). Based on the body of travel behavior literature (Ewing & Cervero, 2010), one would expect to see more walking, biking, and transit use and less driving in these areas. But planners are left with a lack of empirical evidence on how much D variables are desired. How much density and land use diversity are enough in centers? How many jobs should be concentrated in centers? How well connected should a transit system be to centers? Answers to these questions are critical for planners to guide and regulate future development patterns.

We review 126 regional transportation plans in the United States and find that polycentric development is the dominant vision for most (see the next section). Although 90% of the plans mention centers, not all describe a hierarchy of centers that include criteria such as a peaking of employment density at multiple points in the region. What is missing from regional transportation plans, with very few exceptions, are quantitative criteria for designating centers: Only 20% get quantitative. In no case are the quantitative criteria empirically based on proven transportation benefits. This is the unique contribution of our results presented here.

In this study, we investigate how the built environment characteristics of centers are associated with people's travel choices, specifically with vehicle miles traveled (VMT) and mode choices (walk and transit mode choice). We use visual and exploratory approaches through a generalized additive model (GAM). GAM is used to identify nonlinear relationships between different travel choices and D variables within centers.

Our analyses and literature review show recommended values of built environment characteristics (i.e., D variables) including activity density (density), jobs–population balance (diversity of land use), intersection density and percentage of four-way intersections (design of street network), transit stop density (distance to transit), and percentage of regional job access (destination accessibility). These results provide practical implications and guidelines for planning and developing polycentric regions, especially via regional transportation plans. Context-specific strategies could help a region strategically develop centers and reach its goals of smart and sustainable growth.

Understanding Polycentricity

Although there have been many empirical studies on polycentricity since Harris and Ullman in 1945, there is no consistent definition of polycentricity, and its social, economic, and environmental impacts are not confirmed (Davoudi, 2003; Parr, 2004). In other words, polycentricity is defined differently for different purposes. For instance, Meijers and Romein (2002) define polycentric patterns at the regional level as "systems of historically distinct and both administratively and politically independent cities that are located in more or less close proximity and that lack a dominating city in political, economic, cultural and other aspects" (p. 1). Goess, de Jong, and Meijers (2016) argue that in polycentric urban regions, "several distinct cities, none of which is dominant, cooperate and compete with each other to attract inhabitants and firms" (p. 2036). Generally, polycentricity can be described at different spatial scales and, at the same time, different methodological perspectives: functional versus morphological.

In terms of spatial scales, researchers have examined polycentricity at the intra-urban, interurban, and interregional scales (Davoudi, 2003). An *intra-urban* polycentric structure contains multiple subcenters within a single built-up area (Gordon, Richardson, & Wong, 1986), whereas *inter-urban* is characterized by distinct cities connected in a network across a region (Dieleman & Faludi, 1998). Intra-urban studies have focused largely on U.S. cities, and interurban has been applied mostly to European settlements. *Interregional* polycentricity examines the effect across regions larger than a metropolitan area, including concepts like the "megacity" and "megapolitan" regions (Davoudi, 2003; Hall & Pain, 2009; Lang & Knox, 2009).

The debate surrounding polycentricity as functional versus morphological constructs has also not been resolved (Meeteren et al., 2016), and the more recent literature suggests that centers must have functional links between each other to be classified as polycentric (Vasanen, 2012).

Homing in on the functional dimensions, several economic forces could explain polycentric development (Giuliano & Small, 1991; McDonald, 1987). Davoudi (2003) points out that decentralized business activities, increased mobility, increased travel, and demographic changes rendered "the monocentric model increasingly irrelevant to the reality of urban growth patterns" (p. 981), thus making way for the development of polycentric regions. Central to this shift was the increased influence of agglomeration economies and activity clusters on population and employment distribution and, thus, spatial development (Davoudi, 2003; Krugman, 1993; McDonald, 1987; Porter, 2011; Scott, 1988). The correlation between population size and transportation costs was also theoretically demonstrated to cause subcenter creation (Fujita & Ogawa, 1982; McMillen & Smith, 2003). Gross employment density and the employment–population ratio were other measures used to identify subcenters (Anderson & Bogart, 2001; McDonald, 1987). Still, objective measures defining polycentricism are almost completely lacking in policy documents and plans (Masip-Tresserra, 2016), and evidence that polycentrism provides transportation benefits is in even shorter supply (Ewing & Hamidi, 2017).

