Impacts of Network Connectivity on Passenger Vehicle Use and Greenhouse Gas Emissions

Policy Brief

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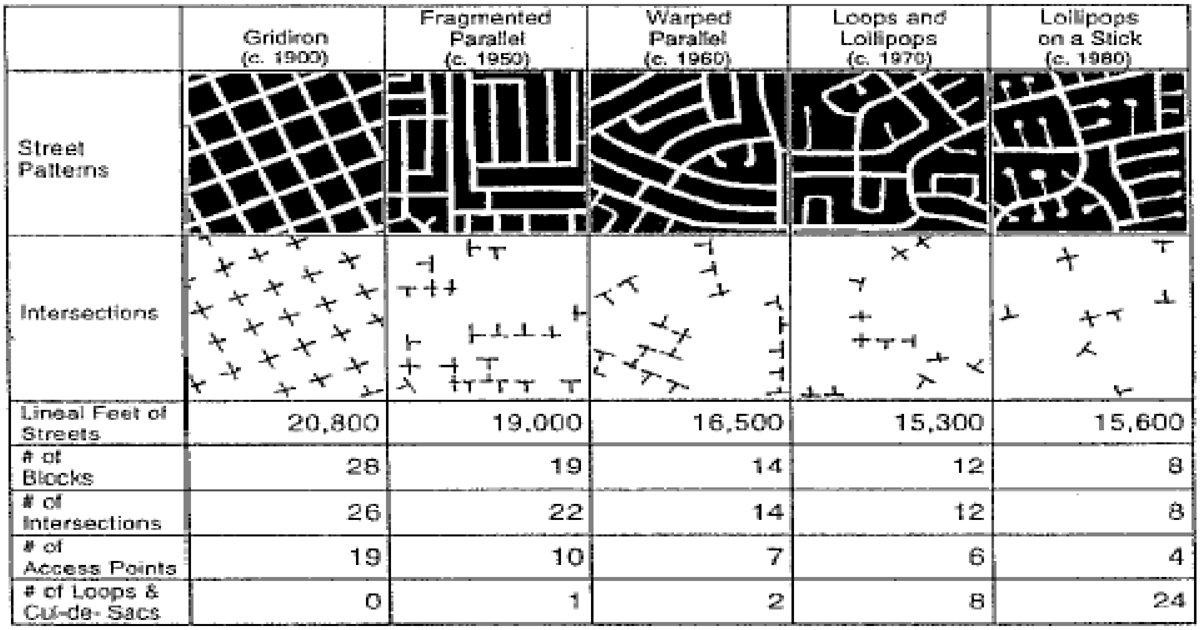
Policy Description

Network connectivity describes the quality of the connections that link each of the points in a community with one another. The structure of the street network, 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, in particular, 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 Figure 1, 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).



	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 Intersections	26	22	14	12	8
# of Access Points	19	10	7	6	4
# of Loops & Cul-de-Sacs	0	1	2	8	24

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

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 greenhouse gas emissions from the effects of these other characteristics can be difficult.

Impacts of Connectivity

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 his 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 (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.

Effect Size

Seven studies provide evidence on the effect of connectivity on VMT. One study reports the effect on person miles of travel (PMT). It is not possible 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 measured either as percent change in VMT or PMT for a 1 percent increase in connectivity.

The studies summarized in Table 1 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). The higher estimated effects are likely to reflect differences between neighborhoods beyond just connectivity, as noted earlier. However, the study by Fan and Khattak (2008) controls for differences in socio-economic characteristics and attitudes of residents, as well as differences in built environment characteristics between neighborhoods, but still has the highest effect size for travel for all purposes. Unfortunately, this study measures PMT and not VMT (though in suburban settings, the effect is likely to be similar given the low use of modes other than driving), and its measure of connectivity, focusing on the prevalence of dead-ends, is useful for comparing cul-de-sac networks to grid networks, but not different grid networks to one another.

Table 1: Network Connectivity and VMT or PMT

Study	**Study Location**	**Study Year**	**Results**		
			Connectivity Variable	*VMT/PMT Variable*	*VMT/PMT Change for 1% Increase in Connectivity*
Cervero and Kockelman (1997)	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%
Zhang et al. (2012)	Seattle, WA	2006	Average block length (miles)*	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%
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%
Fan and Khattak (2008)	Triangle Area, NC	2006	Percent of intersections that are not dead-ends	Person miles of travel (PMT) for all purposes and all modes	-0.26%

*Longer block length equates to lower street connectivity; effect size is shown for 1% *decrease* in average block length.

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 1. 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 metropolitan regions.

Evidence Quality

The studies in Table 1 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). Fan and Khattak (2003) control for more factors than the other studies. By controlling for attitudes, the study reduces the possibility that the differences in VMT between neighborhoods with different levels of connection stem from the “self-selection” of residents who prefer to drive less into neighborhoods with higher connectivity.

