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Assessment of effects of street connectivity on traffic performance and sustainability within communities and neighborhoods through traffic simulation

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ABSTRACT

Street connectivity measures the density of networks and directness of paths. Increasing street connectivity is one of the ways to increase network capacities, achieve a better distribution of traffic flows, improve accessibility and encourage the use of non-motorized traffic modes. This paper analyzes the effects of enhanced street connectivity on traffic performance and sustainability through transportation modeling of three community-scale (mesoscopic) and three neighborhood-scale (microscopic) networks in Utah. It discusses traffic performance and sustainability effects that increased street connectivity has on different types and sizes of networks simultaneously. The analysis was performed as a part of the Utah Street Connectivity Study. On the community-scale level, the results showed a significant reduction in network travel times and delays after the implementation of increased street connectivity alternatives. Increased street connectivity on the community-scale level was compared to street widening, and outperformed it in most cases. The distribution of traffic flows was more balanced in the networks with more connectivity, with a reduction in Vehicle Miles Traveled (VMT). This study relates street connectivity performance measures on different levels to the sustainability of transportation networks. It shows that increased connectivity, especially in neighborhoods, leads to more sustainable environments.

1. Introduction

Street connectivity is a measure of the density of network connections and directness of paths. Good street connectivity has many short links and intersections, with few or no culs-de-sac (Victoria Transport Policy Institute, 2017). It relates to the number of intersections along a segment, and asserts how an area is connected to the system (Tasic, Zlatkovic, Martin, & Porter, 2015). In a network with more connectivity travel distances decrease, shorter paths exist between each origin and destination, and more destinations become accessible within the given time budget. It also improves the viability of active transportation modes and reduces the response time for emergency services (Lehigh Valley Planning Commission (LVPC) (2011)).

Street connectivity is one of the important characteristics of sustainable cities (McInelly et al., 2012; Greenberg, 2008; Porta and Renee, 2005; Randall & Baetz, 2001). People need to be able to travel within the community in a safe and efficient manner. A sustainable street network creates such an environment and enables a choice of transportation modes and routes. Connections among different transportation modes need to be easy and convenient. The routes need to be direct and safe. More street connectivity that can support all modes, provide direct routes and connections and create a safer environment is one way of improving the sustainability of street networks.

A group of transportation and planning agencies in Utah (Wasatch Front Regional Council (WFRC), Mountainland Association of Governments (MAG), Utah Department of Transportation (UDOT), Utah Transit Authority (UTA) and cities) initiated the Utah Street Connectivity Study (USCS) in 2016 to establish recommendations

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applicable to Utah conditions. These recommendations were tested on three community-scale networks and three neighborhood-scale networks of different types. The community-scale networks included Layton (an urban community), Lehi (a suburban community), and Tooele (a rural community). The neighborhood-scale networks consisted of downtown, school, and other high-activity areas within the community networks.

This paper explores the effects of street connectivity improvements on transportation systems for community and neighborhood-scale networks as one of the key steps in developing sustainable environments. The analysis was performed through meso and microscopic traffic simulation modeling. The models were developed in PTV VISUM and VISSIM simulation packages and recorded different levels of traffic performance and measures of effectiveness. This paper is unique in the sense that it simultaneously explores the effects of street connectivity on different sizes and types of networks. These effects are not the same, and in some cases, strategies implemented in different areas might contradict each other. For example, improved connectivity in a part of a community network can have negative impacts on neighborhoods, and vice versa. The measures used for one type of network in most cases are not transferable to other types. This paper aims to determine the most appropriate measures of effectiveness that can directly or indirectly quantify the effects of street connectivity improvements in different environments. It also explores how street connectivity performance measures relate to the sustainability of transportation networks.

2. Literature review

Increasing street connectivity is one of the strategies to increase network capacities, achieve a better distribution of traffic flows, improve accessibility, and increase options for non-motorized traffic modes (Tasic et al., 2015; Zhou, Martin, Zlatkovic, & Tasic, 2013; Lehigh Valley Planning Commission (LVPC), 2011; Alba and Beimborn, 2005; Portland Metro, 2004). Increased street connectivity balances traffic distribution among different routes in a network, providing more options and better accessibility for local traffic. Well-connected street networks also improve mobility by allowing more direct trips (McInelly et al., 2012). Destinations become more accessible by walking, and the capture area of transit stations increases.

Street connectivity research studies reviewed in this paper analyzed traffic mobility, mode choice, traffic safety, and the relationship between street connectivity and sustainability. In general, studies found that enhanced connectivity tends to decrease travel time and congestion, and therefore increase regional mobility. On the other hand, through traffic on local streets must be controlled to prevent the deterioration of conditions in local neighborhoods. Accessibility is improved, with more options for non-motorized traffic and access to transit, creating the prerequisites for sustainable networks.

Simulation modeling has been used to assess the effects of street connectivity on transportation mobility in several studies. McNally and Ryan (1992) analyzed Vehicle Miles Traveled (VMT), average trip lengths and link congestion for two hypothetical networks that modeled the characteristics of neo-traditional (more connectivity) and conventional suburban community (less connectivity). They used mathematical models for trip generation, distribution and assignment, as well as performance measuring. The results showed that the neo-traditional network reduced VMT and trip lengths by 11%, travel times by 13%, and had no links operating at the volume-to-capacity ratio greater than one. Alba and Beimborn (2005) explored the impact of street connectivity of local residential areas on traffic volume of neighboring arterials using a travel model of Tallahassee, Florida as the case study network. The results showed that increased connectivity could reduce the traffic volume of arterials significantly (up to 85%) when the difference in travel speeds between arterials and local streets is small, and the capacity of the arterial is low or fully utilized. Tasic et al. (2015) studied the effects of increased connectivity on traffic operation in West Valley City, Utah. They used traffic equilibrium assignment software and compared twelve different scenarios including increased connectivity, street widening, and traffic calming measures. The increased connectivity scenarios accommodated more traffic than the scenarios with street widening (5%–12% depending on the level of connectivity) and benefited both traversing and local traffic.

