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Modelling the impact of fused grid network design on mode choice behaviour

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ABSTRACT

Introduction: The fused grid (FG) is a an alternative model developed by the Canada Mortgage and Housing Corporation to combine the easy orientation and connectivity of the traditional grid pattern with the land use efficiency and quietness of the contemporary cul-de-sac pattern. One of the main distinguishing principles of the FG design relative to contemporary neighbourhood patterns are the FG's higher non-motorized network connectivity versus vehicle network connectivity. This paper reports on research related to the influence of FG design principles on non-motorized use for home-to-work commuting and home-to-shopping trips.
Methods: This study uses a macroscopic-level approach to investigate the impact of FG on mode choice behaviour through hypothetically retrofitting an existing neighbourhood in Kelowna, BC, using the FG design principles. First, the change in travel distance and time due to retrofitting the neighbourhood was estimated using ArcGIS. Then, the modal shift in home-to-work and home-to-shopping trips due to the change in travel distance and time was estimated using multinomial logit mode choice models that were developed using the 2013 Okanagan household travel survey.
Results: The results suggest that the influence of travel time on choosing the auto mode is much stronger and more significant for home-to-work trips compared to home-to-shopping trips. The results also show that retrofitting the road network resulted in reducing auto modal share by 13 percent and increasing non-motorized modes by 64 percent for home-to-work trips. However, an insignificant shift in modal share towards non-motorized modes for home-to-shopping trips was found.
Conclusions: In conclusion, this study demonstrated the effectiveness of the FG principles in reducing auto use and increasing non-motorized modes use for home-to-work trips. In addition, the study revealed that infrastructure investments related to providing more accessibility for non-motorized users might have more impact on decreasing auto use compared to restricting vehicular network connectivity.

1. Introduction

Community urban planning was originally motivated by the pursuit of public health, back in the early 20th century, when cities were suffering from infectious diseases and poor sanitation (Perdue et al., 2003). During that time, it was well established that

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creating zones to segregate different land uses, such as residential and industrial, would improve public health by limiting emissions and noise in residential areas (Corburn, 2007; Scott, 1969). Scott (1969) affirms that “Zoning was the heaven-sent nostrum for sick cities, the wonder drug of the planners, the balm sought by lending institutions and householders alike”. However, the unlimited expansion of cities and excessive land use segregation have contributed to increasing the distances between trip origins and destinations, and resulted in sprawling cities with low-density development patterns that encourages auto dependency. This trend has led planners and engineers to focus primarily on automobile movement and expand the road infrastructure, while overlooking other modes of transportation (Hanson and Giuliano, 2017).

New triggers including increases in physical inactivity, road collisions, and Greenhouse Gas (GHG) emissions have shifted the focus of planners and engineers towards transportation systems that encourage walking and cycling to support sustainable community development. First, the increasing level of physical inactivity has become a major challenge for public health because it has enormous health costs and increases the possibility of many health problems including heart disease, obesity, and diabetes (Sallis et al., 2004; VanBlarcom and Janmaat, 2013; Wang et al., 2005). The burden of physical inactivity was estimated in Canada to be $6.8 billion in direct and indirect costs in 2009 (Janssen, 2012). In addition, physical inactivity and obesity are responsible for 6 million deaths annually worldwide (Janssen, 2012). Recent studies found that both walking and cycling provide effective physical activity opportunities and thus contribute to reducing obesity and chronic diseases (Pucher and Buehler, 2010). For instance, Gordon-Larsen et al. (2009) found that walking and cycling to work are negatively associated with obesity, triglyceride levels, and higher blood pressure. In addition, Hu et al. (2003) found that walking and cycling reduce the risk of type 2 diabetes.

Second, road collisions are of the leading causes of death and injury worldwide, responsible for approximately 1.24 million fatalities annually (WHO, 2013). The annual economic impact of road collisions was estimated to be 5% of Canada's Gross Domestic Product (GDP), an amount that nearly equals to Canada's national debt. Research conducted by the World Health Organization, WHO (2013), showed that 95 percent of road collisions are a result of driver errors. Such finding has led to calls for reducing private automobile use and increasing non-motorized use.

Third, transportation is a rapidly growing source of GHG emissions around the world. In the US, transportation was the main source of GHG emissions, responsible for 27 percent of the total emissions, with passenger cars being the main contributor in 2011 (EPA, 2013). In Canada, transportation was the second largest source of GHG emissions nationwide in 2012, accounting for 28 percent of the total emissions (Environment Canada, 2018).

