POLICY BRIEF

Street or Network Connectivity

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Project Description

This project reviews and summarizes empirical evidence for a selection of transportation and land use policies, infrastructure investments, demand management programs, and pricing policies for reducing vehicle miles traveled (VMT) and greenhouse gas (GHG) emissions. The project explicitly considers social equity (fairness that accounts for differences in opportunity) and justice (equity of social systems) for the strategies and their outcomes. Each brief identifies the best available evidence in the peer-reviewed academic literature and has detailed discussions of study selection and methodological issues.

VMT and GHG emissions reduction is shown by effect size, defined as the amount of change in VMT (or other measures of travel behavior) per unit of the strategy, e.g., a unit increase in density. Effect sizes can be used to predict the outcome of a proposed policy or strategy. They can be in absolute terms (e.g., VMT reduced), but are more commonly in relative terms (e.g., percent VMT reduced). Relative effect sizes are often reported as the percent change in the outcome divided by the percent change in the strategy, also called an elasticity.

Summary

Strategy Description

Network connectivity describes the transportation connections that link each of the points in a community with one another. Gridded streets with short block lengths have greater connectivity compared to fragmented networks with loops and long block lengths. The structure of the street network is often a proxy for a broad set of transportation and land use characteristics of the era in which the network was originally designed. Separating the effect of connectivity on vehicle miles traveled (VMT) and social equity from the effects of these other characteristics can be difficult because of the related land use patterns that are associated with street network design, and the long time it takes to plan, build, and support urban and rural transportation networks.

Behavioral Effect Size

The effect of increasing network connectivity on VMT varies widely depending on the measure of connectivity. Eight of ten studies report increases in connectivity result in reductions in VMT. More recent studies suggest that the effect of network connectivity is moderated by several other metrics (often VMT reduction strategies themselves), such as land use mix, population density, and others. Recent studies also link network connectivity directly to GHG reduction.

Strategy Extent

Densifying existing networks and ensuring new networks are well connected must be pervasive in regions to expect VMT reduction. While the speed of implementation is slow, the potential for lasting effects is great, given how difficult it has historically been to change street networks. Some evidence suggests the VMT reduction benefits grow over time.

Strategy Synergy

The most obvious strategy synergies are with other land use strategies such as increased population density and land use mix. Without appropriate residential and destination densities, increasing street connectivity may have limited car use reduction, instead only making driving easier by providing more travel routes. Additionally, strategies that reduce the costs and other burdens of active transportation (the quality of mode-specific networks), and public transportation strategies are likely to support shifting from cars to alternative modes.

Equity Effects

Little evidence exists for the connection between network connectivity and social equity. The context for how increased connectivity is implemented may matter more than the connectivity itself in terms of equity outcomes. Given the historical disinvestment in communities of color and low-income communities, increasing network connectivity in those communities is likely to bring more equity benefits if appropriate protections are made for housing in tandem. More research is needed on the relationship between network connectivity and both social equity and environmental justice.

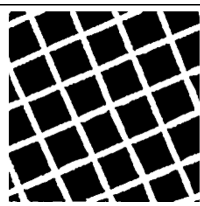
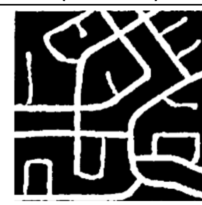
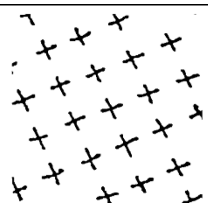
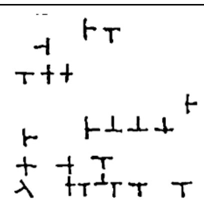
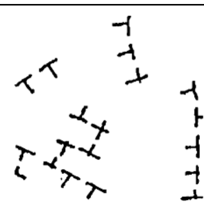
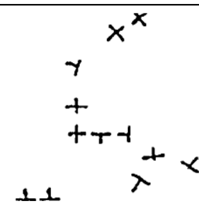
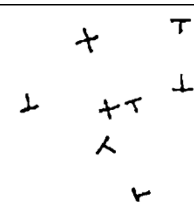
Strategy Description

Network connectivity describes the transportation connections that link each of the points in a community with one another. The structure of the street network (the primary determinant of transportation network connectivity), defined in terms of the patterns of streets and intersections, determines the directness of these connections, which often differ by mode (Handy, et al. 2003). From the transportation standpoint, network connectivity is defined with respect to the directness of connections to potential destinations.