Some empirical studies also found a reduction in VMT in better-connected networks. A study by Portland Metro (2004) found that VMT and trip lengths reduce by 2% and vehicular delays by 14% when a network goes from low to moderate density. Another study in Puget County, WA, found that a 10% increase in relative connectivity for pedestrians resulted in a 23% decrease in VMT of local travel (Victoria Transport Policy Institute, 2017).

Street connectivity measures, in combination with other urban design strategies, have a potential to improve traffic safety. A well-connected local network encourages slower driving, since drivers encounter various travel modes and more intersections. Marshall and Garrick (2011) used data from 24 cities in California over the period of 11 years to analyze the effects of street and street network characteristics on total, severe injury, and fatal crashes. They found that denser street networks experienced fewer crashes for all severity levels, ranging between 15% and 70%, depending on the intersection density per square mile. Mohan, Bangdiwala, and Villaveces, (2017) used the Fatality Analysis Reporting System (FARS) data to determine the changes in fatal crashes for different network configurations in randomly selected cities. The results showed that for every intersection added per kilometer of road, the relative reduction in fatalities per 100,000 was 44%. They also found that longer lengths of non-arterial streets were significantly associated with lower fatality rates. However, longer lengths of main arterials were significantly associated with higher fatality rates.

Well-connected networks encourage active transportation modes and transit use. The Portland Metro study (2004) found that increased connectivity leads to better mobility for cyclists and pedestrians, with improved access to destinations. The study considered three scenarios of different connectivity levels and found that increased connectivity yields better access. The results showed that 74% of destinations were accessible in the moderate connectivity scenario, and 99% in the high connectivity scenario. Access increased due to the shorter distances that pedestrians and bicyclists have to travel. A study of urban neighborhoods in Seattle found that the highest proportion of pedestrian trips (close to 18%) occur in areas where paths are relatively more direct to nearby destinations on foot than by car (Canada Mortgage & Housing Corporation, 2008). Marshall and Garrick (2011) studied different cities in California with different street network shapes and densities. The study found that radial networks (with less connectivity) had a high automobile share (97%). Well-connected grid networks had 78% of automobile share, with greater percentages of transit, bicycle, and pedestrian shares. Berrigan, Pickle, and Dill, (2010) found a statistically significant correlation between aggregate measures of street connectivity on one side, and walking and biking on the other. Yi (2008) explored street connectivity and pedestrian accessibility for typical cul-de-sac and grid networks. He concluded that the grid network provides better accessibility to destinations for pedestrians, but by providing separate pedestrian trails the accessibility of cul-de-sacs can be improved up to a point where it is comparable with a grid network. Tal and Handy (2012) explored various measures of network connectivity and pedestrian accessibility for non-motorized trips. They showed that pedestrian network continuity is an important part of non-motorized accessibility.

Connectivity improves the efficiency of bus transit by providing more direct routes (Lehigh Valley Planning Commission (LVPC), 2011; Tasic et al., 2015). The collector street network plays a major role in improving transit efficiency in suburban areas by providing a connection between arterials and local network for local access, usually by walking. Furthermore, a good collector network creates more options for routing bus transit closer to neighborhoods. Ewing and Cervero (2010) performed a meta-analysis of the past literature on the impact of built environment on travel. They organized built environment measures into five categories called D variables (Density, Diversity, Design, Destination Accessibility, and Distance to transit), which are in direct correlation with street connectivity measures. The results confirmed that street connectivity characteristics have significant impacts on transportation mode choice. Transit use is also related to the measures of design, destination accessibility, distance to transit, and demographics (Ewing et al., 2011; Tian et al., 2015).

Better accessibility to destination, network designs that support non-motorized transportation and access to transit, and safer environments for all users are some of the key requirements for sustainable cities (CNU, 2012). Increased street connectivity provides these benefits. Greenberg (2008) explored sustainability strategies for arterials, neighborhoods and downtown areas. High street connectivity was recognized as the most important feature for sustainable neighborhoods, as well as the desired strategy for downtown areas. Direct and safe pedestrian routes and the presence of transit were also recognized as important features for neighborhoods. Rafiemanzelat, Emadi, and Aida Jalal Kamali, (2017) determined that network connectivity, including streets, public transit, and walkways, are the main elements of functional environments that contribute to city sustainability. Similar findings were reported by Porta and Renne (2005) who investigated the elements of urban design on sustainability. They concluded that a sustainable street network should contain a high proportion of four-way intersections, few cul-de-sacs, and small street block sizes, which are all characteristics of good connectivity.

The literature shows that connected transportation networks perform in a way that contributes to sustainable environments. This paper analyzes the effects of increased connectivity on traffic performance on community and neighborhood levels. It further develops appropriate performance measures and discusses their relations to sustainability.

3. Simulation-based analysis of street connectivity

This paper focuses on traffic-related benefits of street connectivity and their effects on sustainability of networks of different types and sizes. Traffic performance and Measures of Effectiveness (MOEs) were analyzed through traffic simulation. Traffic modeling consisted of two types of models, mesoscopic models of community-scale networks, and microscopic models of selected neighborhood networks. The two types of models were integrated by using the outputs of the mesoscopic models (traffic volumes and routing decisions) as inputs for microscopic models. Mesoscopic traffic equilibrium assignment models were developed in PTV VISUM software, using the existing Regional Travel Model (RTM) developed by WFRC as the base. The three case studies (Lehi, Layton, and Tooele) were created as subnetworks. The Tooele model did not exist in the RTM, and it was manually created in VISUM. The subnetwork models were recalibrated using available traffic data. Recalibrated demand matrices were used to perform network assignment for the case study networks and create models of the existing conditions. The increased street connectivity alternatives were added to the VISUM models, and the assignment was repeated to measure the changes in traffic patterns caused by the changes in street connectivity. Microsimulation models were developed in PTV VISSIM for selected neighborhood areas, such as Thanksgiving Point in Lehi, Downtown area in Layton, and West Erda in Tooele. These areas were selected for the study as representatives of different neighborhood and district types. VISSIM models were exported directly from VISUM to keep the current demand obtained through the traffic equilibrium assignment. These models include more detailed network elements, such as local roads and intersections with the existing control type (signalized, stop-controlled, yield, or uncontrolled). The VISSIM models were developed for the existing conditions and street connectivity alternatives. This hybrid approach recorded different MOEs.