Today, the two most employed neighbourhood designs in North America are 1) the traditional grid pattern and 2) the culs-de-sac or loops and lollypop pattern. The culs-de-sac pattern was employed to address problems associated with the grid street pattern by precluding neighbourhood traffic shortcutting. However, the culs-de-sac pattern has its own disadvantages as it tend to increase the distance between trip origins and destinations, let alone being disorienting to navigate a neighbourhood (Sun and Lovegrove, 2013). Given the limited impact of existing neighbourhood designs in promoting more livable and sustainable communities and non-motorized modes, the Canada Mortgage and Housing Corporation (CMHC) has developed the fused grid (FG) neighbourhood design principles. Fig. 1 depicts the differences between the traditional grid, culs-de-sac, and FG network patterns. The FG principles combine the best characteristics of the traditional grid and culs-de-sac street patterns, plus many sustainable community planning principles, including (Grammenos et al., 2008; Grammenos and Lovegrove, 2015; Sun and Lovegrove, 2013):

1) The tranquility, safety, and efficiency of the culs-de-sac and loop street patterns, but with continuous walking and bicycling routes connecting between culs-de-sacs;
2) The easy orientation and connectivity of the traditional grid pattern, but focused on walking and bicycling network connectivity within neighbourhood while disrupting and focusing vehicular connectivity onto perimeter collector and arterial roads;
3) The Dutch Safe Systems approach to reducing frequency and severity of crashes toward zero fatalities;
4) The Dutch planning principles that seek to maximize the car-free neighbourhood core, land use mix, and dwelling density, thereby minimizing trip distances and auto use; and
5) The ubiquity of large and small restorative, socially interactive, and natural play spaces within a 1 min walk of every person living and/or working in the neighbourhood.

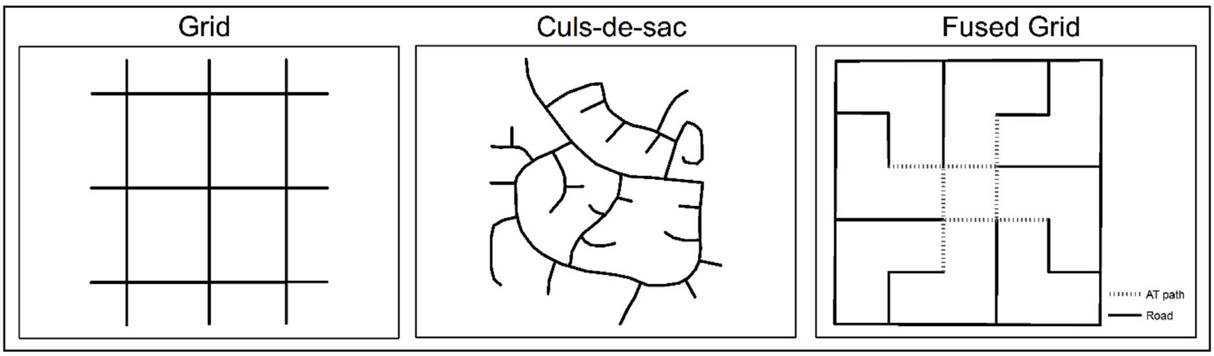

Fig. 1. Network patterns.

The objectives of this paper are:

1) To demonstrate the application of FG design principles in neighbourhood design by hypothetically retrofitting an existing neighbourhood in the City of Kelowna, BC, Canada;
2) To estimate the shift towards non-motorized use in a neighbourhood due to these FG design principles, focusing on relative connectivity between non-motorized and vehicular modes (i.e. increasing the connectivity of the non-motorized network compared to the vehicular network); and
3) To quantify the influence of applying FG design principles on mode choice behaviour for home-to-work and home-to-shopping trips, relative to traditional grid and contemporary culs-de-sac neighbourhood designs.