Network connectivity is shaped by local codes and standard practices. Subdivision ordinances often set standards that encourage street networks with relatively low connectivity (Handy, et al. 2003). Professional guidelines, such as those adopted by the Institute of Transportation Engineers, have also encouraged development patterns characterized by low-connectivity networks for many decades (Southworth and Ben-Joseph 1997). As a result, the structure of residential street networks in the United States has evolved over time, as illustrated in Table 1 (next page), from “grids,” which were common prior to World War II, to networks dominated by cul-de-sacs. Over the last decade, however, many communities throughout the United States have revised their standards to encourage a return to grid networks (Handy, et al. 2003).

Because of the strong association between the era of development and the layout of the street network, connectivity is likely to be correlated with other characteristics of the built environment. For example, pre-World War II neighborhoods tend to have grid networks, small neighborhood stores, and narrower streets, and are located closer to the center of the city, while subdivisions developed during the 1980s are characterized by cul-de-sacs, strip malls and “big box” stores, and wider streets, and are located farther from the center. Therefore, the year in which a neighborhood was first developed often serves as a good proxy for connectivity (with older neighborhoods having greater connectivity), and connectivity, in turn, often serves as a useful proxy for a broader set of characteristics typical of that era. Separating the effect of connectivity on vehicle miles traveled (VMT) and social equity from the effects of these other characteristics can be difficult because of the related land use patterns that are associated with street network design, and the long time it takes to revise the transportation network.

Table 1 . Residential Streets Patterns in the United States (Source: Southworth and Owens, in Southworth and Ben-Joseph 1997)

	Gridiron (c. 1900)	**Fragmented Parallel** (c. 1950)	**Warped Parallel** (c. 1960)	**Loops and Lollipops** (c. 1970)	**Lollipops on a Stick** (c. 1980)
Street Patterns					
Intersections					
Lineal feet of streets	20,800	19,000	16,500	15,300	15,600
# of blocks	28	19	14	12	8
# of inter-sections	19	10	7	6	4
# of access points	19	10	7	6	4
# of loops & cul-de-sacs	0	1	2	8	24

Strategy Effects

Connectivity is important for travel in two ways. First, it determines the directness of the connection between one point and another. A straight line between points, "as the crow flies," yields the shortest travel distance. Second, network connectivity determines the number of possible routes between one point and another. Having multiple routes of similar distance gives a traveler the opportunity to vary their route, whether out of a desire for variety or to avoid occasional obstacles. It also enables traffic to spread more efficiently through the network, reducing traffic on any individual street.

Increased connectivity within residential areas has the potential to reduce VMT, though it might also increase VMT in some situations. The net effect of connectivity on VMT depends on its direct effect on travel distances and its potential indirect effects on trip frequency, destination choice, and mode choice. All else being equal, greater connectivity means shorter travel distances and thus less VMT. However, if greater connectivity results in residents making more frequent trips by car (because distances are shorter and trips are easier and less costly) or choosing more distant destinations (because now they can get there in the same travel time as before), the net effect could be an increase in VMT. On the other hand, greater connectivity could encourage residents to walk or bicycle instead of drive by reducing travel distances to destinations and increasing the variety of possible routes if those connections include safe and protected infrastructure.

Connectivity in and of itself may not affect social equity, but disparities of where changes to connectivity occur will undoubtedly impact equity. For example, increases to connectivity in low-income communities of color have the potential to improve equity by increasing accessibility to essential activities. On the other hand, if those increases to connectivity also increase property values, without adequate protections for existing residents they could cause displacement.

Behavioral Effect Size

Based on 10 selected studies in Table 2 (p. 12), the effect of street connectivity on VMT is likely to be negative (only 2 studies report any positive effects) in that increasing connectivity will result in reductions in VMT. Additional studies report effects related to VMT which are included in the technical and background section. It is not possible to provide a unified range of effects or to directly compare the estimated effect sizes, as connectivity is measured differently in each study and VMT is also not measured in a consistent way. Studies tend to use one of two types of network connectivity measures, and researchers do not agree as to which is most appropriate. The first type looks at facility design, such as the ratio of the number of 4-way or 3-way intersections to all intersections, the ratio of the number of intersections to the number of street segments (“nodes” to “links”), the average block length, or the share of blocks created by the street pattern that are square or rectangular. In the second type of connectivity measure, land area is factored in to calculate intersection density (e.g., intersections per square mile) or street density (e.g., lane miles of street per square mile). The effect of street connectivity is sometimes measured or calculated from other metrics as percent change in VMT for a one percent increase in connectivity.