In terms of quantitative criteria, Meijers and Sandberg (2008) argue that polycentricity should be measured by scoring an area with a value ranging from fully monocentric to fully polycentric. General morphological indicators are primacy: the ratio of people living in the main city over the total population in a region (e.g., ESPON, 2007), rank-size distribution (e.g., ESPON, 2005), and the urban centrality index (Pereira, Nadalin, Monasterio, & Albuquerque, 2013). Functional indicators include the entropy index based on commuting flows (Limtanakool, Dijst, & Schwanen, 2007) and the ordinary polycentricity index (Green, 2007). Studies have shown a positive association between morphological and functional perspectives of polycentricity (Burger & Meijers, 2012; Liu & Wang, 2016; Vasanen, 2012).

In an intra-urban polycentric structure, compact development is a key element. In fact, polycentric development is defined as a "decentralized compact" development (Tsai, 2005). The benefits of compact development are numerous, and many of these benefits are directly linked to transportation. The literature suggests that compact development is associated with increases in walking and transit use, reduced residential energy consumption, reduced pedestrian and motor vehicle fatalities, increased physical activity and reduced obesity, reduced household transportation costs, increased sense of community, increased upward social and economic mobility, increased social interaction and neighborliness, increased social capital, increased innovation capacity, and increased life expectancy (Ewing & Hamidi, 2015). But the presence and strength of centers is only one dimension of compact development in the most widely used measures of compactness versus sprawl (Ewing & Hamidi, 2017). Compared with development density, land use mix, and street connectivity, how important is polycentricity?

Several studies in European, Asian, and South American countries have revealed that living close to the city center means less travel than outer-area counterparts and more nonmotorized trips (e.g., Mogridge 1985; Næss, 2006, 2011; Næss, Røe, & Larsen, 1995; Zegras, 2010). However, in terms of commute time and distance, studies have reached mixed results. Some studies show that polycentricity can increase travel distance and time (Hu, Sun, & Wang, 2018; Schwanen, Dieleman, & Dijst, 2003; Zhao, Diao, & Li, 2017), whereas other studies claim the opposite (Modarres, 2011; Sun, He, Zhang, & Wang, 2016). By analyzing the performance of national spatial planning policies in The Netherlands, Schwanen, Dijst, and Dieleman (2004) find that policies related to concentrated decentralization and compact cities have stimulated the use of public transport, cycling and walking, and reduction in driving. More recent research has focused on Asian cities and continues to reflect the complicated nature of polycentricity. One study finds polycentric development may be increasing commute times and relevant externalities (Hu et al. 2018; Li, Xiong, & Wang, 2019), whereas another finds that a polycentric urban structure had shorter commute distances and low carbon dioxide (CO_2) emissions (Liu, Derudder, & Wang, 2018).

The challenge with studying polycentricity, how it develops, and its effects is still a lack of a clear and objective definition. And despite this lack of clarity, more than 75% of recent spatial plans for large metropolitan areas in Organisation for Economic Co-operation and Development countries consider it the best strategy for managing urban development while achieving sustainability, livability, and accessibility (Meeteren et al., 2016).

Polycentric Developments in Regional Transportation Plans

We review 126 regional transportation plans across the United States and analyze how centers are defined and proposed both qualitatively and quantitatively (Ewing & Bartholomew, 2018). These plans constitute a mixed sample. We started with a list of the 90 largest urbanized areas in the nation, went to metropolitan planning organization (MPO) websites, and retrieved regional transportation plans where posted. If plans were not posted, we dropped MPOs from the sample. As a result, we found 83 plans in 90 regions. To also include the far more numerous smaller urbanized areas (metropolitan areas smaller than 350,000 people), we pulled a random sample of small urbanized areas and repeated the process described above. The final sample includes 126 plans: 83 large regions and 43 small regions.

The regional transportation plan is a long-term plan (e.g., 30 years) for a region's transportation system, usually conducted every 4 or 5 years by an MPO. We searched the regional transportation plans for the keyword *centers*. More details on the method and outcomes are found elsewhere (Sabouri, Choi, Park, & Ameli, 2020). Our review shows that the term *center* is used in connection with various geographic levels: region, subregion, urban, city, town, community, and village. Alternatively, center is used to signify clusters of certain activities or functions: an area with single concentrated use, such as an employment center, transit center, residential center, or entertainment center. Generally, these plans describe a center as the densest part of an area characterized by compact and mixed-use development, multiple transit options, and employment opportunities.

Out of 126 regional transportation plans, nearly 90% (112 plans) mention at least one type of center. On the other hand, only 25 plans (20%) include any type of quantitative criteria for centers, and some of these indicators are overly broad. None has its basis in the empirical literature, relying instead on intuitive arguments. The quantitative criteria found in most of these 25 regional transportation plans cover four dimensions: employment density, residential density, total population or employment, and area size. Other less frequent indicators include land use mix, building design (e.g., floor area ratio), transit service, and street density.