2. Literature review

With physical inactivity becoming a major challenge for public health, there has been a growing interest in understanding how urban design influences walking and cycling (Ewing and Kreutzer, 2006; Saelens et al., 2003; Southworth, 2005; Sugiyama et al., 2008). For instance, Frank et al. (2006) studied the relationship between built environment, measured by a walkability index, and physical activity. After controlling for sociodemographic variables, the results revealed a significant correlation between higher walking and cycling use and living in a "walkable" neighbourhood, characterized by high density, mixed land use, more walking and cycling accessible retail, and connected road network. Zhang (2004) used the MNL model to evaluate the impact of built environment on Mode choice behaviour in Boston and Hong Kong. The results revealed that built environment variables have a variance degree of influence on mode choice behaviour depending on trip purpose (i.e. work or non-work) and the trip end at which the variable was measured (i.e. origin or destination). Cervero (2002) explored the effect of three core dimensions of built environment, known as the "3 Ds" (density, diversity, and design) on mode choice behaviour in Montgomery County, Maryland. The results indicated that the 3 Ds, especially at a trip destination, have low to moderate impact on driving mode choice for work trips. Specifically, the design dimension (e.g. predominant pattern, block length, etc.) revealed the most significant negative relationship with driving. Similarly, Soltani et al. (2006) found that greater route directness and close proximity to employments have the most statistically significant effect on mode choice behaviour. This finding is also supported by Badland et al. (2008) who found that walking and cycling is associated with close proximity to jobs and high street connectivity.

While many of above mentioned built environment elements can be found to varying degrees in all neighbourhood layouts, the most distinct feature of a neighbourhood layout is its network design. Thus, the focus of this research is to investigate how network design and street connectivity influence non-motorized modes use. Street connectivity is usually measured in terms of intersection density and/or link-node ratio, and is associated with increased route options and shorter travel distances. Findings from the literature suggest that high street network connectivity correlate with more walking/cycling and less driving (Frank et al., 2006; Gebel et al., 2005; McNally and Ryan, 1992). For instance, Marshall and Garrick (2010) conducted a study based on 12 California cities to investigate the correlations between street network characteristics (i.e. network density, network connectivity, and network pattern) and transportation modal share. The authors found that intersection density was positively associated with walking and cycling, while increased link-to-node ratio was associated with less driving. Bear in mind that this study evaluated street connectivity based on street network (i.e. vehicular network), and did not take into account off-road pedestrian and bicycle facilities; thus, high connectivity for non-motorized users means high connectivity for motorists as well, which is usually the case in a grid neighbourhood. Other studies based the analysis on full pedestrian and/or bicycle networks. Tal and Handy (2012) conducted a study on nine suburban neighbourhoods to examine the effect of neglecting the actual pedestrian networks when evaluating accessibility and connectivity. The pedestrian networks in these nine neighbourhoods are much richer than the street networks. The authors found that the examined suburban neighbourhoods that have extensive pedestrian networks (e.g. sidewalks, parks, paths, etc.) were more connected and accessible than what is typically estimated in a grid network with small blocks and high intersection density. On the other hand, numerous research studies suggest that high street connectivity is associated with lower traffic safety (Hadayeghi et al., 2003; Ladrón de Guevara et al., 2004; Masoud, 2015). For instance, Sun and Lovegrove (2013) compared the traffic safety level of five different neighbourhood street patterns using macro level collision prediction models. The study found that street connectivity (defined by intersection density) was among the top three factors that negatively affect traffic safety in a neighbourhood.

This dilemma of finding the best trade-off between providing high connectivity and a safer road network encouraged the CMHC to develop the fused grid neighbourhood model. A typical FG plan, as shown in Fig. 2, consists of four 16-ha quadrants. Each quadrant represents a 400-square metre neighbourhood with local roads providing access to local traffic only; through-vehicle connectivity is prevented by central green spaces. The green spaces in each quadrant supplement the local road network to provide a continuous, completely connected walking and cycling grid network of on-road and off-road paths that allow convenient walking and cycling across the neighbourhood in less than 5 min, with small block sizes of 80 m on average (Grammenos and Lovegrove, 2015). In addition, green spaces account for more than 8 percent of a typical FG neighbourhood, including ubiquitous small corner parks and a larger central community green (Masoud et al., 2015). Perimeter roads in the fused grid model facilitate through traffic with the following spacing: 1) collectors at 400 m, 2) minor arterials at 800 m, and 4) arterials at 1600 m; their spacing, alignments, and grades can be adjusted depending on existing ground conditions and the planned land use activities. To eliminate high-speed, severe, and right-angle collisions, all vehicular intersections and crossing points in the fused grid model are controlled by roundabouts, except for intersections between local and perimeter roads, which are controlled by three-way intersections. The blocks located between the perimeter arterial one-way couplet roads are classified as mixed land use zones to provide convenient local services and amenities within a 5-min walk and biking.