The studies summarized in Table 2 suggest a high level of uncertainty about the effect of connectivity. One study, for example, found a negative effect for one measure of connectivity, as expected, but a *positive* effect for a second measure, and found more substantial differences in effect sizes for VMT for all travel than for VMT for non-work trips only (Cervero and Kockelman, 1997). Similarly, a more recent study in Florida found a positive relationship between network connectivity and VMT, but when population density was assumed to moderate the effect of network connectivity, the relationship changed directions (Chen and Felkner, 2019). The higher estimated effects in Table 2 are likely to reflect differences between neighborhoods beyond just connectivity, as noted earlier. However, some studies control for differences in socio-economic characteristics, as well as differences in built environment characteristics between neighborhoods, suggesting a more reliable estimate of the independent effect of network connectivity (Ding et, al., 2017).

The meta-analysis by Ewing and Cervero (2010) of multiple studies may provide a reasonable estimate of effect size for typical conditions and is near the middle of the range of estimates presented in Table 2. However, because the studies they analyzed use different measures of connectivity and different measures of VMT, an averaging of their estimated effect sizes may gloss over important nuances in the relationship between connectivity and VMT. Further, little is known about how the effect might vary across urban or rural areas, as the evidence in this body of literature is largely from within urban areas.

Most studies suggest that network connectivity varies in its effect on VMT by commute and non-commute purposes (Ding et al., 2017; Ewing and Cervero, 2010; Cervero and Kockelman, 1997). Some studies even consider residential self-selection of residents and still find strong effects of network connectivity on VMT reduction (Vance and Hedel, 2007). Further, the connection between network connectivity and VMT is complex in that it simultaneously depends on and influences other key VMT reducing relationships between variables like population density and land use mix (Ding et al. 2017; Barrington-Leigh and Millard-Ball, 2017; Chen and Felkner, 2019)

Co-benefits

Higher connectivity contributes to shorter distances to destinations, which encourages walking and bicycling rather than driving for short trips (Saelens and Handy 2008; Marshall and Garrick, 2010; Khan et al., 2013). The substitution of walking and bicycling for driving leads to a reduction in air pollution and in negative health-related impacts. Non-motorized travel is an important source of physical activity and contributes to many health benefits as well (Handy 2009). Some studies show that grid-networks, characterized by high intersection densities, produce fewer accidents overall than cul-de-sac neighborhoods bounded by high-speed arterial streets (Dunbaugh and Rae 2009; Marshall and Garrick, 2011), although other studies have reached the opposite conclusion (Rifaat et al., 2010). In addition, a shift from driving to walking or bicycling could reduce the need for parking spaces, which may result in reduced land consumption and additional economic and environmental benefits.

Two recent studies provide evidence for the direct effect of street connectivity on transportation greenhouse gas (GHG) emissions (Barrington-Leigh and Millard-Ball, 2017; Boeing et al., 2024). These studies suggest similar effects sizes of street connectivity on GHG reduction as the studies of VMT, with one US-wide study suggesting a policy scenario that successfully converts networks to gridded types could reduce GHGs by 8.8% by 2050 (Barrington-Leigh and Millard-Ball, 2017). Because these studies are more macro in scale and depend on the types of fleet of vehicles and their fuel mix in the study areas, they are discussed in more detail in the technical documentation. For the studies that focus on VMT, translating VMT reductions into GHG emissions reductions depends not only on the types of vehicles, but also on the nature of the VMT eliminated (e.g., speeds, acceleration, deceleration, times vehicle is started). The direct impact of connectivity on trip distances is likely to be relatively uniform for all residents in an area, but residents may differ in their propensity to shift from driving to walking and bicycling in response to an increase in connectivity. Apart from those particular considerations, one would generally expect GHG reduction to be similar to VMT reduction, if vehicle fleet composition and driving patterns are unchanged.

Extent

Scale of Application:

Most evidence for VMT reduction from street network connectivity comes from metropolitan regions and the connectivity metrics focus primarily on residential land uses. Converting to more connected networks needs to happen across neighborhoods to improve local accessibility as a step toward reducing VMT.

Efficiency or Cost:

The expense of and potential political pushback to adding links to street networks suggests great difficulty will be incurred to add connectivity to an existing street network. In contrast, changes in rules that require greater levels of connectivity in development of new streets are relatively inexpensive and easy. Network persistence is also a sign of the power of such changes, in that once more connected networks are implemented they are likely to have long lasting effects on VMT reduction.