Our review shows that although recognizing the multiple roles of centers in a region, regional transportation plans suffer from a lack of consistent indicators to designate centers and guide their developments. They lack criteria regarding minimum center densities and intensities of development; minimum population, employment, or land areas; target land use mixes; and recommended transit service types or levels. Without this type of roadmap, how does an MPO know when it "gets there"? Such absence and inconsistency may hinder planners from pursuing polycentric development and researchers from evaluating the effectiveness of the center-oriented strategies.

Data and Methods

Study Regions and Data

We identify the location of central business districts (CBDs) and centers in 28 metropolitan regions of the

Table 1. Household travel survey data in 28 regions.

No.	Region	Survey year	Number of households in survey	Number of centers	Trip ends (origins and destinations) within centers
1	Albany (NY)	2009	1,447	30	4,940
2	Atlanta (GA)	2011	9,574	17	7,980
3	Burlington (NC)	2009	594	3	5,566
4	Dallas (TX)	2009	2,869	15	16,682
5	Denver (CO)	2010	5,551	42	15,408
6	Eugene (OR)	2009	1,674	45	7,431
7	Greensboro (NC)	2009	1,966	30	16,446
8	Hampton Roads–Norfolk (VA)	2009	1,954	12	2,314
9	Houston (TX)	2008	5,276	5	1,602
10	Indianapolis (IN)	2009	3,777	50	19,570
11	Kansas City (KS–MO)	2004	3,022	37	4,222
12	Madison (WI)	2009	138	23	8,259
13	Miami (FL)	2009	1,402	10	4,035
14	Minneapolis–St. Paul (MN–WI)	2010	8,234	11	760
15	Orlando (FL)	2009	866	29	1,932
16	Palm Beach (FL)	2009	944	7	1,572
17	Phoenix (AZ)	2008	4,314	3	2,428
18	Portland (OR)	2011	4,509	2	1,157
19	Provo–Orem (UT)	2012	1,464	5	2,927
20	Richmond (VA)	2009	612	1	7,702
21	Rochester (NY)	2011	3,438	13	852
22	Salem (OR)	2010	1,668	12	926
23	Salt Lake City (UT)	2012	3,490	33	2,124
24	San Antonio (TX)	2007	1,563	76	4,902
25	Seattle (WA)	2014	4,954	26	3,108
26	Syracuse (NY)	2009	652	2	767
27	Tampa (FL)	2009	2,259	6	179
28	Winston–Salem (NC)	2009	1,459	44	17,696
	Total		79,670	589	163,487

United States (Table 1). For all 28 regions, we collected regional household travel survey data from MPOs or state departments of transportation with confidentiality agreements. A household travel survey, collecting households' daily travel diaries, is widely used to study people's travel behavior.[1] It is also the fundamental input for regional travel demand modeling and forecasting by MPOs across the United States. In the last 7 years, we have contacted more than 100 MPOs and collected household travel survey data. For this study, the *X/Y* coordinates of trip ends are needed to identify trips generated in centers. Not every region was willing to provide *X/Y* coordinates due to confidentiality concerns. We ended up with data for 28 regions. In addition to the survey, we collected other GIS data to compute the D variables, including socioeconomic information, street networks, transit stops, travel times among traffic analysis zones by auto and transit, and land use data at the parcel level. All of these supportive data were for the same years or close enough to the years that the household travel surveys were conducted.

Although carried out by individual organizations, the regional household travel surveys have quite similar structure and questions, akin to the U.S. Department of Transportation's National Household Travel Survey. To gather comprehensive data on travel and transportation patterns, the survey data consistently include, but are not limited to, household demographic information, vehicle information, and data about one-way trips taken during a designated 24-h period, including travel time, mode of transportation, and purpose of trip information. The survey data have exact *X/Y* coordinates, so we could geocode the precise locations of households and the precise origins and destinations of trips. The pooled data set consists of 745,275 trips generated by 79,670 households in the 28 regions (Table 1).

For the employment data, we use the Longitudinal Employer–Household Dynamics (LEHD) database (U.S. Census Bureau, 2015). The LEHD database is assembled by the U.S. Census Bureau and is available from 2002 to 2015 at the census block level and can be aggregated to any larger geography, in this case block groups. For this study, we downloaded and processed LEHD data for the year 2015. The data were aggregated to generate total employment by two-digit North American Industry Classification System code for each block group. In addition, to obtain the total population at the census block group level in 2015, we use 5-year (2012–2016) data from the American Community Survey (U.S. Census Bureau, n.d.). Note that our employment data from LEHD exclude federal employment, military jobs, self-employed workers, informally employed people, and several other specific classes of workers. In addition, our employment data are for 2015, whereas household travel data come from surveys of earlier years starting in 2004.