The models included existing conditions and networks with increased street connectivity. The mesoscopic models were enhanced by adding collector streets and intersections to bring the existing network closer to generally adopted standards for street connectivity. The microscopic models were enhanced by adding local streets and intersections to bring them closer to standards, and improve connection for all modes of transportation. A more detailed description of these networks and a comparison of results are provided in the following sections.

4. Test-case networks of existing conditions

4.1. Community-scale VISUM networks

The community-scale networks for Lehi (suburban), Layton (urban) and Tooele (rural) were developed and simulated in VISUM. The equilibrium traffic assignment was performed based on existing and calibrated Origin-Destination (OD) matrices and field traffic volume data. The community-scale networks were simulated for a typical weekday PM peak period (3–6 pm). The VISUM networks show streets that have a functional class of collectors and higher. Volume data were obtained from three different sources. UDOT's Performance Monitoring Stations (PeMS) data were used to calculate PM peak period volumes and directional distribution for freeways, with April 28, 2016, as the typical day. Volume data for other locations were obtained from UDOT's Annual Average Daily Traffic (AADT) maps and adjusted for the PM volume and directional split. Volumes for certain links near signalized intersections were recorded from the UDOT's Signal Performance Metrics (SPM) system. The existing OD matrices were used for the sub-network equilibrium traffic assignment for Lehi and Layton, while a matrix was created for Tooele based on the defined Traffic Analysis Zones (TAZs). The Lehi network consisted of 60 TAZs, Layton of 51 TAZs, and Tooele of 17 TAZs. The layouts of the networks are given in Fig. 1. Fig. 1 also shows the location of the neighborhood-scale networks analyzed through microsimulation, as described later.

The available link volume data were entered into the corresponding VISUM links for OD estimation purposes and sub-network calibration. The OD matrices were corrected using VISUM's T-Flow Fuzzy function, which adjusts zone productions, attractions, and zone-to-zone distribution to closely match field link volumes. The corrected OD matrices were used to perform equilibrium traffic assignment for the study networks. Model calibration was performed by comparing the observed link volumes to those obtained through simulation. Fig. 2 shows the calibration of the community-scale networks after the T-Flow Fuzzy matrix correction.

4.2. Neighborhood-scale networks

One neighborhood-scale network from each community network was selected for further analysis of connectivity improvements. The networks were analyzed in VISSIM microsimulation software for a more detailed insight into their operations. Thanksgiving Point was chosen from the Lehi network as a representative of a campus neighborhood, which in this study included any campus-type neighborhood, such as an educational campus, shopping center, office park and similar. Downtown Layton from the Layton network was selected as a representative of an urban neighborhood, and West Erda from the Tooele network as a representative of a rural neighborhood. These networks were cut from the VISUM models using previously loaded traffic assignment and exported into VISSIM for further analysis. Detailed traffic signal settings were included in VISSIM with the signal timing data obtained from UDOT's MaxView system. Freeway were not included in the analysis, but the freeway ramps were, where applicable.