Time / Speed of Change:

The conversion of existing street networks to more connected networks and building new connected networks will take time. The timeframe for realizing the benefits will likely be multiple decades. Although connectivity is a slow strategy compared to others, some evidence suggests the benefits grow over time (Halloway et al., 2017). Although not explicitly discussed in the literature, targeting connectivity for active and public transportation may be the most rapid and synergistic way to leverage the effect of network connectivity on VMT by nudging mode shift.

Location within the Region:

The evidence reviewed in this brief focuses on residential land uses and urban regions. Because most of the VMT exists on urban roads, VMT reduction potential may be most beneficial in those locations of regions. However, rural connectivity may have important equity benefits that should not be overlooked, even if it increased VMT in those cases. Further, network connectivity at a wider scale (e.g., regional) possibly increases VMT if it allows shorter car travel times and alternative modes are not available or lack competitiveness with driving.

Differences between Regions:

Regional context has a strong moderating effect on the relationship between network connectivity and VMT. In one global study, intersection density varied in its effect on GHG reduction when comparing existing networks (Boeing et al., 2024). Because most California cities are defined predominantly by low density deformed grids, the effects between regions in California may be more uniform. However, variations in public transit and active transportation infrastructure, and variations in related land use variables such as population density, land use mix, and destination density, are all likely to result in key differences between regions.

Equity Effects

The effects of street connectivity on equity were not reported in any of the studies reviewed. In part, this may be due to the challenges of quantifying the relationship between network connectivity and safety, air quality, and other health disparities. But it is also likely a symptom of a lack of historical focus on equity in transportation research that needs to change.

Although not in the literature relating street networks to car use, at least one study suggests street connectivity and environmental justice outcomes are only weakly directly related (Jiang and Yang, 2022). However, that same study in Los Angeles suggested that street connectivity influences neighborhood ethnic makeup and pollution levels, suggesting a potential indirect effect on environmental justice. This proposed indirect effect suggests that the ramifications of the specific strategy of densifying networks cannot be considered independent of other associated changes such as green space availability, housing availability, and land use mix, among others.

Synergy

Beyond shortening driving distances, increased network connectivity has the potential to shift car travel to more sustainable modes. Although this brief only covers connectivity in a simplistic representation that do not account for the quality of the connections in the network, making those network connections safe and comfortable for walking and bicycling is likely to provide great synergy for VMT reduction. Closing the gaps in the network is a common strategy in bike and pedestrian planning, as distance and safety are long-standing barriers for active transportation. The same is true for the quantity and quality of public transportation networks (e.g., longer distance public transportation, rideshare/vanpool, and microtransit are the only reasonable substitutes for driving). This is especially the case in rural areas.

Confidence

Evidence Quality

The studies in Table 2 use accepted statistical methods to analyze high quality data for individual households. Although they provide the best available evidence of the effect of connectivity on VMT, the cited studies have notable limitations. The estimated effects in all studies are based on a comparison between neighborhoods at one point in time (e.g., a cross-sectional design) rather than changes in VMT that result from a change in connectivity (e.g. a “before-and-after” design). The lack of standardization of effects, particularly the lack of elasticity reporting in the more recent studies, makes them difficult to compare. Also, because the studies use different connectivity variables and do not control for the same factors, it is not possible to determine whether the differences in the estimated effects accurately reflect the range of effects under different conditions or simply reflect the differences in the connectivity variables and the control variables. Only Cervero and Kockelman (1997) use data from California exclusively, and the estimated effect sizes of the others may not be accurate for California communities.

The relationship between network connectivity and equity outcomes is a major gap in the academic literature. Although there are reasons to suggest that the VMT and GHG reduction potential of increased network connectivity is generally aligned with equity goals given marginalized communities are disproportionately impacted by the climate crisis, more near-term effects are largely unknown and likely dependent on relationships between network connectivity, housing availability, and land use mix.

Caveats

When applying the results of the cited studies, it is important to note that they mostly focus on street connectivity in residential areas or in broad geographies that don't differentiate between land use and urban context. Connectivity in residential areas is likely to have the greatest effect on short distance trips, particularly when increased connectivity puts schools, stores, and other potential destinations within walking distance. Residential connectivity can also reduce VMT by reducing distances to destinations for driving trips, but the reduction is likely to be small compared to the total length of the trip. It is possible that connectivity around transit stations and mixed-use centers, where it is easier to use modes other than driving, would have a greater effect on VMT than connectivity in residential areas. In addition, the connectivity of the pedestrian and bike network might be different from the connectivity of the street network owing to mode-specific connections (e.g., trails, cut-throughs) and barriers (e.g., freeways) (Tal and Handy, 2012). This difference is often not explicitly measured in the studies in the literature, but it should be considered in efforts to reduce VMT that encourage a shift from driving to active transportation.