Identifying Centers: CBDs and Local Density Peaks

We identified centers in two steps: 1) We identified the location of CBDs in 28 U.S. regions using a local spatial autocorrelation technique and 2) we found the location of potential employment subcenters using geographically weighted regression (GWR). The spatial structure of metropolitan areas primarily depends on the location and distribution of employment subcenters within them. Employment subcenters are clusters of activities outside the traditional CBD large enough to influence real estate and thus the spatial form of nearby areas (Giuliano, Agarwal, & Redfearn, 2008). Cervero (1989) describes them as "secondary office and retail centers within their respective metropolitan markets" (p. 63).

First, to find CBDs among census block groups in each region, we used the spatial statistic local Moran's *I*. Local Moran's *I* is an indicator of the extent of significant spatial clustering related to the variable of interest (in this case, employment density) around each observation (see the Technical Appendix for more details). It can be used to locate hot spot block groups in a metropolitan statistical area in terms of the employment density. We ran the Moran's *I* analysis at the block group level for 28 regions using LEHD employment data. The cluster census block group(s) with the highest Moran's *I* value were considered candidates for the CBD location.

We then applied multistep criteria to minimize error and exclude cases that were not CBDs even though they had the highest cluster of employment density. There are clusters of block groups containing large organizations such as hospitals, malls, and university campuses. We excluded them from the analysis by considering the CBD as an area with no more than 75% in any single employment sector. As a result, we identified 35 CBDs in the 28 study regions.

Second, we used GWR to identify potential employment subcenters. The GWR approach, proposed by Brunsdon, Fotheringham, and Charlton (2010), is one of the most common nonparametric methods used in polycentricity studies. The GWR method estimates an employment density surface using only neighboring observations for any block group while giving more weight to the closer observations (see the Technical Appendix for more details). Our dependent variable is the employment density of a block group; the independent variable is the distance of the block group population centroid from the CBD. Then GWR identifies candidate subcenters as positive residuals of a nonparametric regression of the natural logarithm of employment density on distance from the CBD. The major advantage of GWR over a local spatial autocorrelation approach is that GWR takes into account the distance from the CBD in addition to the employment density. GWR thus qualifies local peaks that are far from the CBD even if they are not as dense as areas closer to the CBD.

The clusters of one or more block groups with the highest positive residuals—2.5 times greater than predicted values, the value validated in the Salt Lake City (UT) region with centers identified in a polycentric plan, the Wasatch Choice 2050 plan—were considered as our subcenter candidates. Using a procedure similar to that for the CBD analysis, we excluded cases containing large employment firms such as hospitals, shopping malls, and universities with more than 75% of the block group employment. We also excluded potential candidates if the ratio of employment to population was less than 1—fewer jobs than residents—or greater than 15, thereby requiring centers to have a mix of uses. If several block groups meeting the above criteria were adjacent to each other, we merged them into one center.

Using GWR methods, we identified a total of 589 centers in the 28 U.S. regions (Table 1). The final centers include both CBDs and local density peaks. The number of centers in each region varies from 1 (Salem [OR]) to 76 (Dallas [TX]), with an average of 21 per region. Out of 79,670 households included in the travel surveys, 1,506 households live within centers and 78,164 households live outside centers. Then, we extracted trip ends—trip origin or destination points—within centers and found

Table 2. The D variables.

D variable	Measurement in this study	Data source
Density	Activity density = Sum of population and employment per square mile	Metropolitan planning organizations
Diversity	1. Jobs–population balance = 1 − [ABS(employment − 0.2 * population)/(employment + 0.2 * population)], where ABS is the absolute value of the expression in parentheses 2. Entropy index = − [residential share * ln(residential share) + commercial share * ln(commercial share) + public share * ln(public share)]/ln(3), where ln is the natural logarithm	County tax assessors
Design	1. Intersection density = number of intersections/mi^2 2. % 4-way intersection = number of 4-way intersections divided by the total number of intersections	TomTom®
Destination accessibility	1. % of regional employment within 10 min by car = % of jobs that can be reached within 10 min by automobile (over total regional jobs) 2. % of regional employment within 30 min by transit = % of jobs that can be reached within 30 min by transit (over total regional jobs)	Metropolitan planning organizations
Distance to transit	Transit density = number of stops/mi^2	General Transit Feed Specification

Note: Revised from Ewing et al., 2015.

163,487 trip ends (an average of 278 per center). Figure A-1 in the Technical Appendix shows centers identified in the regional plan, Wasatch Choice 2050, in Salt Lake County and those identified in this study, which supports the validity of our approach.