Fig. 2. A typical fused grid neighbourhood (Sun and Lovegrove, 2013).

Designing a fused grid neighbourhood requires a series of steps to fuse four layers (Grammenos and Lovegrove, 2015). The first layer is the 80 m local walkable grid block size and it is considered the base layer for all other layers and transportation networks in the neighbourhood, where the human scale is the measure of all aspects as per the Dutch Safe System design approach. The second layer is modified slightly from the base layer by removing through-street vehicle segments and replacing this freed up street space with added restorative green spaces (including a grid of corner parks and a large central green), thus creating a discontinuous local vehicular traffic (culs-de-sac and loop street patterns) that discourages high speed, high volume shortcutting traffic and encourages local social interaction and destination play spaces. The third layer is the non-motorized off-road pathway network, to create a fully-connected non-motorized grid network. The final layer is the perimeter arterial/collector road network that frames the 16-ha neighbourhood module to provide for commercial land uses and local amenities, in addition to mobility at the regional level.

Several studies have examined some key features of the fused grid model including: increasing safety (Sun and Lovegrove, 2013), high traffic performance (IBI Group, 2007), and increase walkability (Frank and Hawkens, 2007). However, this research focuses on the impact of applying the fused grid in a medium size community on mode choice behaviour.

3. Study area and dataset

3.1. Study area

The study area of this research is a neighbourhood located in the South-Central part of Kelowna, British Columbia, as shown in Fig. 3. It is approximately 16 ha and is designated as a heritage conservation area with mostly single family residential units. The layout of the neighbourhood is mainly a grid network with a few culs-de-sacs. In addition, the neighbourhood is bounded by two major trip generators, including Kelowna General Hospital institutional uses on the south, and Okanagan Lake recreational uses on the west. These two major trip generators bounding the neighbourhood create increased traffic volumes due to shortcutting and on-street parking shortages (Grammenos and Lovegrove, 2015).

To estimate the modal shift in the neighbourhood due to applying the FG design principles, the study area was hypothetically retrofitted using the FG principles as presented in Grammenos and Lovegrove (2015). Further, a traffic impact analysis was performed to evaluate the potential impact of the proposed FG street network and to verify that the proposed design meets city requirements, appropriate traffic circulation, and fused grid principles (e.g. not to close a major corridor). In particular, three fused grid design