5. Networks with increased connectivity

The existing networks were analyzed for the main connectivity

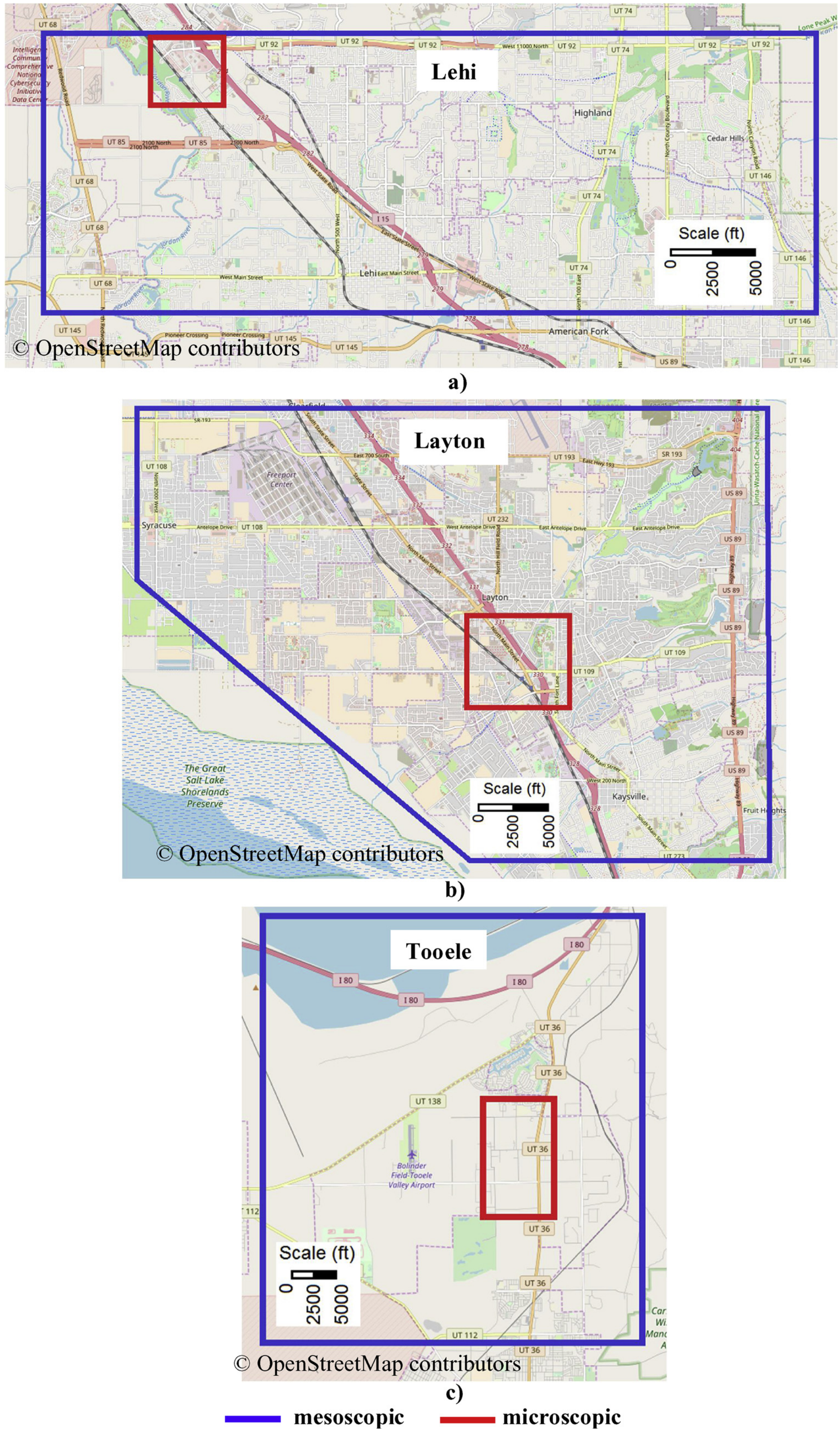

Fig. 1. Layout of Community-Scale Networks.
a) Lehi; b) Layton; c) Tooele.

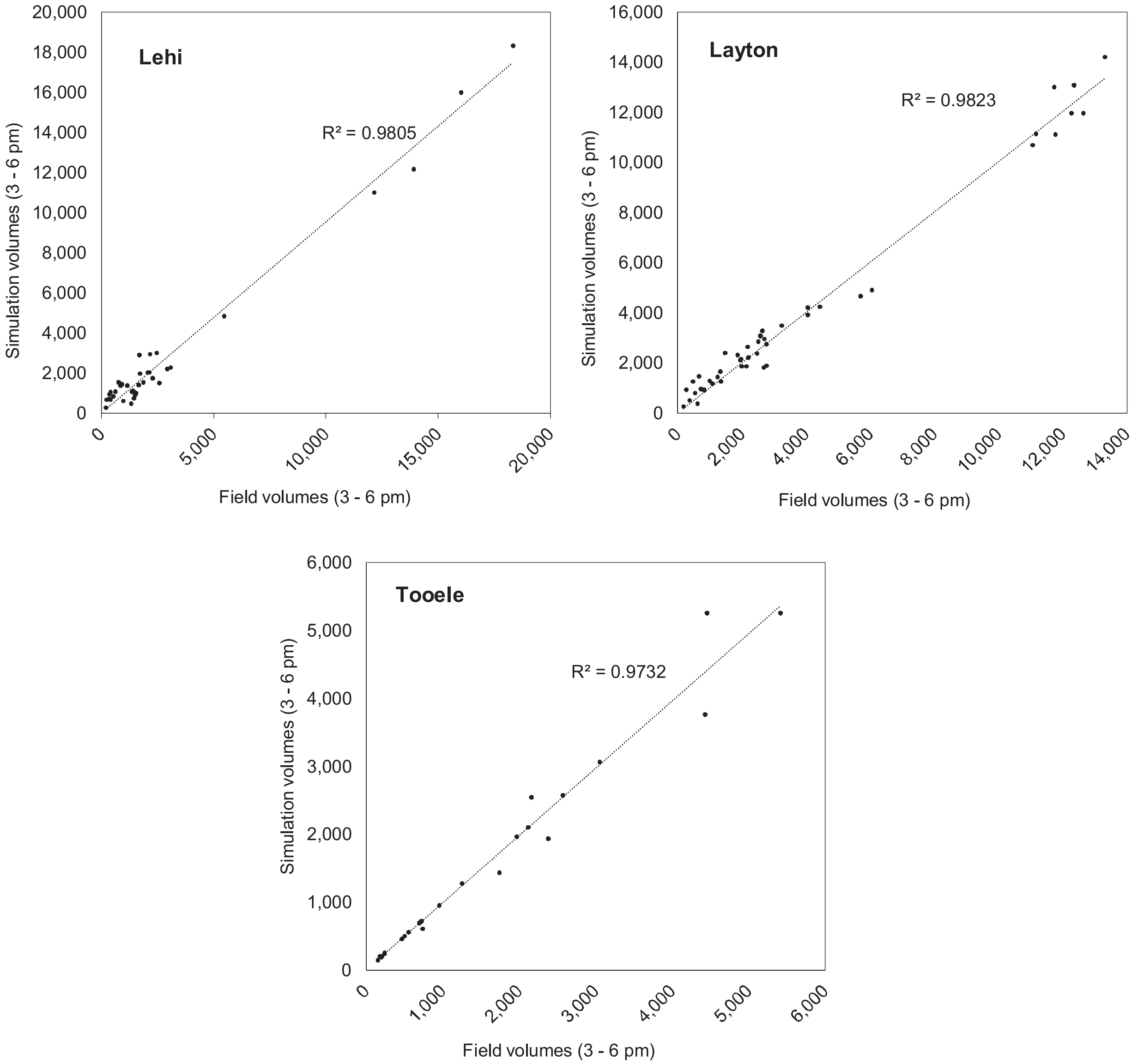

Fig. 2. Calibration of Community-Scale Models.

parameters that included connectivity index, intersection density, destination access, and accommodation for all users. Street connectivity strategies were then developed and implemented for each network based on the findings and recommended standards from the literature. To make a comparison to the existing conditions, the same OD matrices were used to perform traffic assignment in the new models. By controlling the OD demand, traffic flows were distributed throughout the networks based on street characteristics, mainly connections, capacities, speeds, and volume-to-capacity ratios. This approach allowed for measuring traffic effects caused only by the changed street connectivity. The community-scale networks were enhanced by adding collector streets and corresponding intersections. The locations for added connections were determined by the research team after analyzing the existing networks and identifying parts where the street connectivity was below the recommended standards.

