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Off the Grid ... and Back Again?

The Recent Evolution of American Street Network Planning and Design

Geoff Boeing 

ABSTRACT

Problem, research strategy, and findings: In this morphological study I identify and measure recent nationwide trends in American street network design. Historically, orthogonal street grids provided the interconnectivity and density that researchers identify as important factors for reducing vehicular travel and emissions and increasing road safety and physical activity. During the 20th century, griddedness declined in planning practice along with declines in urban form compactness, density, and connectivity as urbanization sprawled around automobile dependence. But less is known about comprehensive empirical trends across U.S. neighborhoods, especially in recent years. Here I use public and open data to examine tract-level street networks across the entire United States. I develop theoretical and measurement frameworks for a quality of street networks defined here as griddedness. I measure how griddedness, orientation order, straightness, 4-way intersections, and intersection density declined from 1940 through the 1990s, while dead-ends and block lengths increased. However, since 2000, these trends have rebounded, shifting back toward historical design patterns. Despite this rebound, when controlling for topography and built environment factors, all decades after 1939 are associated with lower griddedness than pre-1940 decades. Higher griddedness is associated with less car ownership—which itself has a well-established relationship with vehicle kilometers traveled and greenhouse gas emissions—while controlling for density, home and household size, income, jobs proximity, street network grain, and local topography.

Takeaway for practice: Interconnected grid-like street networks offer practitioners an important tool for curbing car dependence and emissions. Once established, street patterns determine urban spatial structure for centuries, so proactive planning is essential.

Keywords: street grid, street networks, transportation, urban form, urban morphology

... they spent two hours in this strikingly American town [Salt Lake City], built on the pattern of other cities of the Union, like a checker-board, "with the sombre sadness of right-angles," as Victor Hugo expresses it. The founder of the City of the Saints could not escape from the taste for symmetry which distinguishes the Anglo-Saxons.—Jules Verne, *Around the World in Eighty Days* (1873/2004)

The orthogonal grid was the primary mode of geometric spatial ordering in U.S. cities from the 18th century through the early 20th century, with only occasional exceptions, such as the picturesque movement in suburban design (Southworth & Ben-Joseph, 1997). But during the 20th century, new automobile-centric transportation technologies and engineering standards emerged to organize new cities and suburbs according to radically different spatial logics (Jackson, 1985; Wheeler, 2008). Around World War II, the automobile's popularity—and urban planning's responses to it—had gradually reached a tipping point. Planners and engineers tried to accommodate shifting cultural

preferences and mobility patterns through a new street network design paradigm predicated on winding loops, cul-de-sacs, and automobile-oriented suburbanization (Hayden, 2004; Southworth & Ben-Joseph, 1995). As griddedness, connectivity, and density declined, block sizes and street circuitry grew. The resulting sprawl shapes American life today (Forsyth & Southworth, 2008).

Hundreds of studies in recent decades have identified the role that street network design plays in travel behavior, public health, and environmental sustainability. Traditional patterns, such as fine-grained interconnected grids, are associated with higher rates of active transportation and less driving. But after a century of building cities around the spatial logic of the automobile, planners today face car-oriented crises in public safety, physical inactivity, traffic congestion, and rising environmental pollution and greenhouse gas emissions. This is of enormous importance to planning practice, which sits at a critical leverage point to shape these outcomes. In the past 25 years, planning scholars and prominent practitioner groups such as the Congress for

the New Urbanism (CNU) have highlighted the links between physical planning and these transportation and environmental crises. How has U.S. planning practice responded to these calls?

In this study I offer a comprehensive empirical analysis of all U.S. streets to analyze these trends at neighborhood scales. I explore how U.S. street network design has changed over time, especially in recent years, and consider what this means for automobility and its second-order effects. This study makes two primary contributions. First, it measures exactly how street network design grew more coarse grained, disconnected, and circuitous nationwide over the 20th century before rebounding in the past 20 years, offering a new scorecard to assess planning practice's progress toward public health and sustainability goals. Second, it identifies new relationships between vintage, urban form, and car dependence while employing previously underused but essential topographical controls. To accomplish this, I develop a theoretical and measurement framework for street network griddedness as well as several new urban form vintage estimation methods and algorithms.

In sum, this study provides a new quantitative post-war history of American street network geography nationwide at the local scale. First, I review street patterns in planning history and the literature on network design, sprawl, sustainability, and travel. This literature identifies the advantages of interconnected grids and traces the evolution of network design through primarily historical and case study research, but it tells us less about nationwide empirical patterns and little about recent developments.

In this study I pick up this research thread to take a deeper look. I use computational big data methods to model the street networks and vintage of every U.S. census tract, collectively comprising approximately 19 million intersections/dead-ends and 24 million street segments. This offers a new glimpse into the spatial outcomes of planning practice and a critical empirical assessment of its recent directions. In particular, it reflects on what planners can do to continue the promising nascent trend toward more sustainable urban forms. Retrofitting existing suburbia offers one opportunity but can be challenging because road networks and land parcels create strong path dependence (Boarnet et al., 2011; Dunham-Jones & Williamson, 2011). Ongoing greenfield development, infill projects, and targeted redevelopment offer practitioners important opportunities to plan proactively for a more sustainable urban future. Street network design cannot merely reflect short-sighted transportation paradigms: Due to its near-permanence, planners must carefully plan for decades or centuries of travel behavior, flexibly and sustainably.

Background

Defining the Grid

Street networks provide a physical substrate and connective tissue that organize a city's human dynamics. A street network's pattern, configuration, and grain reflect prevailing technologies, design paradigms, politics, power, terrain, and local cultural and economic conditions (Rose-Redwood & Bigon, 2018). The grid is the world's most ubiquitous planned pattern. From Hippodamus's urban design of Piraeus in ancient Greece, to the Spanish Crown's colonial Law of the Indies, to the New York Commissioners' Plan and Salt Lake City's (UT) Plat of Zion, the classic street grid has been used for millennia to impose urbane order on the landscape, to streamline transportation systems, to make land legible to speculation and development, and to organize the city democratically or around symbols of power and spaces of control (Grant, 2001; Groth, 1981; Kostof, 1991; Marcuse, 1987; Martin, 2000; Scheer, 2017).

The word *grid* first appeared in English in 1839 as a back-formation of *gridiron*, a metal grate traditionally used to broil food over an open flame (Oxford University Press, 1989). Its composition of parallel and perpendicular bars has inspired centuries of appropriation for similar geometric patterns, such as the playing field in American football and the design of certain street networks. Much like the gridiron from which its etymology arises, the classic street grid consists of a set of streets characterized by three properties: orientation order, straightness, and 4-way junctions. That is, to be a grid, a street network must have an internally consistent orientation, be relatively straight, and primarily comprise 4-way intersections instead of 3-way "T" junctions or dead-ends. Each of these components is necessary but alone insufficient for griddedness. Only in unison do they make a street grid, as illustrated by Figure 1.