Examples

Several cities across the U.S. have adopted changes in their subdivision ordinances to promote greater street network connectivity (Handy, et al. 2003). Eugene, Oregon and Corvallis, Oregon, for example, have maximum block lengths of 600 feet with requirements for pedestrian connections at least every 300 feet. Several cities in North Carolina have adopted requirements based on the ratio between intersections (nodes) and street segments (links). Some communities have restricted the use of cul-de-sacs in residential subdivisions. Retrofitting communities to increase connectivity is more challenging than requiring high levels of connectivity when a neighborhood is first built, but examples can be found throughout California. The cities of Berkeley and Davis, for example, have increased pedestrian and bicycle connectivity by constructing bridges over and a tunnel under, respectively, Interstate 80. The effects of these policies and programs on VMT and greenhouse gas emissions have not been measured. Beyond treating network connectivity in isolation, neighborhood certification processes such as LEED-ND (Neighborhood design; https://www.usgbc.org/leed/rating-systems/neighborhood-development) score network connectivity along with several other elements, many of which are covered in other Policy Briefs in this series.

Technical & Background Information

Study Selection

No studies were identified that directly test the effect of a change in network connectivity on vehicle miles traveled (VMT) or greenhouse gas (GHG) emissions, though network connectivity has been considered in several studies that examine the association between the built environment and travel behavior. Connectivity in these cases is measured primarily for residential neighborhoods, from the perspective of households, but not for areas around transit stations or trip destinations. It has also been measured more broadly at city levels without differentiation for land use. Measuring the impact of connectivity on VMT and GHGs, while controlling for socio-demographic characteristics (e.g., income, household size), population density, and land-use mix, is challenging. This suggests a research opportunity that directly links network connectivity with VMT by key equity indicators (such as CalEnviroScreen 4.0).

The key criterion for including studies in the policy brief was reporting of the effects of network connectivity on VMT and GHG emissions while controlling for socio-demographic characteristics and built environment characteristics. Additional considerations included U.S. location for the data (though studies in other developed countries were also considered), published since 1990, and data collected from a sample of residents of both areas with transit supply and areas without it.

Studies meeting the criteria were included in Table 2. Additionally, several relevant studies that are not included in Table 2 are discussed below.

Fan and Khattak (2008) reports person miles of travel (PMT) rather than VMT, but that study is unique because it adjusts for attitudes, in this case meaning one's beliefs about and feelings towards transportation. That study reports a larger effect of connectivity on PMT than most studies of VMT (Table 3; p. 14). Vance and Hedel (2007) was excluded from Table 2 since it focuses on a non-U.S. location and because an elasticity for this study is reported in Ewing and Cervero (2010), though not available from the original source. Notably, both Fan and Khattak (2008) and Vance and Hedel (2007) help to reduce the possibility that their models' estimated connection between network connectivity and VMT stem from the "self-selection" of residents who prefer to drive less into neighborhoods with higher connectivity. This provides important evidence that supports the findings of the other studies that didn't account for self-selection.

Two studies, Barrington-Leigh and Millard-Ball (2017) and Boeing et al. (2024), report on the relationship between network connectivity and GHG reduction across the US and world, respectively. They are the first studies to show that the connectivity and VMT relationship also shows up in macro-level GHG reduction. While the Boeing et al. (2024) study covers cities worldwide, their class of low-density deformed grid cities is almost uniformly the type of street networks in California cities. Results from those parts of their models suggest several connectivity variables have strong effects on transportation GHG emission reductions (Table 3). However, this study only examines the macro relationship between transportation emissions and connectivity. Transportation emissions are not only a function of VMT; they are also a function of fleet efficiency and fuel mix, both likely to be strong determinants of GHGs yet not having a causal link to network connectivity. In the US-wide study by Barrington-Leigh and Millard-Ball (2017), model-based simulations that account for the connection between land use, housing, and network connectivity suggest a policy scenario that successfully converts networks to gridded types could reduce GHGs by 8.8% by 2050. This is the most exhaustive link between network connectivity and GHGs found in the literature. However, it relies on several assumptions about the complex interactions among factors driving transportation GHGs that are yet to be validated.