Capacity increase and operational improvements in a network can also be achieved by street widening, i.e. adding travel lanes to existing roadways, which is a traditional way of adding capacity. The result would be a redistribution of traffic flows within the network, with the roads with increased capacity attracting more traffic. Street widening scenarios were tested on the three community-scale networks for the purpose of comparing street connectivity with street widening. In Lehi, the following streets were widened by adding a lane in each direction: SR 92, Lehi Main Street, State Street, and Alpine Highway. In Layton, a lane was added to the Main Street south of Antelope Drive, Fairfield, and Antelope Drive east of Hillfield. In Tooele, an extra lane in each direction was added to West Erda Way and Bates Canyon Road.

Therefore, on the community-scale level, three scenarios were developed for each network: Base (existing conditions), Increased Connectivity, and Street Widening. Outputs from VISUM were used to compare the three scenarios for the network length (in lane-miles), 3-hour traffic volumes, free-flow and actual network travel times, as well as delays and VMT. A comparison of VMT and delays for some of the main arterials and collector streets was also performed.

According to the recommendations for neighborhood connectivity improvements, the existing networks were modified with added connections, which were defined as local streets and adjoining intersections. Street widening was not performed on the neighborhood level, so two scenarios were developed and compared for each sub-network: Base and Increased Connectivity. The same vehicle inputs were used in each pair of scenarios so that the effects of street connectivity could be measured and compared directly. The new traffic assignment/routing for the increased connectivity scenarios was created in VISUM and then replicated in VISSIM. Since these analyses were performed in microsimulation, each scenario was run for ten different randomly seeded runs to account for variations on the individual vehicle level. Each simulation included a 15-minute warm-up time and three hours of output recording.

6. Results and discussion

The original data of this study include simulation results (meso and micro) in Excel format, as well as the detailed statistical test results performed in SPSS in pdf format. The data files are available at Mendeley Data (https://doi.org/10.17632/7mgxgb86rs.1).

Sets of statistical tests were performed on the simulation results to determine the statistical significance in performance measures among different scenarios. Based on the parameters and input data, an appropriate test was chosen for analysis. A One-Way MANOVA is an Analysis of Variance (ANOVA) with several dependent variables. The purpose of a One-Way MANOVA is to discover if the dependent variables change with the independent variable. Dunnett's multiple comparison post hoc test (or Dunnett's T3 when equal variances could not be assumed) was conducted to identify the alternative scenario that was statistically significantly different from the base scenario at the 95% confidence level. The Kruskal-Wallis (KW) test is a nonparametric version of the ANOVA/One-Way MANOVA, and was used when sample sizes were small and non-normal. For the community-scale networks with three alternatives, the KW test compares all pairs of alternatives and reports the lowest p-value, but does not directly show where the statistical difference exits. Therefore, where KW test reported p-values of less than or equal to 0.05, Dunn's post hoc test was conducted to identify the alternative that was statistically significantly different from the Base scenario at the 95% confidence level.

6.1. Community-scale networks

Table 1 shows MOE comparisons on the community-scale level for the Lehi network for the three scenarios. The KW/One-Way MANOVA and post hoc tests were used to determine the statistically significant difference in alternatives compared to the Base scenario.

The lane-miles increase in the increased street connectivity scenario was 25%, about twice as much as in the street widening scenario. The total volumes and VMT in the increased connectivity scenario were significantly reduced, while they increased after street widening. Street widening resulted in about the same actual travel time as increased connectivity, but the delay reduction is still higher in the street connectivity scenario (24% vs. 17% reduction), both of which are significantly different compared to the base scenario. The total network capacity in the connectivity scenario increased 18%, opposed to a 13% increase in the street widening scenario.

The same analysis was performed for the Layton community-scale network. The results for the network level MOEs are given in Table 2. The data for the entire Layton community-scale network were of equal variances and non-normal; however, since the sample sizes were large, a One-Way MANOVA test was performed. Significant differences were not found, therefore univariate and post hoc tests were not conducted.

The lane-miles increase in the increased street connectivity scenario was about 11%, twice as much as in the street widening scenario. There was about 3% increase in traffic volumes with more connectivity, opposed to a 1% reduction after street widening. A small reduction in VMT was recorded in both alternatives. The total network capacity in the connectivity scenario increased more than 10%, compared to a 4% increase for street widening. A total delay reduction of about 9% was recorded in both alternatives. None of the changes on the network-wide level for the Layton network were statistically significant.

Table 3 shows the MOE results for the Tooele community-scale network. Compared to base, the total lane-miles in the street connectivity scenario increased about 15%, which was a significant increase, compared to 4% in the street widening scenario. The traffic volumes slightly increased in both alternative scenarios, but the VMT remained unchanged. More connectivity significantly increased the total network capacity by about 11% compared to the base scenario. A significant reduction in total network delays was recorded in both alternatives (15% and 20% reduction in increased connectivity and street widening, respectively).

Table 4 shows MOEs for some of the major arterials in all three community-scale networks. The comparisons were performed for increased connectivity and street widening scenarios versus the base scenario.

In the Lehi network, the widened streets attracted more traffic, with an increase between 8% and 31%, but the delays reduced due to the lower volume-to-capacity ratios. All major arterials experienced reduced VMT and delays in the increased connectivity scenario, with most of them being significantly different from the base. For all major arterials in the Layton network, increased connectivity resulted in reductions in VMT (1% to 24%) and total delays (1% to 65%). The delay reduction was statistically significant for SR 193 and Gordon Avenue. Street widening resulted in both reductions and increases in VMT, depending on the street, and the total delays reduced 3% to 35%. None of the changes in the street widening scenario were statistically significant. In the Tooele network, the distribution of traffic volumes was different in the two scenarios, with increased street connectivity reducing VMT and delays along the analyzed streets, with an exception of Village Blvd. The VMT were reduced 3% to 35%, with a 15% increase along Village Blvd. The delays were reduced up to 60%. In the street widening scenario, VMT were mostly increased, with a reduction in delays due to the lower volume-to-capacity ratios. This shows a much better distribution of traffic flows in a more connected network.