American Street Network Patterns

The grid has a long history in the United States. Some pre-Columbian gridded patterns likely existed, but Spain's 1573 Law of the Indies spread urban grids throughout its American colonies by systematizing the design of rectilinear street networks around central plazas (Low, 2009; Rose-Redwood & Bigon, 2018; Wheeler, 2015). Beyond the Spanish model, other prominent colonial urban grids include Penn's 1682 plan of Philadelphia (PA) and Oglethorpe's 1733 plan of Savannah (GA).

Two years after America won its independence, Thomas Jefferson and his Age of Enlightenment associates drafted the Land Ordinance of 1785 followed by the Northwest Ordinances of 1787 and 1789, dividing the American frontier into a regular grid of townships

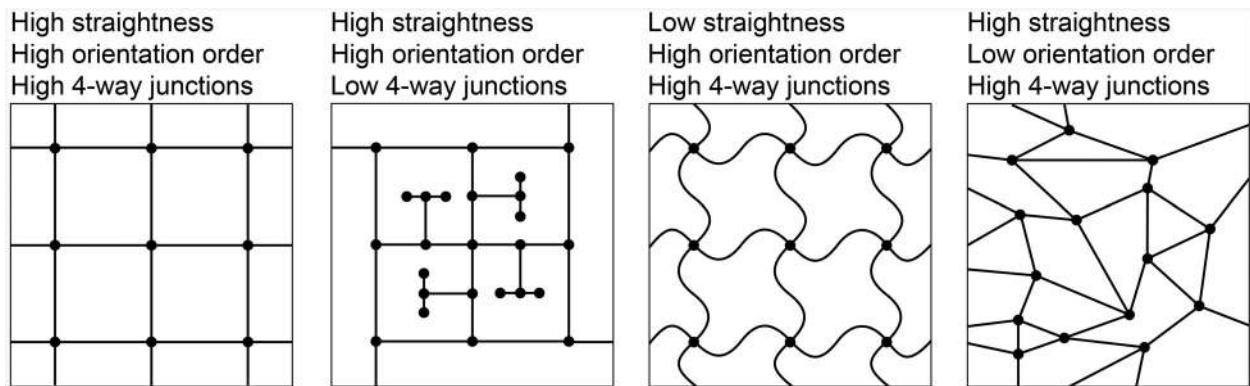


Figure 1. Street grids. Theoretically, a street grid has an internally consistent orientation, is relatively straight, and comprises mostly 4-way intersections. Each of these three characteristics is necessary but alone insufficient: only in unison do they make a street grid.

and parcels that shaped subsequent U.S. expansion (Jacobson, 2002). This rationalist-utopian ideal culminated in the U.S. Homestead Act of 1862, which partitioned the Midwest and Great Plains into square miles subdivided into 160-acre quarters to promote rapid westward expansion, settlement, standardization, transportation, legibility, and a sense of civilization in the wilderness (Grant, 2001; Jackson, 1985; Sennett, 1990). To lay out local transportation networks and parcel land, town planners adopted these pre-existing orthogonal spatial frameworks or reoriented them to the local terrain. U.S. town planning subsequently evolved through eras of fine-grained grids, rectangular streetcar suburbs, and later degenerate grids (Southworth & Owens, 1993; Wheeler, 2015).

These models of gridded spatial order prevailed into the 20th century, until the close of the 1930s marked a rupture between traditional urbanism and modern automobile dependence. Just a decade earlier, experimental gestures toward the new urban future had appeared: In 1929, Clarence Perry published his neighborhood unit concept—an influential model of physically segregated communities (Lawhon, 2009)—and the first residents moved into Radburn (NJ), a vanguard town for the motor age (“First Settlers Move Into Radburn Homes,” 1929). Catering to shifting public preferences and burgeoning automobile adoption, these experiments in a new kind of urbanism for a modern society proved wildly successful by the end of the 1930s. Within a few years they had become the mainstream of American urbanization, exemplified by the 1940s’ car-centric, segregated Levittown (NY) and its derivatives that proliferated in the wake of World War II (Jackson, 1985).

As America suburbanized around the automobile, new technocratic institutions like the Federal Housing Administration and Institute of Transportation Engineers (ITE)—both founded in the 1930s—reshaped its spatial

form (Southworth & Ben-Joseph, 1995), as illustrated by Figure 2. The Federal Housing Administration underwrote developers’ bank loans, but to be deemed a sound investment the proposed subdivision had to adhere to aesthetic standards that—explicitly inspired by Perry and Radburn—embraced automobility and abandoned the grid. Meanwhile, the ITE sought to tame ballooning traffic through geometric design. In 1939, the federal government tasked the ITE with developing its first of many road engineering handbooks. As one such example, ITE’s influential 1965 *Recommended Practices for Subdivision Streets* directed planners and engineers to internally disconnect street networks, avoid 4-way intersections, and adopt curving loops and cul-de-sacs.

Yet traffic and sprawl swelled unabated, and it was not until the 1990s to the 2000s that institutionalized street design standards began to emphasize neotraditional compactness and connectedness.¹ Southworth and Ben-Joseph (1997) trace these radical overhauls of street network ideology through morphological eras of interconnected grids (ca. 1900s), fragmented grids (ca. 1930s), warped parallels (ca. 1940s–1960s), “loops and lollipops” (ca. 1960s–1970s), “lollipops on a stick” (ca. 1980s–1990s), and turn-of-the-millennium neotraditionalism.