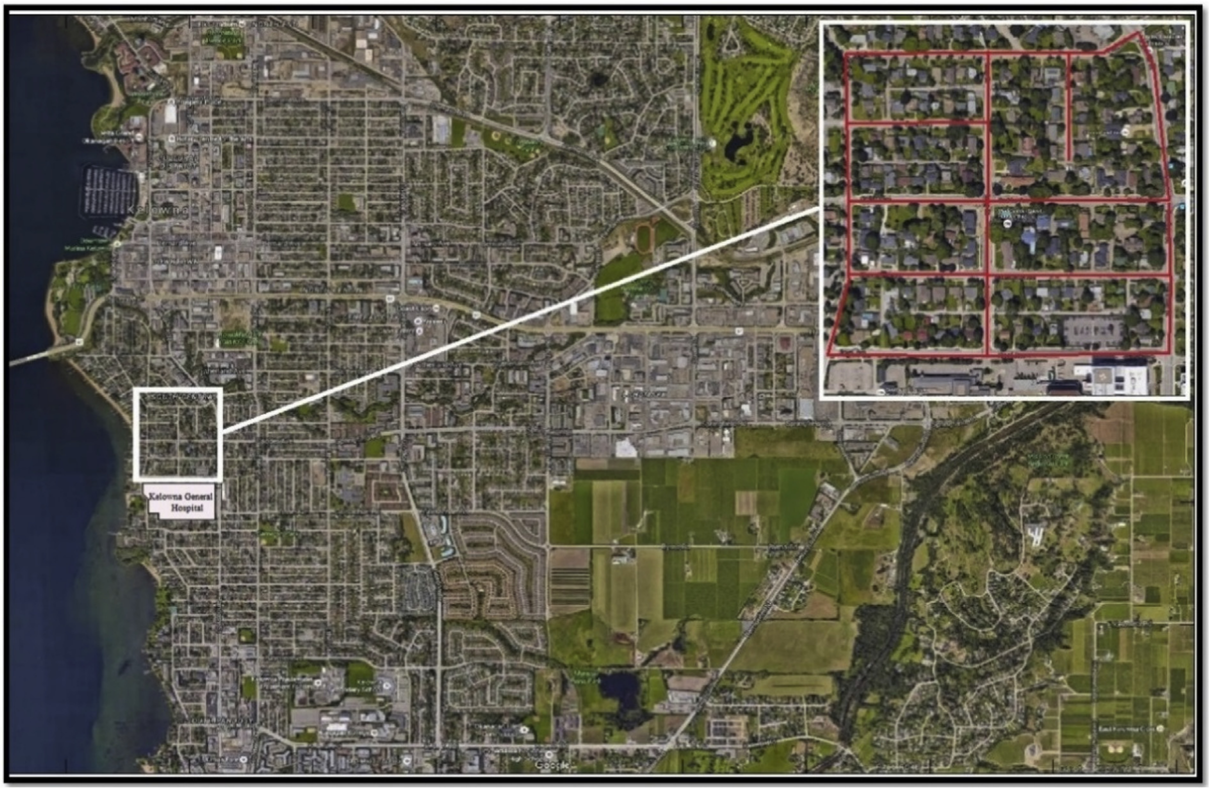

Fig. 3. Neighbourhood location.

alternatives were adopted for this investigation, as follows:

- Alternative 1: only the road network is retrofitted (keeping the non-motorized network intact);
- Alternative 2: only the non-motorized network is retrofitted (keeping the road network intact); and
- Alternative 3: retrofitting both the road and non-motorized networks (i.e. full-fledged FG design).

Fig. 4 shows the three design alternatives that have been evaluated in this study. Alternative 1, as represented by Fig. 4 (c) and (b), is based on a series of local road closures to preclude through traffic on local roads and direct it to the perimeter, without altering the existing non-motorized network. Moreover, some areas that resulted from road closures were used to provide green spaces in the neighbourhood. These green spaces eventually supplemented the local road network to provide pathways that allow convenient walking and cycling across the neighbourhood. Alternative 2, as represented by Fig. 4 (d) and (a), is based on a series of pathway additions to permit more options for walking and cycling across the neighbourhood, without altering the existing road network. Finally, Alternative 3, as represented by Fig. 4 (c) and (d), superimposed Alternative 1 and Alternative 2. For the scope of this study, the shift in modal share was estimated based on the change in trip time and distance between the existing network and the proposed design alternatives.

3.2. Dataset

The dataset used to develop mode choice models in this study comes from the Okanagan Travel Survey (OTS). The OTS is a household-based travel survey for the Central Okanagan region and city of Vernon's residents. The last survey was conducted during the weekday in the fall 2013 with a response rate of 3.3 percent, a total response of 3050 households, and 22,500 trip records. The OTS data includes both socioeconomic and demographic characteristics (e.g. auto ownership, income, age, and sex) as well as information on mode choice. In this study, only observations where both trip ends are located in Kelowna were used. In addition, the dataset was cleaned to exclude observations with missing data, such as the chosen mode and trip information as shown in Fig. 5. Further, level-of-service (LOS) attributes (travel time and distance) were generated for car, transit, walk, and cycle using the Google Directions API for all trips given respondents' residential and work postal codes (Idris, 2013). Approximately 2047 and 943 observations were used to estimate the home-to-work and home-to-shopping trip mode choice models, respectively. Home-to-work and home-to-shopping trips were used in this study due to their permanence, non-discretionary nature, and resemblance of long-term decisions. Table 1 shows the characteristics of the sample data used to develop the mode choice models.