In general, increased capacities and reduced delays were observed in all community-scale networks. These are the desired characteristics of sustainable networks, therefore increased street connectivity leads to more sustainable communities. Better connectivity also creates transit-friendly environments, with more choices for transit routing and larger catchment areas. This is another characteristic of sustainable networks, and it should be explored more in follow-up studies.

Table 1
MOE Comparison for Lehi Community-Scale Network.

	Base	Increased Connectivity	Street Widening	Inc. con. / Base	Street wid. / Base	KW p-value
Length (lane-mi)	313.64	391.78	349.53	24.91%	11.44%	0.306
Volumes (vp3 h)	910,023	901,750 *	918,807	−0.91%	0.97%	< 0.001
Total network capacity (veh/h)	739,312	875,028	833,402	18.36%	12.73%	0.387
Free-flow travel time (h)	8.17	10.52	8.17	28.82%	0.00%	0.308
Actual travel time (h)	38.11	33.25 *	33.07 *	−12.74%	−13.23%	0.001
Total Delay (h)[1]	29.94	22.73 *	24.90 *	−24.08%	−16.84%	< 0.001
3 hr VMT (mi)	320,135	314,238*	319,486	−1.84%	−0.20%	0.003

[1] Delay defined as actual travel time minus free-flow travel time.
* Value statistically significantly different from the corresponding Base value based on Dunn's post hoc test.

Table 2
MOE Comparison for Layton Community-Scale Network.

	Base	Increased Connectivity	Street Widening	Inc. con. / Base	Street wid. / Base
Length (lane-mi)	356.05	396.45	376.79	11.35%	5.82%
Volumes (vp3 h)	1,405,481	1,446,527	1,389,940	2.92%	−1.11%
Total network capacity (veh/h)	905,662	1,000,130	943,052	10.43%	4.13%
Free-flow travel time (h)	7.31	8.54	7.31	16.81%	0.00%
Actual travel time (h)	40.40	38.81	37.55	−3.94%	−7.05%
Delay (h)	33.09	30.27	30.25	−8.53%	−8.61%
3 hr VMT (mi)	531,861	528,495	530,424	−0.63%	−0.27%

Table 3
MOE Comparison for Tooele Community-Scale Network.

	Base	Increased Connectivity	Street Widening	Inc. con. / Base	Street wid. / Base	KW p-value
Length (lane-mi)	437.60	502.19 *	454.48	14.76%	3.86%	0.015
Volumes (vp3 h)	360,539	376,206	368,055	4.35%	2.08%	0.337
Total network capacity (veh/h)	1,267,400	1,399,900 *	1,309,800	10.45%	3.35%	< 0.005
Free-flow travel time (h)	11.14	13.09	11.14	17.49%	0.00%	0.048 **
Actual travel time (h)	13.24	14.88	12.82	12.41%	−3.15%	0.748
Delay (h)	2.10	1.80 *	1.68 *	−14.55%	−19.83%	0.017
3 hr VMT (mi)	120,625	120,302	121,499	−0.27%	0.72%	0.116

* Value statistically significantly different from the corresponding Base value based on Dunn's post hoc test.
** Adjusted p-value from post hoc test did not show a significant difference.

6.2. Neighborhood-scale networks

The microsimulation results, averaged from ten simulation runs, for the Thanksgiving Point (Lehi), Downtown Layton (Layton) and West Erda (Tooele) are combined and provided in Table 5. The same types of statistical tests were performed on the results to obtain the statistical significance of changes in parameter values.

In the Thanksgiving Point network with increased connectivity, the total volume increase was close to 18%, followed by the similar increase in travel times and average vehicular delays, with about a 4% reduction in average speeds. Total traveled distances and VMT increased by about 12%. The changes in all MOEs were statistically significant. The increase in volumes and VMT is attributed to the traversing traffic that used new network connections through the neighborhood. Part of the increase in travel times and number of stops is also attributed to new intersections in the network. However, the reduction in speeds and increase in stops is beneficial for non-motorized modes since it leads to improved safety along local streets and at intersections. Increased traffic volumes through neighborhood areas can be controlled by other measures, such as traffic calming and speed limit reduction.

No changes in traffic volumes were recorded in the increased connectivity scenario of the Downtown Layton network, meaning that the traversing traffic was avoiding the downtown area, even with the added connections. The distance traveled and VMT slightly increased, with about 6% reduction in average speeds and an increase in delays, travel times, and stops (22%, 9%, and 80%, respectively). This can be attributed to the increased number of intersections, as well as the low-speed connections introduced to the network. All changes, except for the total volumes, were statistically significant. The speed reduction can benefit non-motorized traffic from the safety standpoint. Since no additional traffic was recorded in this network, there would be no need for other strategies to control volumes.

No changes were observed in traffic volumes and VMT in the West

Table 4
Arterial VMT and Total Delays for Community-Scale Networks.