Street Network Design: Values and Impacts

The grid fell out of favor during the 20th century in both theory and practice. Modernist polemics decried it as the fountainhead of urban suffering (Kostof, 1991). Mumford (1961) argued that its monotony annihilated all rapport with the local environment, merely commodifying land for endless expansion without any hierarchical or functional order. Meanwhile, planning practice shifted away from dense, interconnected, gridded street networks in a bid to simultaneously attenuate the

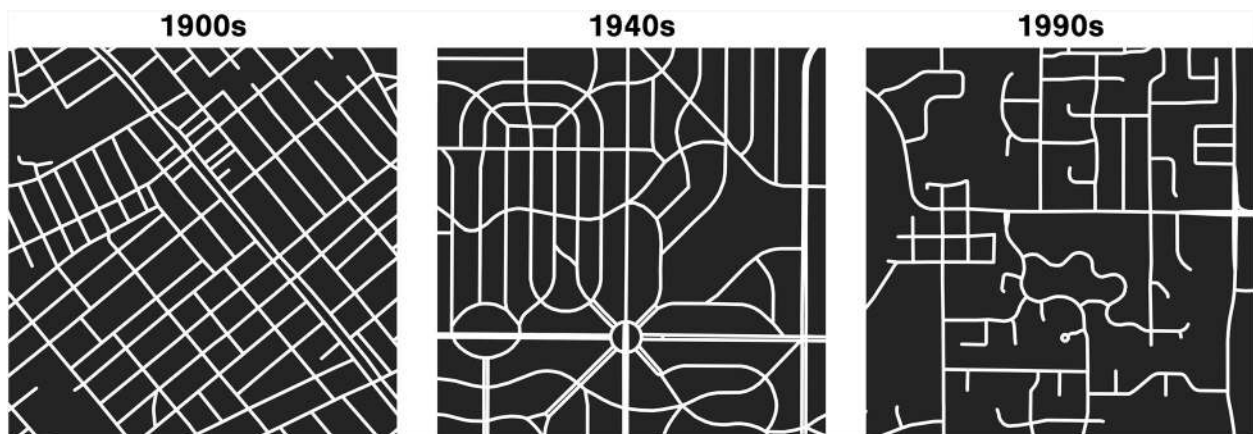


Figure 2. Real-world street network patterns from different decades. 1900s: interconnected, imperfect grid. 1940s: increasingly circuitous car-centric suburbs. 1990s: disconnected, dendritic, car-dependent sprawl.

automobile's negative externalities (e.g., noise, pollution, streetscape blight, congestion, mortality) in residential communities while still empowering the populace to travel by car because it was fast and convenient (Flink, 1990). But the subsequent development of disconnected, coarse-grained neighborhoods discouraged nonmotorized trips, stymied mass transit provision, and exacerbated car dependence and its negative externalities.

Despite their abandonment during the motor age, street grids have been reappraised in recent decades. Grids lend themselves to navigation and legibility (Lynch, 1960; Sadalla & Montello, 1989); the organization of symbolic, important, and memorable places (Kostof, 1991; Lynch, 1984); platting and extension (Ellickson, 2013; Grant, 2001; Lai & Davies, 2020); efficient transportation (Institute of Transportation Engineers, 2010); comfort and wind mitigation (Kenworthy, 1985); and adaptability to technological change (Jackson, 1985). In conjunction with supportive streetscaping, density, and land use mix, the grid's interconnectedness supports route choice, access, and the human dynamics of social mixing, activity, and encounter (Alexander, 1965; Forsyth & Southworth, 2008; Groth, 1981; Guo, 2009; Jacobs, 1995; Moudon & Untermann, 1991; Zhu et al., 2020). Grids support active travel by providing pedestrians relatively direct routes across the network, without needing to navigate circuitously around cul-de-sacs and disconnected blocks. They also support public transit: Buses cannot efficiently route through dead-end-dominated neighborhoods, and bus routing should involve few turns for operational efficiency and user navigability (Brown & Thompson, 2012).

Today urban planners work in cities choked with automobile gridlock, face intertwined public health crises from physical inactivity and environmental pollution, and struggle to impede climate change. Physical design matters for several reasons. More-connected street

networks—of which grids are the ultimate example—are associated with lower rates of vehicle ownership and reduced greenhouse gas emissions (Barrington-Leigh & Millard-Ball, 2017) as well as increased walkability (Adkins et al., 2017; Hajrasouliha & Yin, 2015). In their classic paper, Cervero and Kockelman (1997) argue that higher proportions of 4-way intersections and grid-like patterns are associated with reduced single-occupancy vehicle travel. Ewing and Cervero (2010) identify a relatively large elasticity of vehicle kilometers traveled (VKT) with respect to design metrics such as intersection density and street connectivity (compare with Salon et al., 2012; Stevens, 2017). Street network design also affects travel behavior and safety (Boer et al., 2007; Braza et al., 2004; Dumbaugh & Li, 2010; Ewing & Handy, 2009; W. Marshall & Garrick, 2010; W. Marshall et al., 2014). Yet once street networks are initially built, they remain a semipermanent city backbone that is difficult to change (Bertaud, 2018; Scheer, 2001; Xie & Levinson, 2009). Their initial planning and design thus lock in circulation patterns and needs for decades.

These planning processes exist today within broader sustainability contexts that shape practice (Meerow & Woodruff, 2020). For example, the smart growth movement and the CNU promote compact, connected development for more sustainable, healthy communities (Talen & Knaap, 2003). The Leadership in Energy and Environmental Design for Neighborhood Design (LEED-ND) certification system—developed in part by CNU—rates neighborhoods on sustainable design, including criteria such as street network patterns, compactness, and connectivity (Ewing et al., 2013; Szibbo, 2016). Although various global, national, and local institutions now call for a return to traditional network patterns as a pillar of urban sustainability, we know little about recent implementation and effects. Accordingly, research examining street network design

trends can provide important monitoring and evaluation of planning outcomes.

Most research on street network evolution uses idealized theoretical models, individual case studies (e.g., Strano et al., 2012; Wheeler, 2003), or small-sample cross-sectional analyses (e.g., Mohajeri & Gudmundsson, 2014; Southworth & Owens, 1993). Less is known comprehensively and empirically about trends in neighborhood-scale street network design across the entire United States. Recent work by Barrington-Leigh and Millard-Ball (2015) offers a valuable exception, exploring how urbanized areas' average node degrees (i.e., the number of streets connected to each intersection/dead-end) evolved over time, using U.S. Census Bureau TIGER/Line shapefiles and a sample of U.S. counties. They estimate street network vintage in multiple ways, including as residences' median year built in each unit of analysis. In this study I build on this past work by analyzing every census tract across the United States, estimating vintage in several new ways, and analyzing several new indicators of street network design and sprawl.

Methods

Given the literature's theorized importance of griddedness, density, and connectivity on travel behavior and VKT, I ask the following questions. 1) How have griddedness, density, and connectivity outcomes changed in planning practice during the postwar era of ubiquitous automobility and, particularly, how have they trended in recent years? 2) Controlling for income, commute length, home and household size, local topography, and street network density and grain, what is the relationship between griddedness and car ownership? To answer these questions, I develop new methods to identify and measure griddedness and estimate urban form vintage algorithmically using open data.