Methodological Considerations

In applying the estimated effects, several methodological limitations should be considered. First, every study uses a different measure of connectivity. Little work has been done to compare different measures or to assess their ability to distinguish different types of networks. Thus, it is not possible to favor one study over another based on the connectivity measure it uses. In addition, the effect of connectivity on VMT likely depends on connectivity to destinations, rather than connectivity in and of itself. The studies do not all control for land use patterns in the same way. Because the studies use different connectivity variables and do not control for the same factors, it is not possible to determine whether the differences in the estimated effects accurately reflect the range of effects under different conditions or simply reflect the differences in the connectivity variables and the control variables.

Second, all the studies base their measures of network connectivity on the street network only. Pedestrian/bicycle network connectivity can be significantly different than street network connectivity in some places, depending on connections and barriers that affect pedestrians and bicyclists only (Tal and Handy, 2012). In places where connectivity has a significant effect on walking and bicycling, the use of a street network connectivity measure could under-represent the importance of connectivity for VMT.

Third, most of the cited studies focus on street connectivity in residential areas. However, connectivity around destinations is also likely to be important. For example, increased connectivity around transit stations at the destination-end of a trip could put more destinations within walking distance of the station and increase the feasibility of using transit. As another example, connectivity around worksites could reduce VMT during the workday by making it easier for workers to walk to restaurants and other services on their lunch hours. Incorporating destination connectivity into analyses of VMT is not straightforward, as most people visit multiple destinations each day. Chapman and Frank (2004) measured destination connectivity, as well as residential connectivity, and included this measure in mode choice models (as a component of a "destination walkability" variable), but not VMT models.

Finally, the studies all use cross-sectional designs that compare VMT for neighborhoods with different connectivity at one point in time, rather than longitudinal designs that measure changes in VMT in response to changes in connectivity within a neighborhood. Cross-sectional designs leave open the possibility that the observed effects are partly attributable to the "self-selection" of residents who prefer to drive less into neighborhoods with higher connectivity. Most studies also ignore the complex interactions that result as a function of changing network connectivity. Some evidence suggests the indirect effects of network connectivity may be even stronger than the direct effects (Ding et al., 2017), and more research is needed that incorporate the complex interactions like those models in the work by Barrington-Leigh and Millard-Ball (2017).

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Table 2. Network Connectivity and VMT or PMT

Study	Study Location	Study Year	Connectivity Variable	Results	
				VMT/PMT Variable	***VMT/PMT Change for 1% Increase in Connectivity***
Cervero and Kockelman (1997)	San Francisco Bay Area, CA	1990	Proportion of intersections that are 4-way	VMT per household for all purposes	No effect
				VMT per household for non-work only	-0.59%
			Proportion of neighborhood blocks that are quadrilaterals (i.e. four straight sides, shaped as either a square or rectangle)	VMT per household for all purposes	0.18%
				VMT per household for non-work only	0.46%
Bento et al. (2003)	Nationwide	1990	Road density (lane miles per square mile)	VMT per person for all purposes	-0.07%
Boarnet et al. (2004)	Portland, OR	1994	Number of 4-way intersections within 1 mile of household	VMT per person, non-work only	-0.06%
			Number of intersections within 1 mile of household		-0.19%
Chapman and Frank (2004)	Atlanta Region, GA	2001-2002	Intersection density (number of intersections within 1km around each home)	VMT per person for all purposes	-0.08%
Ewing and Cervero (2010)	Multiple locations	Multiple years	Percent 3– or 4-way intersections	Various measures, including VMT for all purposes, commute only, and non-work only	-0.12%
			Intersection or street density		-0.12%

Table 2 - continued

Study	Study Location	Study Year	Connectivity Variable	Results: VMT/PMT Variable	Results: VMT/PMT Change for 1% Increase in Connectivity
Zhang et al. (2012)	Seattle, WA	2006	Average block length (miles)[1]	VMT per person for all purposes	-0.05%
	Norfolk and Richmond, VA	2009			-0.10%
	Baltimore, MD	2007			-0.03%
	Washington, DC	2007			-0.005%
Khan et al. (2013)	Seattle, WA	2006	Number of 3-way intersections within ½ mile of household	VMT per household for all purposes	-0.09%
			Number of 4-way intersections within ½ mile of household		-0.03%
Holloway, Sundquist, and McCahill (2016)	Massachusetts	2008-2015	Number of intersections linking at least three road segments per square mile of land area	Model-simulated VMT per household[2]	-0.3% (2020) -0.7% (2030) -1.0% (2040)
Ding et al. (2017)	Baltimore metropolitan area, MD	2001, 2007	Street network connectivity within ¼ mile buffer of each trip origin	VMT for commuting trips	−0.265[3]
				VMT for non-commuting trips	−0.111[3]
Chen and Felkner (2019)	Florida	2017	Intersection Density within the city	VMT per capita	0.19%[4]

[1] Longer block length equates to lower street connectivity; effect size is shown for 1% *decrease* in average block length.
[2] Model simulation assumed the effects of increasing the intersection density to the 75th percentile of the state in all areas except the inner core communities, which were already well connected.
[3] Standardized coefficients reported. These effects indicate a one standard deviation increase in network connectivity results in a reduction of driving by 0.265 and 0.111 standard deviations of VMT for commuting and non-commuting trips, respectively.
[4] When interactions between population density and connectivity are included, the main effect of connectivity is uncertain and near zero.