Street	MOE	Base	Increased Connectivity	Street Widening	Inc. con. / Base	Street wid. / Base
SR 92 (Lehi)	3 hr VMT	30,499	25,599	35,251	−16.06%	15.58%
	Total Delay (min)	123.23	38.50 *	64.37	−68.76%	−47.77%
Mountain Valley Corridor (Lehi)	3 hr VMT	6,408	3,065 *	5,700	−52.17%	−11.05%
	Total Delay (min)	14.87	3.18 *	9.72	−78.59%	−34.64%
2300 W (Lehi)	3 hr VMT	2,855	984 *	2,489	−65.53%	−12.81%
	Total Delay (min)	37.27	2.12 *	26.55	−94.32%	−28.76%
SR 193 (Layton)	3 hr VMT	16,471	13,396	15,297	−18.66%	−7.12%
	Total Delay (min)	19.00	7.68 *	13.52	−59.56%	−28.86%
Antelope (Layton)	3 hr VMT	16,542	13,678	18,828	−17.31%	13.82%
	Total Delay (min)	142.93	102.07	112.95	−28.59%	−20.98%
Layton Pkwy (Layton)	3 hr VMT	4,634	4,438	4,413	−4.23%	−4.76%
	Total Delay (min)	6.50	3.35	5.35	−48.46%	−17.69%
Gordon Ave (Layton)	3 hr VMT	6,421	4,882	5,696	−23.97%	−11.29%
	Total Delay (min)	21.88	7.70 *	14.25	−64.81%	−34.88%
SR 138 (Tooele)	3 hr VMT	14,776	13,007	11,685	−11.98%	−20.92%
	Total Delay (min)	26.33	18.78	16.17	−28.67%	−38.61%
East Erda Way (Tooele)	3 hr VMT	1,647	1,021	1,593	−37.98%	−3.28%
	Total Delay (min)	1.80	0.73	1.72	−59.26%	−4.63%
Village Blvd (Tooele)	3 hr VMT	894	1,031	876	15.23%	−2.05%
	Total Delay (min)	4.68	4.90	4.40	4.63%	−6.05%

* Value statistically significantly different from the corresponding Base value.

Table 5
MOE Comparison for Neighborhood-Scale Networks.

MOE	Network	Base	Increased Connectivity	Difference
Total vehicles (veh/3 h)	Thanksgiving Point	15,843	18,676 *	17.88%
	Downtown Layton	17,054	17,087	0.19%
	West Erda	9,844	9,849	0.05%
Distance traveled (mi)	Thanksgiving Point	29,784.97	33,434.44 *	12.25%
	Downtown Layton	23,001.57	23,612.77 *	2.66%
	West Erda	18,070.31	18,047.00	−0.13%
Average speed (mph)	Thanksgiving Point	26.13	25.05 *	−4.13%
	Downtown Layton	24.72	23.25 *	−5.95%
	West Erda	39.98	39.20 *	−1.95%
Total travel time (h)	Thanksgiving Point	1,140.09	1,334.86 *	17.08%
	Downtown Layton	930.61	1,015.69 *	9.14%
	West Erda	451.96	460.39 *	1.87%
Total delay (h)	Thanksgiving Point	150.29	211.12 *	40.48%
	Downtown Layton	192.63	234.43 *	21.70%
	West Erda	51.93	57.51 *	10.75%
Total number of stops	Thanksgiving Point	19,852	31,002 *	56.17%
	Downtown Layton	23,759	42,658 *	79.54%
	West Erda	3,034	4,613 *	52.03%

* Value statistically significantly different from the corresponding Base value.

Erda network, meaning that the traversing traffic did not use the new connections. A 2% reduction in speeds, with a similar increase in travel times and a more significant increase in delays and number of stops, were recorded in the increased connectivity scenario. This can be attributed to the increased number of intersections, as well as the low-speed connections introduced to the network. Statistically significant differences were not observed only for the total number of vehicles and distances traveled. Compared to the previous two networks, significantly higher speeds and lower delays and number of stops per vehicle were observed in West Erda. This is because of the rural nature of the neighborhood, with higher speed limits and lower traffic volumes. The extension of safety benefits for non-motorized traffic, in this case, would be lower than for the previous two networks, but the operational benefits would be significant due to better accessibility and shorter travel distances within the network.

A common characteristic for all neighborhood-scale networks is lower observed speeds for alternatives with increased connectivity. While this impedes vehicular traffic, it benefits other modes, especially non-motorized. Lower vehicular speeds are desirable in neighborhoods, improving safety for all users. More neighborhood connectivity also creates pedestrian and bicycle friendly environments, however these effects need to be addressed in follow-up studies. In general, well-connected neighborhood networks are of a major importance for creating sustainable neighborhoods.

7. Conclusions

This paper presents an analysis of increased street connectivity on traffic performance and sustainability in three community-scale and three neighborhood-scale networks in Utah. The analysis was performed using traffic simulation. In urban and suburban community-scale networks, increased connectivity resulted in a significant reduction in network travel times and delays which ranged between 9% and 24%. VMT on higher-rank streets were in most cases significantly reduced (1%–53%), as a result of a more balanced distribution of traffic flows within the network. Travel times in the tested rural network were increased by about 13%, but the total delay was reduced by 15%. This is a consequence of the different characteristics of a rural network, which generally has higher speed limits and fewer intersections. The traffic benefits of a more balanced traffic distribution, as well as shorter travel distances, are evident in all community-scale networks. Street widening generally contributed to higher VMT than increased connectivity on the network level, but the changes were not significant. However, on some of the analyzed arterials, a significant increase in VMT in street widening over increased connectivity is evident. This is caused by the redistribution of through traffic within the networks, which used higher capacity arterials as faster connections to the destinations.

A campus-type neighborhood network with more street connectivity was shown to attract more traversing traffic, with an 18% increase in traffic volumes. However, this does not have to be the rule in all cases. The change will depend on the location of the network and the proximity of high-capacity and high-speed highway facilities, as well as connections to those facilities. Improving connectivity in urban and rural neighborhoods does not seem to attract more traversing traffic. The total delay increases in better-connected networks, and this increase ranges between 20% and 40% in urban and suburban neighborhoods, and about 10% in rural. The average speed is also reduced, 4%–6% in suburban/urban and 2% in rural neighborhoods.