Data Collection

In this study I examine the street network of each U.S. census tract ($N = 74,133$) in terms of its vintage. I use tracts to capture urban patterns at a roughly neighborhood scale, better reflecting how development occurs piecemeal over time than municipal or metropolitan scales would. Tracts are drawn to be reasonably homogenous and consistent over time and generally follow real-world social and physical boundaries. They thus provide sensible spatial units for examining street network "chunks" and related socio-demographic and built environment characteristics from administrative data.

To construct the tract-level street network models, I used OSMnx (Boeing, 2017) to download data from OpenStreetMap, a high-quality worldwide mapping

project and geospatial data repository (Basiri et al., 2016; Maier, 2014). I then assembled these data into undirected network models, where nodes represent intersections and dead-ends and edges represent the street segments that link them (for network modeling details and data repository, see Boeing, 2019b). These models collectively comprise approximately 19 million nodes and 24 million edges. OSMnx then attaches elevation to each node and calculates each street's grade (i.e., incline).

I then downloaded 2018 U.S. Census Bureau American Community Survey (ACS) tract-level data on built environment characteristics, demographics, and vehicles per household (see Table 1 for variables). Finally, to identify tract vintage, I downloaded from the ACS each tract's proportion of residential structures built before 1940 and in each decade since 1940.² These variables report the proportion of structures that were first constructed (not remodeled or converted) in each decade, as discussed further below.

Typical quantitative analyses of urban form measure street networks in terms of density, connectivity, and block lengths or areas (Boeing, 2020; Clifton et al., 2008; Fleischmann et al., 2020; Knight & Marshall, 2015; S. Marshall, 2004; Porta et al., 2014; Song & Knaap, 2004; Song et al., 2013), all of which are operationalized in this study. Once the street network models had been constructed and the census data downloaded, several tract-level indicators were calculated: intersection density, average street segment length, average node degree, node elevation interquartile range (IQR, a proxy for hilliness; i.e., how much variation exists in a tract's elevation), the proportion of nodes that are 4-way intersections, the proportion of nodes that are dead-ends, and whether a tract is urban or not (i.e., population density $\geq 1,000$ persons per square mile, following U.S. Census Bureau convention).

Calculating the Grid Index

Next, I constructed a composite grid index to equally weigh the three components of griddedness identified theoretically in the background section and shown in Figure 1: straightness, orientation order, and the proportion of 4-way intersections. Technical details appear in the Technical Appendix, but I summarize these components and the index creation process here.

First, *straightness* is the ratio of the average great-circle distance between each street segment's end-points and the average length of the street segment itself. Thus, straightness measures how closely the tracts' streets approximate straight lines.

Second, *orientation order*, developed in detail in Boeing (2019a) and illustrated in Figure 3, measures the relative internal consistency of the streets' orientations.

Table 1. Variables used in the study.

Theme	Variable	Description/units
Griddedness	Grid index	Composite index of orientation order, straightness, and 4-way intersection proportion
	Orientation order	Extent to which the streets align in the same directions as each other
	Straightness	How straight the streets are on average
	4-way intersect proportion	Share of nodes that are 4-way street junctions
Settlement density/scale	Land area	Land area in 1,000s of square kilometers
	Population density	1,000s of persons per square kilometer
	Single-family detached home proportion	Proportion of housing stock that is single-unit detached
	Median rooms per home	Median number of rooms per housing unit
Street network scale/connectivity	Intersection density	Number of street intersections per square kilometer of land area
	Mean street segment length	Average street segment length between intersections/dead-ends, in meters
	Dead-end proportion	Share of nodes that are dead-ends
	Average node degree	Average number of edges incident to each node in the street network
Local topography	Node elevations IQR	Interquartile range of node elevations, in meters above sea level
	Mean street grade	Average absolute incline (rise-over-run) of streets in the network
Socioeconomics	Mean household size	Average number of persons per household
	Median household income	Median household income, in 1,000s of inflation-adjusted 2018 U.S. dollars
	Mean commute time	Average travel time to work, in minutes
	Vehicles per household	Number of vehicles available per household

This process calculates the bidirectional compass bearings of every street. It then calculates each tract's street orientation entropy, normalizes it, and linearizes it as an indicator of orientation order. Put simply, this orientation order indicator measures to what extent a tract's streets point in the same directions relative to each other.

Third, the *proportion of 4-way intersections* measures what share of a tract's nodes are 4-way street junctions. Finally, I calculated a composite grid index measuring griddedness by taking the geometric mean of these three components. Each of the components ranges from 0 to 1. Because they are nonsubstitutable, I use the geometric mean as a noncompensatory method of aggregation into an index. See the [Technical Appendix](#) for details on index construction, validation, and robustness.

Tract Vintage Estimation

In this study I use ACS structures-built data to examine street network patterns as a function of tract vintage.

These data are not perfect: They rely on respondents' memories of construction dates and estimates by long-time residents. They capture information about residential unit construction rather than other built form development and thus yield proxy estimates of the development era. Nevertheless, they provide a useful and best-available approximation of urbanization era nationwide, with a track record in the literature for similar street network vintage estimation and validation (e.g., Barrington-Leigh & Millard-Ball, 2015; Fraser & Chester, 2016). Historical data on street networks are scarce, but due to spatial lock-in and path dependence their patterns tend to remain stable once built (Scheer, 2001). Thus, in this study I examine snapshots today of tract street networks of various vintage.

I estimate tract vintage algorithmically via three different methods: a primary method plus earliest and assessor methods as robustness checks. The primary vintage estimation method operates as follows. If most of a tract's structures were built during a certain decade, it tags the tract as "primarily built" in that decade. If no single decade exceeds 50%, it recursively searches for