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.

Caveats

When applying the results of the cited studies, it is important to note that they mostly focus on street connectivity in residential areas. 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 network might be different from the connectivity of the street network, owing to pedestrian 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 walking.

Greenhouse Gas Emissions

No available studies provide direct evidence on the effect of connectivity on greenhouse gas (GHG) emissions. Translating VMT reductions into GHG emissions reductions depends on the nature of the VMT eliminated (e.g. speeds, acceleration, deceleration, times vehicle is started) and the types of vehicles owned by residents who decrease their driving. 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 emissions reductions to be similar to VMT reduction, if vehicle fleet composition and driving patterns are unchanged. While the pattern of such changes in response to connectivity has not been documented, it is reasonable to expect that policies that reduce VMT will also lead to reductions in GHG emissions.

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 health-related impacts. Non-motorized travel is an important source of physical activity and contributes to many health benefits as well (Handy, 2009). Recent 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.

Examples

A number of 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 at 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 a bridge 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.

References

Bento, A.M., Cropper, M.L., Mobarak, A.M., and Vinha, K. (2003). The impact of urban spatial structure on travel demand in the United States. World Bank policy research working paper, 3007.

Boarnet, M. G., Nesamani, K. S., and Smith, C. S. (2004). Comparing the influence of land use on nonwork trip generation and vehicle distance traveled: An analysis using travel diary data. Paper presented at the 83rd annual meeting of the Transportation Research Board, Washington, DC.

Cervero, R. and Kockelman, K. (1997). Travel demand and the 3Ds: Density, diversity, and design. *Transportation Research D*, 2(3): 199-219

Chapman J. and Frank L (2004). *Integrating Travel Behavior and Urban Form Data to Address Transportation and Air Quality Problems in Atlanta*. SMARTRAQ full final technical report, Georgia Tech Research Institute, Atlanta, GA.

Dumbaugh, E. and Rae, T. (2009). Safe Urban Form: Revisiting the Relationship Between Community Design and Traffic Safety. *Journal of the American Planning Association*, 75(3): 309-329.

Ewing, R. and Cervero, R. (2010). Travel and the Built Environment: A Meta-Analysis. *Journal of American Planning Association*, 76(3): 265-294.

Fan, Y. and Khattak, A.J. (2008). Urban Form, Individual Spatial Footprints, and Travel: Examination of Space-Use Behavior. *Transportation Research Record,* 2082: 98–106.

Handy, S. (2009). Walking, Bicycling, and Health. In S. Malekafzali, ed., *Healthy, Equitable Transportation Policy*, PolicyLink and Prevention Institute, Oakland, CA. Available: http://www.convergencepartnership.org/atf/cf/%7B245a9b44-6ded-4abd-a392-ae583809e350%7D/HEALTHTRANS_FULLBOOK_FINAL.PDF

Handy, S., Paterson, R., and Butler, K. (2003). *Planning for Street Connectivity: Getting from Here to There*. Planning Advisory Service Report Number 515. Chicago, IL: American Planning Association.

Khan, M., K. M. Kockelman and X. Xiong (2013). Models for Anticipating Non-motorized

Travel Choices, and the Role of the Built Environment. Paper presented at the 92nd annual meeting of the Transportation Research Board, Washington, DC.

Marshall, W. E. and Garrick, N. W. (2010). Effect of street network design on walking and biking. *Transportation Research Record: Journal of the Transportation Research Board*, 2198(1): 103-115.

Marshall, W. E. and Garrick, N. W. (2011). Does street network design affect traffic safety? *Accident Analysis & Prevention*, 43(3): 769-781.

Rifaat, S. M., & Tay, R. (2009). Effects of street patterns on injury risks in two-vehicle crashes. *Transportation Research Record*, 2102: 61-67.

Rifaat, S.M., Tay, R., and de Barros, A. (2010). Effect of Street Pattern on Road Safety Are Policy Recommendations Sensitive to Aggregations of Crashes by Severity? *Transportation Research Record,* 2147: 58-65.

Saelens, B. and Handy, S. (2008). Built Environment Correlates of Walking: A Review. *Medicine & Science in Sports & Exercise* 40(7S): S550-S566.

Southworth, M. and Ben-Joseph, E. (1997). *Streets and the Shaping of Towns and Cities*. New York: McGraw-Hill.

Tal, G. and Handy, S. (2012). Measuring non-motorized accessibility and connectivity in a robust pedestrian network. *Transportation Research Record* 2299, 48-56.

Zhang, L., J. H. Hong, A. Nasri and Q. Shen (2012). How built environment affects travel behavior: A comparative analysis of the connections between land use and vehicle miles traveled in US cities, *Journal of Transport and Land Use,* 5(3): 40-52.

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