Measuring Travel Outcomes and Built Environment Variables

For each trip end, we have both trip and traveler attributes: mode of transportation, trip length, trip purpose, age, driver's license, employment status, etc. We only include walking, transit, and auto trips in our analyses because bike and other modes only account for limited mode shares—1.65% and 1.56%, respectively—within the centers. Within 589 centers, we finally identified 163,487 trip ends: 19% walking, 7% transit use, and 73% driving.

Then, we assigned built environment characteristics of centers to each trip end. The built environment factors associated with travel behaviors are often referred as "5D" variables (Ewing & Cervero, 2010). Table 2 describes the measurements of D variables (see Appendix Table A-1 for more detailed descriptions). We compute built environment variables for each center.

Table 3 presents descriptive statistics for travel outcomes and D variables. Note that the sample size for VMT is smaller than other trip measures because, for that variable, we excluded non-auto trips (i.e., walk and transit trips). In addition, six centers have no trip ends in the surveys at all and thus were dropped.

Finding Desirable Values of D Variables: Generalized Additive Models

The objective of our study is to find desirable values of each D variable to minimize VMT and maximize walking and transit use associated with polycentric development. In most cases, a built environment variable is not linearly related to travel behavior. For example, the influence of doubling a residential density from 20 to 40 persons per acre on walk mode share may be different from—and probably bigger than—the influence of the same rate of change from 200 to 400 persons per acre. The latter may have rather negative impacts on walking if it leads to overcrowding and degraded walkability.

Descriptive statistics in Table 3 indicate some extreme values of D variables. For example, activity density ranges from 2.26 to 92,435, with an average of 11,084 (sum of population and jobs per acre); transit stop density varies between 0 and 361.54, with an average of 31.85 (per square mile). The existence of extreme values can affect the results of our correlational analyses by lowering the predictive power of a model. In addition, these outliers may be less relevant to the practical application of our models. After examining descriptive statistics and histograms and running an iterative process to find the best percentile value (see the Technical Appendix for more details), we replaced outliers with the 0.99th percentile value, a process called *winsorization* (Ghosh & Vogt, 2012; Yang, Xie, & Goh, 2011). As a result, for example, the maximum value of activity density is dropped from 92,435 to 49,585, the 99th quantile of the original variable.

Table 3. Descriptive statistics of travel outcome and built environment variables.

Variables	*N*	Mean	*SD*	Min.	Max.
Trip/traveler attributes					
Walk trip (1 = yes, 0 = no)	163,487	0.19	0.40	0	1
Transit trip (1 = yes, 0 = no)	163,487	0.07	0.26	0	1
Auto trip (1 = yes, 0 = no)	163,487	0.73	0.44	0	1
VMT	118,988	6.54	7.78	0	99.00
Senior (over 65 years old; 1 = yes, 0 = no)	163,487	0.16	0.37	0	1
Child (less than 15 years old; 1 = yes, 0 = no)	163,487	0.06	0.25	0	1
Driver's license (1 = yes, 0 = no)	163,487	0.59	0.49	0	1
Worker (1 = yes, 0 = no)	163,487	0.65	0.48	0	1
Trip purpose: home-based work (1 = yes, 0 = no)	163,487	0.16	0.37	0	1
Trip purpose: home-based other (1 = yes, 0 = no)	163,487	0.32	0.47	0	1
Trip purpose: non-home-based (1 = yes, 0 = no)	163,487	0.51	0.50	0	1
Center-level walk mode share (%)	583	6.21	10.01	0	100.00
Center-level transit mode share (%)	583	1.74	3.37	0	23.09
Center-level auto mode share (%)	583	92.05	11.77	0	100.00
Center-level VMT	583	6.35	3.13	0	31.67
Built environment attributes					
Activity density ((pop + emp)/mi^2)	583	11,084	10,800	2.26	92,435
Jobs–population balance	583	0.28	0.22	0.01	0.99
Entropy index	583	0.74	0.21	0.05	1.00
Intersection density (number of intersections/mi^2)	583	129.34	80.92	10.86	730.65
% of 4-way intersections	583	38.71	16.02	5.49	86.79
Transit stop density (number of stops/mi^2)	583	31.85	42.86	0.00	361.54
% of regional employment within 10 min by car	583	7.05	10.26	0.00	79.34
% of regional employment within 30 min by transit	583	18.42	20.07	0.00	91.15

We use GAMs to reveal a nonlinear relationship between each D variable and travel outcome. The GAM is a generalized linear model in which the linear predictor depends on the local smooth functions of some predictor variables (Hastie & Tibshirani, 1990). For example, a regression might be estimated between the two variables for some restricted range of values for each variable, and the process is repeated across the range of each variable while controlling for other explanatory variables. Then, we aggregate the series of local estimates by drawing a line to summarize the relationship between the two variables (Hothorn & Everitt, 2014; see the Technical Appendix for more details).