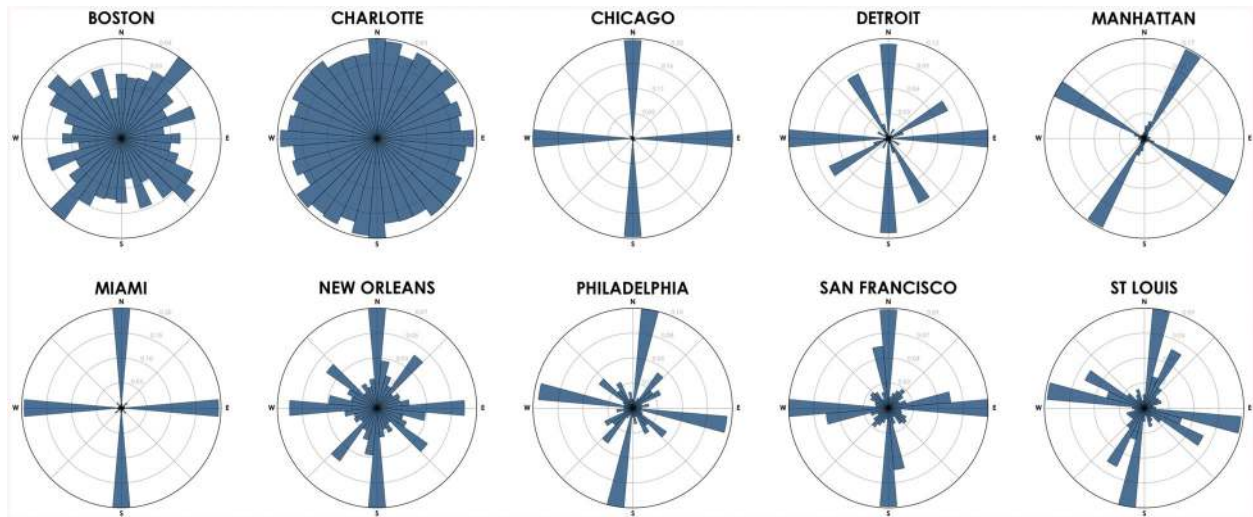


Figure 3. Examples of street network orientation for cities proper (except the borough of Manhattan, NY). The polar histogram bar directions represent compass bearings and bar lengths represent the proportion of city street segments with those bearings. Chicago (IL) and Manhattan illustrate high orientation order (they have internally consistent orientations because nearly all of their streets point in just four different directions), whereas Charlotte (NC) and Boston (MA) illustrate low orientation order (their streets point more evenly in all directions). See Boeing (2019a) for methodological details, further interpretation, and worldwide findings.

the earliest decade in which at least 40% of its structures were built, then 30%, and so on until it eventually finds a decade to tag.

As a robustness check, I separately estimate each tract's earliest-built decade by identifying the earliest decade in which at least 20% of its structures were built, conforming to the theory that most tracts' street networks were built around the time that their older buildings were constructed, following Fraser and Chester (2016). Barrington-Leigh and Millard-Ball (2015) similarly use these ACS data to validate street vintage, confirming that the results cohere with a smaller-sample parcel-based identification of construction dates.

As a final assessor-based robustness check, I re-estimate vintage using Historical Settlement Data Compilation for the United States property records and assessor data (Leyk & Uhl, 2018). The [Technical Appendix](#) contains further details on vintage estimation and validation. Because different possible biases could influence each different vintage estimation method, in this study I inspect decadal trends across all three as a robustness test to see how they diverge or cohere with each other.

Regression Modeling

Next, I estimate a linear spatial-lag model (Model I) of tract griddedness as a function of vintage. The model's response variable is the grid index and the predictors of interest are eight variables representing tract vintage decade. The model includes controls for settlement scale, street scale, topography, and county fixed effects. I additionally estimate two linear spatial-error models (Models II and III) of car ownership as a function of

griddedness. The response variable is vehicles per household, which doubly serves as a linear proxy for household VKT because the two are strongly correlated (Barrington-Leigh & Millard-Ball, 2017). Model II's predictor of interest is the grid index and Model III's are the grid index's components: straightness, orientation order, and proportion of 4-way intersections. Both models include controls for settlement scale, street scale, topography, median household income, jobs proximity, and county fixed effects. All three regression models are estimated on urban tracts only ($N = 46,362$) to focus on city planning and design. Complete model specification and estimation details appear in the [Technical Appendix](#).

Findings and Discussion

Nationwide Spatial Trends

Figure 4 maps each tract in the contiguous United States by its grid index value. The Great Plains and Midwest exhibit the most grid-like street networks on average, whereas New England and Appalachia exhibit the least. Vermont (grid index = 0.13), New Hampshire (0.15), West Virginia (0.16), and Maine (0.17) are the least grid-like by median tract, whereas South Dakota (0.58), Iowa (0.58), Illinois (0.57), and Nebraska (0.55) are the most grid-like. New England's hilly landscape made it difficult to plan large-scale grids, and its development occurred incrementally over centuries around an organic network of country roads and paths. Meanwhile, large-scale Midwest platting and subdivision occurred rapidly across vast swaths of relatively flat land during the heyday of the gridded paradigm.

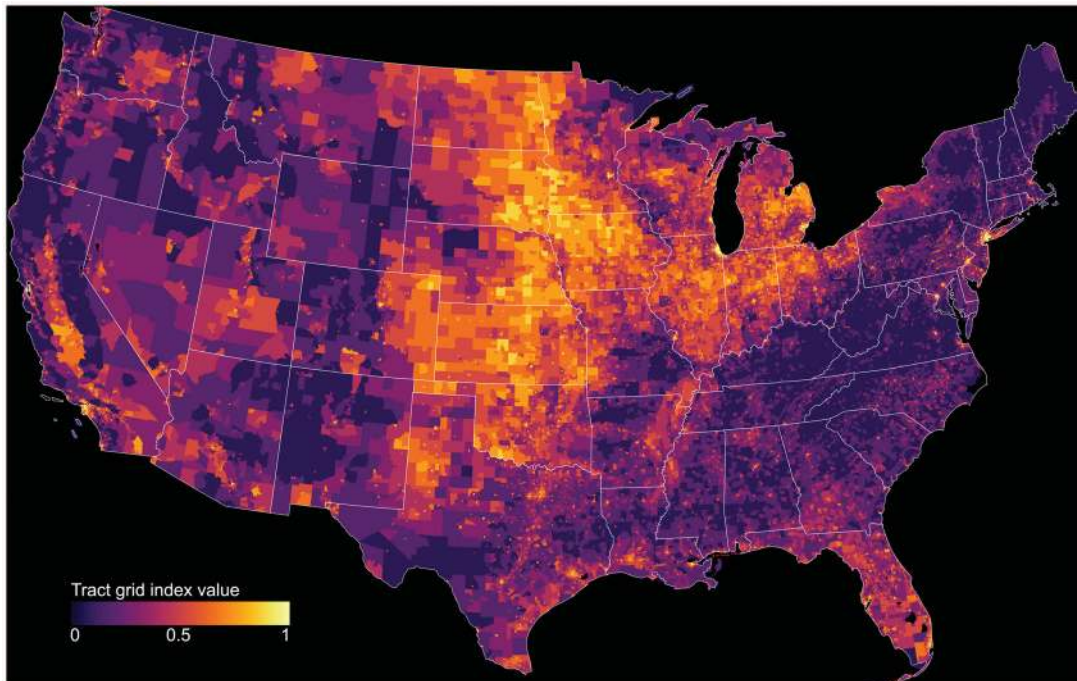


Figure 4. Tract grid index values across the contiguous United States.