The results show different effects of increased street connectivity on community and neighborhood scale networks. The traffic performance is better in community networks, with higher capacities, better distribution of traffic flows, and lower delays. These characteristics, as well as options for more transit-friendly environments, are sustainability features that can be achieved through well-connected community-level networks. Street widening also benefits traffic performance. However, it creates an auto-oriented environment with fewer options for non-motorized modes. In neighborhood networks, increased connectivity causes deterioration in traffic performance, mainly related to average vehicular speeds and delays. However, while impacting automobile traffic, more connections in neighborhoods can significantly benefit other modes. Travel distances are shorter, improving walkability and bicycle traffic, access to destinations, and access to transit. Transit also has more options for routing through neighborhoods. Lower vehicular speeds mean safer environments for all modes, reducing the risk of crashes and crash severities. In terms of sustainability, these are the desired characteristics. Therefore, increased street connectivity on the neighborhood level is of significant importance for sustainable environments.

The main limitation of the study is that it does not assess how increased connectivity affects mode distribution and mode-specific performance. This is an area that needs to be addressed in future studies. Also, since the study is using traffic simulation, the recorded traffic performance uses only external factors, such as street capacities, speeds, and congestion. The actual performance might differ due to other factors, as well as the subjective choices made by the transportation system users. An empirical study should be performed on partitions of the analyzed networks once the recommended connectivity strategies are implemented.

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References

Alba, C. A., & Beimborn, E. (2005). *Analysis of the effects of local Street connectivity on arterial traffic. Proceedings of the Transportation Research Board 84th Annual Meeting*.

Berrigan, D., Pickle, L. W., & Dill, J. (2010). Associations between street connectivity and active transportation. *International Journal of Health Geographics, 9*, 20. https://doi.org/10.1186/1476-072X-9-20.

Canada Mortgage and Housing Corporation (2008). *Giving pedestrians an edge—Using street layout to influence transportation choice.* http://publications.gc.ca/collections/collection_2008/cmhc-schl/nh18-23/NH18-23-108-013E.pdf.

Ewing, R., & Cervero, R. (2010). Travel and the built environment: A meta-analysis. *Journal of the American Planning Association, 76*(3), 265–294. https://doi.org/10.1080/01944361003766766.

Ewing, R., Greenwald, M., Zhang, M., Walters, J., Feldman, M., Cervero, R., Frank, L., & Thomas, J. (2011). Traffic generated by mixed-use developments: A six-region study using consistent built environmental measures. *Journal of Urban Planning and Development, 137*(3).

Greenberg, E. (2008). Sustainable streets: An emerging practice. *Institute of Transportation Engineers (ITE) Journal, 2008*(May), 29–39 HighBeam Research.

Lehigh Valley Planning Commission (LVPC) (2011). *Street connectivity guidance document.* http://www.lvpc.org/pdf/streetConnectivity.pdf.

Marshall, W. E., & Garrick, N. W. (2011). Does street network design affect traffic safety? *Accident; Analysis and Prevention, 43*, 769–781. https://doi.org/10.1016/j.aap.2010.10.024.

McInelly, M., Garrrick, N., Kronemeyer, T., Smith, H., Readdy, J., Dumbaugh, E., Ericson, P., Grimshaw, J., Hogan, L., Marshall, W., Norquist, J., Schulman, B., Siegman, P., Sullivan, T., Donnelly, B., Lewyn, M., & Lydon, M. (2012). *Sustainable street network principles.* Congress for the New Urbanism (CNU).

McNally, M., & Ryan, S. (1992). *A comparative assessment of travel characteristics for NeoTraditional development.* University of California, Irvine, Institute of Transportation Studieshttps://escholarship.org/uc/item/03n6593v.

Mohan, D., Bangdiwala, S. I., & Villaveces, A. (2017). Urban street structure and traffic safety. *Journal of Safety Research, 62*, 63–71. https://doi.org/10.1016/j.jsr.2017.06.003.

Porta, S., & Renne, L. J. (2005). Linking urban design to sustainability: Formal indicators of social urban sustainability field research in Perth, western Australia. *Urban Design International, 10*(1), 51–64. https://doi.org/10.1057/palgrave.udi.9000136.

Portland Metro (2004). *Street connectivity: An evaluation of case studies in the Portland region. Report No. 2004-11008-PLN*http://library.oregonmetro.gov/files/connectivityreport.pdf.

Rafiemanzelat, R., Emadi, M. I., & Aida Jalal Kamali, A. J. (2017). City sustainability: The influence of walkability on built environments. *Transportation Research Procedia,* (24), 97–104. https://doi.org/10.1016/j.trpro.2017.05.074.

Randall, T. A., & Baetz, B. W. (2001). Evaluating pedestrian connectivity for suburban sustainability. *Journal of Urban Planning and Development, 127*(1), 1–15.

Tal, G., & Handy, S. (2012). Measuring nonmotorized accessibility and connectivity in a robust pedestrian network. *Transportation Research Record: Journal of the Transportation Research Board,* (2299), 48–56. https://doi.org/10.3141/2299-06.

Tasic, I., Zlatkovic, M., Martin, P. T., & Porter, R. J. (2015). Street connectivity versus Street widening: Impact of enhanced Street connectivity on traffic operations in transit-supportive environments. *Transportation Research Record: Journal of the Transportation Research Board,* (2494), 57–68. https://doi.org/10.3141/2494-07.

Tian, G., Ewing, R., White, A., Walters, J., Goates, J. P., & Joyce, A. (2015). *Traffic generated by mixed-use developments – 13-region study using consistent built environment measures. Proceedings of the Transportation Research Board 94th Annual Meeting*.

Victoria Transport Policy Institute (2017). *Roadway connectivity: Creating more connected roadway and pathway networks.* Accessed 5 October 2018 http://www.vtpi.org/tdm/tdm116.htm.

Yi, C. (2008). *Utilizing GIS to measure Street connectivity and pedestrian accessibility: Comparing Cul-De-Sac and grid neighborhoods in the Houston Metropolitan Area. GIS-t student paper contest*.

Zhou, X., Martin, P. T., Zlatkovic, M., & Tasic, I. (2013). *Traffic modeling of transit oriented development: Evaluation of transit friendly strategies and innovative intersection designs in West Valley City, UT, MPC-14-270, North Dakota State University – Upper Great Plains Transportation Institute* (pp. 2011). .