We ran two GAMs, one for mode choice and one for VMT. Mode choice is a categorical variable with three options—walking, transit, and automobile modes—and thus is modeled through multinomial logistic models (reference category: automobile). VMT, a continuous variable, was log-transformed to deal with the right-skewed distribution and modeled through a Gaussian GAM.

To control for variations among 28 regions, we estimated fixed-effects GAMs with regional dummy variables. We added a total of 27 dummy variables (with one region—Kansas City [MO]—as a reference group) but did not report individual region effects in the result tables. The *gam* function (*mgcv* package) in R 3.6.0 (R Core Team, 2019) was used to generate the GAMs. This enabled us to see whether the physical environment variables were nonlinearly related to travel outcomes such as mode share or vehicle use and where the tipping points maximizing sustainable travel behaviors were.

The multistep approach in this study has some limitations. First, despite the use of comprehensive, microscale data sets from 28 diverse regions, our samples are not completely random. Regional household surveys are not available for all regions in the United States, with a bias toward larger regions. Not all agencies share their survey results with *X/Y* coordinates of the trip ends. Next, although polycentricity applies to multiple scales such as regional center, urban center, and town

Table 4. Patterns of travel outcomes with regard to D variables from trip-level generalized additive models.

	Walking (reference: automobile)	Transit use (reference: automobile)	VMT
Activity density ((pop + emp)/mi^2)	High at around 20,000 Maximum at around 40,000	Maximum at between 20,000 and 25,000	Minimum at between 5,000 and 20,000
Jobs–population balance	Maximum at 0.5	No clear pattern	Low at >0.2
Entropy	No clear pattern	Maximum at <0.3	No clear pattern
Intersection density (number of intersections/mi^2)	Generally, the higher the better Maximum at around 300	Maximum at around 300 Also high at 150–200	Generally, the higher the better outcome (i.e., lower VMT) Minimum at around 300
% of 4-way intersections	No clear pattern	No clear pattern	Generally, the higher the better Minimum at >60%
Transit stop density (number of stops/mi^2)	Maximum at around 175 Also high between 25 and 75	Generally, the higher the better Maximum at around 175	No clear pattern
% of regional employment within 10 min by auto	No clear pattern	Maximum at around 30%	No clear pattern
% of regional employment within 30 min by transit	No clear pattern	Maximum at around 60%	Low at between 35% and 65% Also low at 5%

center, our study only identifies *center* in a general sense. The use of GWR enables us to find local employment density peaks that are far from the CBD even if they are not as dense as areas closer to the CBD. A further analysis, such as clustering, may differentiate centers in a hierarchy.

We also acknowledge a degree of subjectivity in our choice of numerical criteria to distinguish centers from other concentrations of employment. There is no generally accepted operational definition of a center. We are creating one in this study and documenting its validity in two ways: by showing the 1) transportation benefits of polycentric development and 2) overlap with the polycentric plan of the Wasatch Front Regional Council.

Analyzing Nonlinear Relationships Between Travel Outcomes and Built Environment Variables in Centers

GAMs show how travel outcomes—mode choice and VMT—are related to the built environment characteristics of centers when we control for trip-related variables. Figures A-2 to A-4 in the Technical Appendix show GAM plots. In sum, several D variables—activity density, jobs–population balance, intersection density, transit density, and regional job accessibility (*pctemp30t*)—have significantly nonlinear relationships with travel outcomes (Table 4). Mostly, they show an optimal range that maximizes the likelihood of walk and transit mode choice and minimizes driving distance. This finding can inform guidelines for polycentric developments in regional plans, policies, and regulations.

Table 4 shows that when controlling for other trip-related and D variables, the likelihood of walk mode choice over driving becomes maximized at 40,000 activity density (sum of population and jobs per acre; secondarily at around 20,000), 0.5 jobs–population balance, around 300 intersection density (per square mile), and around 175 transit stop density (per square mile). The likelihood of riding transit over driving becomes highest at 20,000 to 25,000 activity density, less than 0.3 entropy index, around 300 intersection density (secondarily at 150–200), around 175 transit stop density, around 30% regional job access in 10 min by car, and around 60% regional job access in 30 min by transit. Last, VMT is likely to be minimized at 5,000 to 20,000 activity density, more than 0.2 jobs–population balance, around 300 intersection density, more than 60% four-way intersections, and 35% to 65% of regional job access in 30 min by transit (secondarily at 5%), when controlling for other effects.