Accordingly, across the relatively flat Great Plains (North Dakota, South Dakota, Nebraska, Kansas, Oklahoma), griddedness is ubiquitous as both urban and rural tracts have median grid index values of 0.52, demonstrating the influence of the Homestead Act and similar historical orthogonal planning instruments across the region. However, in the northeastern United States (Maine, New Hampshire, Vermont, Massachusetts, Rhode Island, Connecticut, New York, New Jersey, Pennsylvania), griddedness is an exclusively urban phenomenon: this region's urban tracts have a median grid index value (0.49) nearly three times greater than that of its rural tracts (0.18).

This archipelago of urban grids stretches across the eastern seaboard and the south in Figure 4. Beyond urban–rural divides, this map also suggests an unsurprising negative relationship between griddedness and mountain ranges such as the Sierra Nevada, Rockies, Appalachians, and Adirondacks. In this study I isolate these individual relationships between terrain, vintage, urban form, and street network patterns through regression analysis, which I discuss in the following section.

Griddedness and Tract Vintage

The [Technical Appendix](#) contains descriptive statistics of the various indicators and decadal averages across all U.S. tracts. The latter represents a snapshot of average indicator values today in tracts of various vintage. The law of constant travel time budgets (Marchetti, 1994)

appears to hold as commute times are nearly invariant across vintage, even though street network characteristics and vehicle ownership rates vary substantially between decades.

Controlling for covariates, [Table 2](#) presents the relationship between urban tract vintage and griddedness. Model I has an R^2 of 0.74, and its estimated coefficients of interest are all significant. Each decade variable is associated with lower griddedness than the pre-1940 base class; that is, tracts primarily built after World War II may be larger, more spread out, or hillier, but even when controlling for these characteristics, planners and engineers designed these street networks to be less grid-like than was typical prior to 1940. For instance, urban tracts primarily built in the 1980s or 1990s correspond to grid index values 0.15 points lower than those of prewar tracts, all else being equal.³ Urban tracts primarily built in the 2000s are 0.12 points lower and those built in the 2010s are 0.09 points lower.

Tract size has a negative relationship with griddedness because larger urban tracts are more likely to comprise amalgams of street orientations and development eras. Greater topographical variation within a tract is associated with less griddedness, suggesting the difficulty of building consistent grids across extreme terrain—though San Francisco (CA) provides a well-known exception of engineering a grid irrespective of the underlying landform.

Figure 5 illustrates how key variables in urban tracts trend together across vintage. It presents variables' mean values across all the urban tracts of each decade, showing the primary vintage estimation method along

Table 2. Regression model parameter estimates.

	Grid index		Vehicles per household			
	Model I		Model II	Model III		
Constant	0.4633***	(0.0421)	0.8150***	(0.1798)	0.9869***	(0.1806)
Primarily built in 1940s	-0.0352***	(0.0036)				
Primarily built in 1950s	-0.0686***	(0.0021)				
Primarily built in 1960s	-0.1113***	(0.0025)				
Primarily built in 1970s	-0.1340***	(0.0025)				
Primarily built in 1980s	-0.1513***	(0.0028)				
Primarily built in 1990s	-0.1488***	(0.0030)				
Primarily built in 2000s	-0.1184***	(0.0033)				
Primarily built in 2010s	-0.0901***	(0.0077)				
Grid index			-0.1809***	(0.0069)		
Straightness					-0.2215***	(0.0239)
Orientation order					-0.0336***	(0.0045)
4-way intersection proportion					-0.1263***	(0.0073)
Land area	-5.0168***	(0.2490)				
Population density	0.0039***	(0.0003)	-0.0055***	(0.0003)	-0.0053***	(0.0003)
Single-family detached home proportion	0.0457***	(0.0036)	0.4679***	(0.0065)	0.4716***	(0.0065)
Median rooms per home	-0.0220***	(0.0008)	0.0269***	(0.0018)	0.0272***	(0.0018)
Mean household size			0.1885***	(0.0031)	0.1880***	(0.0031)
Median household income			0.0036***	(0.0001)	0.0036***	(0.0001)
Mean commute time			-0.0031***	(0.0002)	-0.0031***	(0.0002)
Intersection density	0.0009***	(<0.0001)	-0.0006***	(<0.0001)	-0.0006***	(<0.0001)
Mean street segment length	0.0003***	(<0.0001)	0.0003***	(<0.0001)	0.0003***	(<0.0001)
Node elevations IQR	-0.0012***	(0.0003)				
Mean street grade	-1.4293**	(0.5353)	-0.2339*	(0.1150)	-0.2202	(0.1149)
Spatial lag (ρ)	0.3316***	(0.0101)				
Spatial error (λ)			0.6319***	(0.0046)	0.6286***	(0.0046)
<i>n</i>	46,208		45,594		45,594	
Pseudo- <i>R</i> ²	0.737		0.853		0.854	

Notes: Standard errors in parentheses. County-level fixed effects not shown. Estimated on urban tracts only. Variables' units/descriptions are provided in Table 1.
* $p < .05$. ** $p < .01$. *** $p < .001$.

with the two alternative methods as robustness tests. Compared with the primary method, the assessor-based robustness test has some important limitations, including a nonrepresentative sample that likely underestimates average griddedness while overstating sprawl (see details in the [Technical Appendix](#)). Accordingly, the assessor trend line tends to peak/trough earlier and demonstrates a more conservative rebound in the past 20 years, bracketing some of these findings. Nevertheless, the indicator values track relatively well across all three estimation methods, and their trends across decades tell the same story: Griddedness and its constituent components declined steadily from their prewar highs through the 1990s.

The average grid index value is 84% higher in pre-1940 urban tracts than it is in 1990s-vintage urban tracts, whereas the 4-way intersection proportion is 168% higher. The average proportion of dead-ends is 163% higher in 1990s urban tracts than in pre-1940 urban tracts. Street networks also grew coarser grained: The average intersection density in pre-1940 urban tracts is double that of 1990s urban tracts, whereas the 1990s' average street segment length is 20% greater than those built before 1940 (equivalent to a 25-m increase in absolute terms). The average node elevation IQR rose 57% between the 1940s-vintage urban tracts and the 1990s-vintage urban tracts, suggesting that U.S. cities developed on hillier terrain during the latter part

of the century, perhaps as they expanded beyond coastal or riparian origins and into surrounding hills.