Table 3. Network Connectivity and VMT or PMT

Study	Connectivity Measures	Travel Behavior Measures	Effect Size Source	Notes
Cervero and Kockelman, 1997	Proportion of neighborhood blocks that are quadrilaterals (i.e. 4 straight sides, square or rectangle), based on randomly sampling 20 blocks per sampled neighborhood	Personal VMT per household (VMT per household divided by vehicle occupancy), from 1990 Bay Area Travel Survey (BATS)	Reported in Table 14 in cited paper: For all trips:0.185 For non-work trips: 0.463	Uses ordinary least-squares regression
	Proportion of intersections that are four-way (e.g. not T or Y intersections)		For all trips: No effect For non-work trips: -0.592	
Bento et al., 2003	Road density (lane miles per square mile); area over which connectivity is measured is not specified	VMT per person, from Nationwide Personal Transportation Survey	-0.07 Reported in Table 10 in cited paper, for total impact excluding New York City, as 0.7% increase in VMT for 10% increase in road density	Based on sample that excludes New York City. Uses a two-step model: multinomial logit model for the number of cars per household and a set of ordinary least-squares regression model for VMT per vehicle, with separate models for each category of car ownership (e.g. 1, 2, or 3 or more vehicles per household)
Boarnet et al., 2004	Number of 4-way intersections within a mile of the household	VMT for non-work purposes only, from the 1994 Portland Travel diary survey	-0.06 Reported in Table A-3 in Ewing and Cervero (2010)	Uses ordinary least squares regression
	Number of intersections within 1 mile buffer		-0.19 Reported in Table A-3 in Ewing and Cervero (2010)	

Table 3 - continued

Study	Connectivity Measures	Travel Behavior Measures	Effect Size Source	Notes
Chapman and Frank, 2004	Number of intersections with three or more road approaches intersecting within 1 km road network- based buffer around each home	VMT per person, from the 2001-2002 Atlanta Region travel survey	-0.08 Calculated based on regression coefficient (β) (see Table 114 in cited paper), average intersection density (x_o) and average VMT (y_o) (see Table 113 in cited paper): β=-0.06405 x_o=33.893 y_o=28.236 elasticity = $\beta * x_o / y_o$ = -0.0769	Uses ordinary least squares regression
Vance and Hedel, 2007	Street density measured as kilometers of street links per square kilometer	Person kilometers of travel; from the German mobility panel, collected between 1996 and 2003	-0.04 Reported in Table A-3 in Ewing and Cervero (2010)	Study reports coefficients from VMT models, but no average VMT available needed to calculate percent reduction in VMT associated with increases in connectivity
Fan and Khattak, 2008	Percent of intersections in the household's neighborhood that are not dead ends; dead ends are counted as intersections	Person miles of travel (daily travel distance by all modes) from the 2006 Greater Triangle Travel Study	-0.26 Calculated based on log-linear regression coefficient (β) (see Table 2 in cited paper) and average intersection density (x_o) (see Table 1 in cited paper): β=-0.389 x_o=0.665 elasticity = $\beta * x_o$ = -0.2587	Survey included only workdays and therefore over-represents commute travel. Uses ordinary least squares regression

Table 3 - continued

Study	Connectivity Measures	Travel Behavior Measures	Effect Size Source	Notes
Ewing and Cervero, 2010	Percent 3- or 4-way intersections	Studies analyzed reported VMT per person or per household, for total VMT, commute VMT, or non-commute VMT	-0.12 Reported in Table 3 in cited paper.	Meta analysis of 9 studies, all using different measures of connectivity and VMT; individual elasticities weighted by sample size and averaged
	Intersection (number per area) or street density (street length per area)		-0.12 Reported in Table 3 in cited paper.	
Zhang et al., 2012	Average block size (the larger the block, the lower the street connectivity)	VMT per person, for all purposes	Computed from the ratio of the percentage change in VMT divided by the percentage change in average block size by metropolitan area: Seattle: 0.0454 Virginia: 0.1029 Baltimore: 0.0303 Washington: 0.0048 Note: Increase in block size equates to decrease in connectivity	Uses a Bayesian multilevel model to estimate the effects of average block size and other variables in each metropolitan area
Khan et al., 2013	Number of 3-way intersections within ½ mile of the household	VMT per household, for all purposes	-0.0886 Calculated based on marginal effects reported in Table 6 and values of mean and standard deviation of the independent variables in Table 1 in cited paper	Uses Tobit model to predict VMT and non-motorized miles traveled, using data from the Puget Sound Regional Council 2006 Household Travel survey