Table A-1 in the Technical Appendix shows two GAMs. All trip and traveler attributes except for employment status in the transit mode model are associated with the outcome variables at a statistically significant level ($p < .001$). If a person is a senior or a child, she or he is more likely to use an automobile—either driving or riding—but maybe for a shorter distance (i.e., lower VMT). The likelihood of walking and transit use also decreases with driver's license and if the trip is home based. On the other hand, home-based trips are related to longer driving distance.

Recommended values of D variables may be related to the second highest (or second lowest for VMT) likelihood of the specific travel outcome, if it would be more feasible to be realized. For example, in Table 4 and Technical Appendix Figure A-2, although

Table 5. Recommendations for built environment characteristics of centers.	
Built environment variables	**Recommendations**
Activity density ((pop + emp)/mi^2)	10,000–25,000 (according to center type)
Jobs–population balance	Minimum 0.2–0.5 (according to center type)
Intersection density (number of intersections/mi^2)	Minimum 150–300 (according to center type)
% of 4-way intersections	Minimum 60%
Transit stop density (number of stops/mi^2)	Minimum 25 (small center) or 150 (large center)
% of regional employment within 30 min by transit	Minimum 5% (small center) or 35% (large center)

the probability of walking becomes maximized at 40,000 activity density, 20,000 activity density (32 per acre) also shows such a strong association with walk mode choice; thus, it may be more desirable.

Based on our analyses and literature review, we provide regional and local planners with recommendations for achieving polycentricity and its benefits (Table 5). For successful centers, we recommend 10,000 to 25,000 activity density (16–40 population and jobs per acre; varying by center type), a minimum of 0.2 to 0.5 jobs–population balance, a minimum of 150 to 300 intersections per square mile, more than 60% of four-way intersections, more than 25 or 150 transit stops per square mile (according to center type), and a minimum of 5% or 35% of regional job access within 30 min by transit (according to center type). Note that one of the land use diversity variables, entropy, is not strongly associated with any travel outcome in centers and thus we have no specific recommendation. Neither is the percentage of regional job access within 10 min by automobile. In the literature, however, the entropy index and regional job accessibility variable are found to encourage walking and transit use and discourage vehicle use (Ewing & Cervero, 2010; Ewing et al., 2015).

Implications for Planners to Achieve Polycentricity

In this study, we use a nontraditional statistical model—GAM—to explore nonlinear relationships between D variables and travel outcomes to find desirable values minimizing VMT and maximizing walking and transit use associated with polycentric developments. By relaxing the assumption of linearity between independent variables and a dependent variable, GAM plots show the tipping points of individual built environment variables, maximizing the likelihood of walk/transit mode choice or minimizing vehicle use.

The research findings in this study can contribute to polycentric urban development in two ways: by identifying existing and potential centers and by establishing development guidelines for centers. In most polycentric developments we reviewed, identifying existing or emerging centers precedes establishing center development strategies, but the lack of empirical evidence makes practitioners rely on intuitive arguments and reach to ambiguous goals. For the efficient development of centers, plans first need to identify potential locations of centers and maximize the use of current land use regulatory systems. In this regard, our findings provide empirically driven guidelines of center designation that can be shared across MPOs, transit agencies, and municipalities.

To be eligible for regional investments in a center, a city or county could establish a boundary for its centers and perform a comprehensive assessment of the (existing or potential) centers, including D variable computation; a market analysis; assessment of regulatory barriers to mixed-use, pedestrian-friendly, and transit-supportive development; and an analysis of the development code with respect to each of the above. Although many planners use local knowledge to prioritize areas for center development, the knowledge of practitioners may vary in area size, boundaries, and development patterns. Without empirical evidence, it may be challenging to reach consensus on how much area should be considered a center, how a center boundary should be delineated, and what urban structure should be preserved or changed. The suggested quantitative criteria would help to arrive at such agreements.

Second, our research findings can help planners establish polycentric development goals and monitor the development progress. Once regional plans identify the different scales of centers within their boundary, local planning authorities may establish zoning ordinances directing desirable development patterns, including housing investments, government services, arts and culture, accessibility, connections, and green infrastructure in and between centers. In doing so, setting desirable built environment goals is critical. Centers should maintain the center-like built environment characteristics but also avoid overdevelopment or overcrowding. Using, or adjusting if necessary, the targeted built environment values, planning agencies can quantify the progress being made in the region to concentrate growth in centers and describe in detail how the designated centers have achieved the goals over time (e.g., the State of the Centers report in Portland [OR]; Oregon Metro, 2011). This helps to measure progress in creating the type of centers envisioned in the regional plans and to illustrate the kind of investments that contribute to a successful center.