Most interesting, however, is that all of these variables' trends have reversed in the past 2 decades. Since 2000, the grid index and its components have risen back to levels not seen since the mid-20th century. The average grid index value is 13% higher in 2000s-vintage urban tracts than it is in those of the 1990s. Intersection density is 6.5% higher, the 4-way intersection proportion is 23% higher, and the dead-end proportion is 14% lower.

Griddedness and Car Ownership

Figure 5 also reveals that car ownership follows a vintage trend similar to these various street network indicators, rising from 1940 through the 1990s before declining in post-2000 tracts. The average urban tract of pre-1940 vintage has 1.3 vehicles per household today, but the average 1990s tract has 1.9. In other words, households in 1990s-vintage urban tracts own approximately 50% more cars on average than those in prewar tracts do. However, tract vintage correlates with other important factors like household size, income, and job proximity.

Controlling for such covariates, Model II estimates the relationship between car ownership and griddedness at the urban tract level with a full set of controls (Table 2). A unit increase in the grid index is associated with a decrease of approximately 0.18 vehicles per household. Re-estimating Model II as a standardized regression reveals that the grid index has the largest effect size (that is, beta coefficient magnitude) among the predictors outside of three socioeconomic variables (household income, household size, and single-family home proportion).

One potential limitation here is that some of the most grid-like neighborhoods are old enough to predate the zoning logic of modern functional segregation. Thus, there may be an unobserved factor pertaining to traditional land use patterns influencing car ownership in older gridded neighborhoods. As a robustness test, Model II is re-estimated on only those tracts of 2000s or 2010s vintage to better isolate design in the modern regulatory context. The results ($n = 3,618$, $R^2 = 0.89$) remain substantively similar, including an estimated coefficient on the grid index of -0.14 ($p < .001$). As a final robustness test, Model III decomposes the grid index into its constituent components and predicts vehicles per household using them instead. Each index component is significantly and negatively associated with car ownership. Models II and III have essentially identical R^2 values (0.85) and yield similar parameter estimates, suggesting the stability of the index's construction and interpretation, as well as its usefulness as a one-dimensional indicator of griddedness.

The Death and Life of Great American Grids

For more than a century, American spatial planning deployed the orthogonal grid as its primary mode of geometric ordering. But new transportation technologies and cultural preferences emerged in the early 20th century to challenge its theoretical and practical prominence. As Radburn's co-chief architect Clarence Stein (1951, p. 41) put it, "The flood of motors had already made the gridiron street pattern, which had formed the framework for urban real estate for over a century, as obsolete as a fortified town wall." Planners, designers, engineers, and developers turned to new network patterns to accommodate the automobile, but accommodation soon grew into dependence. In this study I take 1940 as a rupture point—following 20 years of rising car adoption—when massive state intervention in rebuilding mobility infrastructure around the technological and spatial logic of the automobile began to fully dominate American urbanization.

The stark effects of this rupture can be seen throughout this study's findings. Controlling for tract size, terrain, and building and street scale, each decade of vintage after 1939 is associated with lower griddedness than pre-1940 vintage. Griddedness, orientation order, straightness, 4-way intersections, and intersection density all declined steadily from pre-1940 vintage through 1990s vintage, whereas dead-ends, block lengths, and car ownership rates steadily rose. Urban planners and engineers reorganized cities around the logic of and demand for the automobile after World War II, and we can clearly see this inscribed in the urban form of tracts of different vintage today.

But, importantly, these trends have slowed or reversed since the year 2000, though not to prewar levels. Nevertheless, post-2000 urban tracts exhibit griddedness, density, and connectivity not seen since the 1950s or 1960s, as well as lower vehicle ownership rates than any other decade after 1939, though the assessor-based method exhibits a more conservative trend in the latter. These findings—across multiple indicators and every urban census tract—show consilience with other research, including Barrington-Leigh and Millard-Ball's (2015) node-degree finding and the historical-morphological case studies of Southworth and Ben-Joseph (1997).

Conclusions

Summary of Findings

In this study I develop a new computational big data approach to model the entire U.S. street network per tract, estimate and compare vintage in different ways, and calculate a basket of new measures and indicators of street network design and sprawl. I modeled the relationship between vintage and form and the relationship

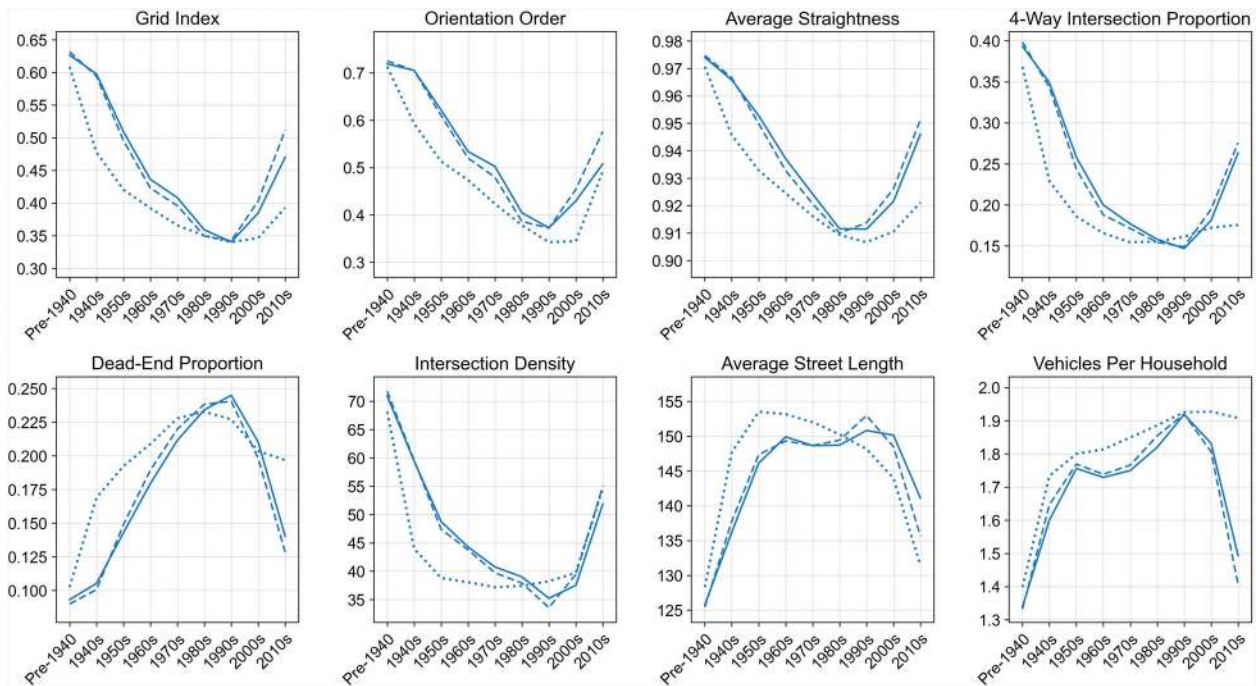


Figure 5. Urban tract variables' mean values by vintage. Solid line represents the primary vintage estimation, dashed line represents earliest-decade estimation, and dotted line represents the assessor-based estimation. Variable units/descriptions are provided in Table 1.