Table 3 - continued

Study	Connectivity Measures	Travel Behavior Measures	Effect Size Source	Notes
Khan et al., 2013 (continued)	Number of 4-way intersections within ½ mile of the household		-0.0306	
Wang et al., 2014	Roadway length ("LENGTH")	CO_2 emissions, (CO/ gallon)/MPG	Model 1: β = −0.008 e^(β) = 0.992 Model 2: β = −0.020 e^(β) = 0.980 Reported in Table 3 in cited paper.	Uses two models to estimate log transformed CO2 emissions Model 1: Heckman sample selection regression Model 2: Conventional OLS regression
	Connected node ratio / Number of all intersections divided by the number of intersections plus cul-de-sacs ("CNR")		Model 1: β = −0.149 e^(β) = 0.862 Model 2: β = 1.510 e^(β) = 4.527 Reported in Table 3 in cited paper.	
	Link node ratio / Number of roadway segments divided by the number of intersections or cul-de-sacs in a buffer ("LNR")		Mean = 1.37 SD = 0.262 Reported in Table 2 in cited paper.	

Table 3 - continued

Study	Connectivity Measures	Travel Behavior Measures	Effect Size Source	Notes
Wang et al., 2014 (continued)	Number of cul-de-sacs ("NDANGLE")		<u>Model 1:</u> β = −0.001 e^(β) = 0.999 <u>Model 2:</u> β = 0.004 e^(β) = 1.004 Reported in Table 3 in cited paper.	
	Length per node ("LENGPN")	CO_2 emissions, (CO/gallon)/MPG	<u>Model 1:</u> β = 0.182 e^(β) = 1.200 <u>Model 2:</u> β = −0.387 e^(β) = 0.679 Reported in Table 3 in cited paper.	
Holloway et al., 2016	Number of intersections linking at least three road segments per square mile of land area	VMT per household	-0.082 (standardized coefficient) Reported in Table 4 in cited paper.	Uses multiple linear regression.
Barrington-Leigh & Millard-Ball, 2017	Mean nodal degree of block	Vehicles owned per household	-0.15 Reported in Table 3 in cited paper.	Uses instrumental variable model, where topography is an 'instrument' for street-network sprawl. Study also controls for arbitrary (unmeasured) fixed effects at the scale of counties or States.
	Number of intersections with 4 or more lanes (% of block intersection)	Vehicles owned per household	−0.72 Reported in Table 3 in cited paper.	

Table 3 - continued

Study	Connectivity Measures	Travel Behavior Measures	Effect Size Source	Notes
Barrington-Leigh & Millard-Ball, 2017 (continued)	Immediate action to promote a gridded street network	Model-simulated VMT	5.6% - 8.8% Reported in Section 3.3	
Ding et al., 2017	Street network connectivity calculated using number of intersections (except cul-de-sacs) within ¼ mile buffer of each trip origin	Study analyzed commute VMT and non-commute VMT per household, from 2001 National Household Travel Survey (NHTS) Baltimore Add-on, Employment data is from 2007.	Commuting coefficient: −0.265 Non-commuting coefficient: −0.111 Reported in Table 4 in cited paper.	Uses multiple-group structural equation model (SEM)
Chen and Felkner, 2019	The density of intersections within the city boundary	VMT per capita	0.193 Reported in Table 3 in cited paper.	Uses multiple regression models, one with interaction terms while the other without.
Boeing et al., 2024	Intersection density (In units of 10,000 intersections per square kilometer)	CO_2 emissions in tonnes per person	-102.619 Standard error (20.849), $p<0.001$ Reported in Table 5 in cited paper.	Uses a global ordinary least squares (OLS) regression mode
	k average		-1.500 Standard error (0.570), $p<0.01$ Reported in Table 5 in cited paper.	
	Straightness Ratio of straightline distances between nodes to network distances between nodes		-2.682 Standard error (1.795) Reported in Table 5 in cited paper.	