Polycentric development requires high-quality transit connections between centers. Coordinated efforts between a transit agency, an MPO, and municipal governments will help to manifest the region's polycentric growth. This coordination may include the development of new capital projects and fixed-guideway transit lines, the concentration of resources to specifically designated corridors in the form of high-frequency service, and the acquisition and retention of important real estate.

Transit agencies or the state department of transportation could provide grants for projects near transit to encourage denser development than developers would otherwise build. When transit-adjacent projects qualify, a transit-oriented development program may provide funding and support to increase the density of these projects. Funding amounts may be based on the projected increase that such density would have on transit ridership. A program of this sort is run by Tri-Met, the transit operator for the Portland metropolitan area (Ewing et al., 2019; Oregon Metro, 2019).

An essential element for maintaining transit ridership is creating an environment that is safe and convenient for other active transportation modes, because transit trips often start with walking and bicycling. Planning agencies would need to urge cities and counties to extend the reach of transit by creating a more walkable and bikeable environment that connects well to transit lines in a first-mile, last-mile priority scheme. First-mile, last-mile priority schemes operate throughout the United States and feature wayfinding strategies, local transit, carsharing and ridesharing services, microtransit, rezoning for infill development, and streetscape, something municipalities can do in coordination with transit operators (Utah Transit Authority, 2015).

Comprehensive plans of municipalities are critical to achieving polycentric development as a planning guide for defining future land uses and development. Aligned with a regional plan such as a regional transportation plan, a comprehensive plan may first identify the different scale of centers—central city, regional center, town center, etc.—within its jurisdiction boundary. Zoning is the pre-eminent tool to direct development patterns through comprehensive plans and planning practice. Providing zones with high allowances for intensity (e.g., dense multidwelling residential development, mixed-use development, and high-intensity commercial development) gives planners the ability to direct growth to already designated centers, limiting sprawl and consumptive development patterns (Levine, 2006; Talen, 2013).

In addition to the above-mentioned strategies, a recent review of literature on growth management effectiveness suggests that all of the following can be used by planners to channel development into desired areas: urban containment policies, upzoning, density bonuses, transfer and purchase of development rights, tax increment financing, priority funding areas, graduated impact fees, and concurrency and adequate facilities ordinances (Lyons et al., 2020). If polycentric development is desired, these regulatory and financial tools should be able to help channel growth into centers. For example, Montgomery County (MD) uses most of these tools in its growth management efforts (Montgomery County, 2015).

A further analysis, such as clustering, may differentiate centers in a hierarchy; then, a specific guideline for center designation and development may be based on not only our general recommendations for the D variables but also the existing built environment condition of centers in each region, contextual knowledge, and best practices in regional transportation plans, especially in comparable regions. We also acknowledge that there are other criteria beyond transportation outcomes that should be part of center designation in specific regions. Guidelines should be context specific with input from local planners and policymakers, as is already the case in the regional transportation plans we reviewed.

Concluding Remarks

A polycentric urban structure has the potential to encourage and support smart and sustainable growth. Rather than continuing the expanse of low-density development radiating from an urban core, cities could invest in central nodes and transit connections. The result would be centers—compact nodes servicing a wider area—spread across a region and connected through quality transit corridors. Centers can vary in scale—for example, rural areas have small town centers, metropolitan areas house regional centers and multiple city centers—but each would provide public services, housing, employment opportunities, and recreational experiences for the surrounding population, and each would be functionally connected to the other centers, creating a true polycentric network (Burger, De Goei, van der Laan, & Huisman, 2011; Green, 2007; Hall & Pain, 2009). Context-specific strategies could help the region strategically develop centers within its communities and reach its goals of economic growth, community preservation, environmental sustainability, connected transportation networks, and air quality improvement, to name a few.

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RESEARCH SUPPORT

This research was funded by the National Institute for Transportation and Communities (NITC), Utah Department of Transportation, Utah Transit Authority, Wasatch Front Regional Council, and Mountainland Association of Governments. NITC is a program of the Transportation Research and Education Center at Portland State University and a U.S. Department of Transportation University Transportation Center.

SUPPLEMENTAL MATERIAL

Supplemental data for this article can be accessed on the publisher's website.

NOTE

1. A household travel survey is a report of individual trips made by household members over a 24-h period. Trips are coded by household member number, purpose of trip, place of origin and destination, means of transportation, time of day, time spent in travel, and so forth. A travel diary is just the compilation of trips for an individual household member.

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