between vehicle ownership and griddedness to explore car adoption and dependence in the context of griddedness itself. As is true of all algorithms, this study's vintage estimation methods are imperfect and need not be the final word: In the future, new algorithms should be developed and tested to further home in on precise trends over time. In addition, the role of urban renewal and redevelopment remains only partly understood. Future work should explore how urban renewal altered pre-existing street patterns over time and unpack variation between places in each decade to understand the local contexts that guided these histories heterogeneously within each era.

Keeping these limitations and opportunities in mind, this study makes two primary empirical contributions. First, it comprehensively measures how nationwide street network design grew more coarse grained, disconnected, and circuitous between 1940 and the 1990s and identifies a nascent return to classic urbanism patterns in the past 20 years across multiple dimensions. This is a promising though preliminary trend given the impacts of car dependence, VKT, and emissions on urban sustainability, public health, and social justice. Putting numbers to these trends helps monitor and assess planning practice's outcomes and progress toward sustainability goals. Second, it identifies new relationships between urban form, vintage, and car dependence while controlling for related characteristics and—importantly—local topography. Previous studies have not fully unpacked these relationships between

topography and street network form or held topography constant to explore other relationships. Beyond these empirical contributions, it develops a novel grid index that offers a new lens to measure and compare urban patterns quantitatively in a theoretically sound way. Finally, it develops a new set of urban form vintage estimation methods and evaluates their robustness.

Implications for Planning Practice

In recent years, urban planning and public health scholars have identified significant relationships between VKT, road safety, active travel behavior, and street design variables like block length, intersection density, and 4-way intersection proportions. The body of theory arising from this research emphasizes the importance in planning practice of network connectivity and density for active travel, safety, and accessibility, yet planners, designers, engineers, and developers steadily drifted away from such connectivity and density as they abandoned the grid and embraced sprawl during the 20th century. This occurred in both greenfield and redevelopment projects: As but one example of the latter, redevelopment efforts in Detroit (MI) through the late 20th century typically destroyed the project area's grid to fuse the original blocks into a single superblock (Ryan, 2006).

But there exists another path forward for planning practice. As discussed earlier, new certification standards like LEED-ND promote neotraditional grid-like street

network patterns as instruments of sustainability planning in new communities. But even redevelopment and retrofitting projects offer practitioners important opportunities. For instance, Syracuse (NY) is currently planning to tear down its 1950s-era Interstate 81 freeway and restore the original street grid (Scheer, 2020). Such planning decisions can help shift cities away from car dependence and back toward finer-grained, interconnected street networks that support active transportation. Meanwhile, in new communities, planners might require minimum intersection densities and proportions of 4-way junctions or use supportive certification standards like LEED-ND to cut red tape. Incentivizing infill development offers further opportunities to take advantage of pre-existing urban grids rather than relying on neotraditional greenfield projects at the urban fringe far from job centers.

A shift back toward traditional network patterns may also reflect market demand for more walkable places. As Handy (2017) points out, while academics continue to home in on relevant explanatory variables and regression elasticities, practicing planners, designers, engineers, and developers have recently proceeded with more compact development for myriad reasons beyond theoretical VKT reductions. Such projects offer clear economic and equity benefits and can be profitable due to market demand (Kim & Bae, 2020). This is an important arrow in planners' quivers as they advocate for more sustainable street patterns.

In sum, what does this all mean for planning practice? This study's findings can be read as something of a scorecard for the profession in the past 80 years by assessing the trajectory of street network planning and design. Privileging automobility over all other modes, 20th-century planners locked in generations of car dependence. But since the 1990s, planning scholars and prominent practitioners have called for better evidence-based practice to create more sustainable, healthy, and just cities. To successfully implement climate action plans or attenuate pervasive car dependence, practitioners must plan for denser, interconnected networks that allow for nonmotorized travel and mass transit provision. In this study I find preliminary evidence of some promising trends in this direction toward more sustainable urban forms.

This includes a key takeaway message for practitioners: The initial layout of streets and attendant land parcelization determine urban spatial structure for centuries, locking in mobility needs and capabilities for generations to come. Due to this spatial lock-in, street network patterns are difficult to change once established. So what can practitioners do today?

First, individual suburban retrofits can improve connectivity but are limited by the path dependence of infrastructure and land parcelization. Second, larger redevelopment projects offer strategic opportunities to incorporate (or restore) fine-grained, highly connected

circulation networks into their design. Good design can mitigate historical criticisms of the grid's monotony by providing public space, human-scaled streetscaping, and façade variation. Third, greenfield development may offer practitioners the most straightforward opportunity to continue the aggregate trend back toward more-connected patterns, but such projects are often disconnected from the rest of the urban fabric and far from job centers. Finally, interconnected and relatively fine-grained grids already exist in the cores and inner-ring suburbs of most large U.S. cities. Instead of building new grids on the urban fringe, planners can promote infill and densification where the physical infrastructure already best supports active transportation and freedom of mode choice. Overall, planners and policymakers should review and revise codes and design guidelines at local, state, and federal levels to encourage and streamline the development of networks that support broader sustainability and public health goals.

Interconnected grids defined American spatial patterns for more than a century before the rise of the automobile. Across a basket of indicators, I identify planners' morphological response to and exacerbation of this rise. Rather than merely reacting to fleeting mobility trends, practitioners must plan proactively for the dense, interconnected networks that can attenuate car dependence and advance city climate action plans.

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SUPPLEMENTAL MATERIAL

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

NOTES

1. See, for instance, ITE's 1993 *Guidelines for Residential Subdivision Street Design*, ITE's 1994 *Traffic Engineering for Neo-Traditional Neighborhood Design*, Oregon's 2001 *Neighborhood Street Design Guidelines*, and the 2009 LEED-ND Neighborhood Pattern and Design certification criteria.
2. Because these data are from the 2018 ACS, the 2010s decade does not cover the entire decade and thus includes a smaller set of tracts (see [Technical Appendix Table A3](#)).
3. See the [Technical Appendix](#) for details on interpreting parameter estimates in a spatial-lag model.

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