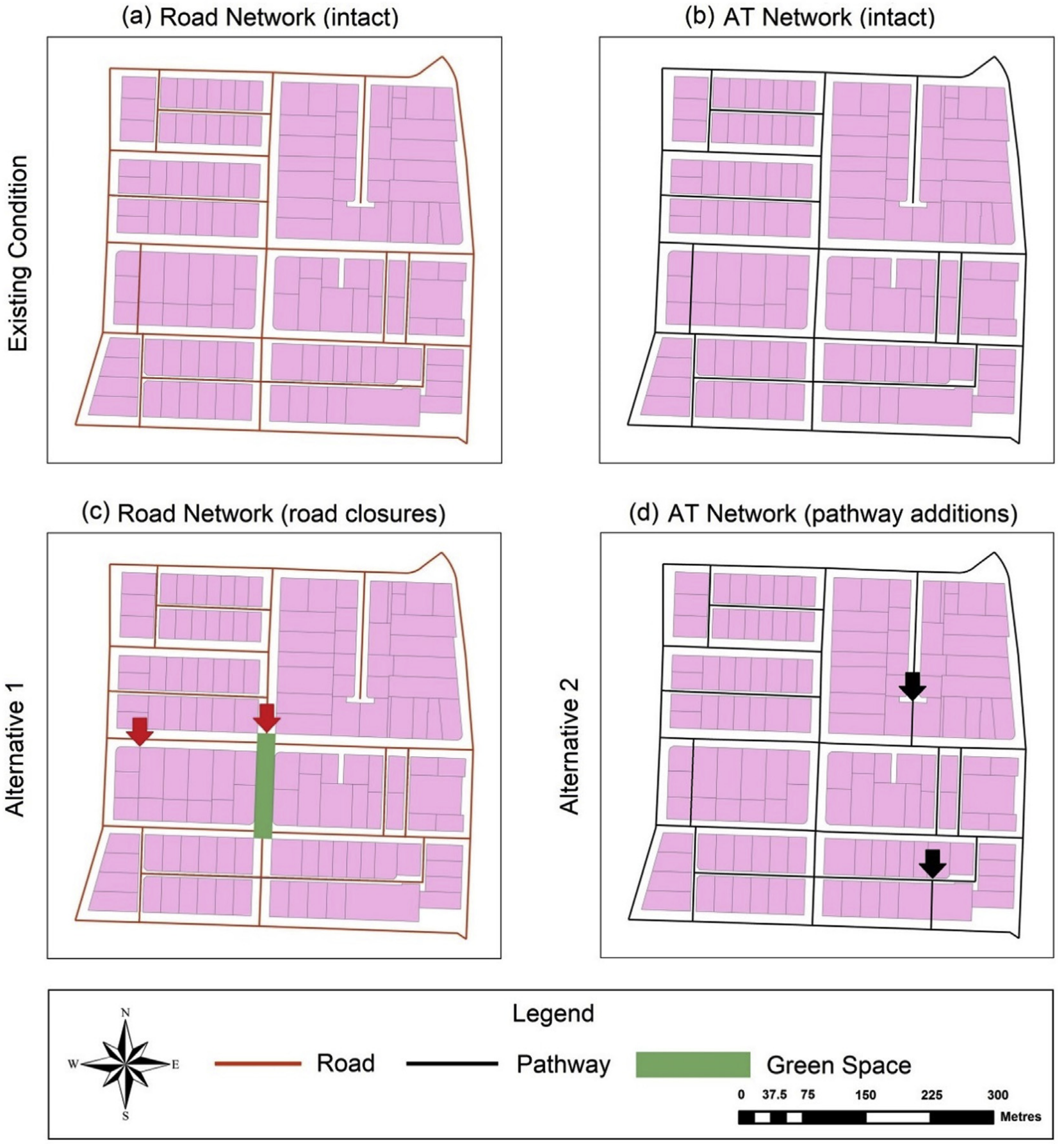

Fig. 4. FG design alternatives.

To create the GIS datasets used to perform the analysis for this investigation, the following steps were undertaken. First, three networks were developed to represent the existing condition for each road user (i.e. motorists, non-motorized, and public transit) based on the road centerlines shapefile from the City of Kelowna's open data website. Second, the developed networks were altered to reflect each design alternative by modifying the existing condition shapefiles. Finally, site visits took place to verify the accuracy of the developed GIS maps and to collect travel speed limits for each link in the network.

4. Methodology

This section describes the methodology used in this research to quantify the influence of fused grid design principles on mode choice behaviour, focusing on street connectivity. First, a neighbourhood was selected in the City of Kelowna, BC, Canada and it was defined in terms of its transportation network for car, transit, and non-motorized modes. This particular neighbourhood was chosen over others for several reasons, including:

1) It had been extensively studied by the City of Kelowna in response to ongoing resident complaints of parking and traffic intrusion;
2) As a result of these City studies, it had a readily available dataset including traffic volume and road collisions; and
3) The City had requested research assistance on this neighbourhood, including the possibility of retrofitting it using FG neighbourhood design principles.

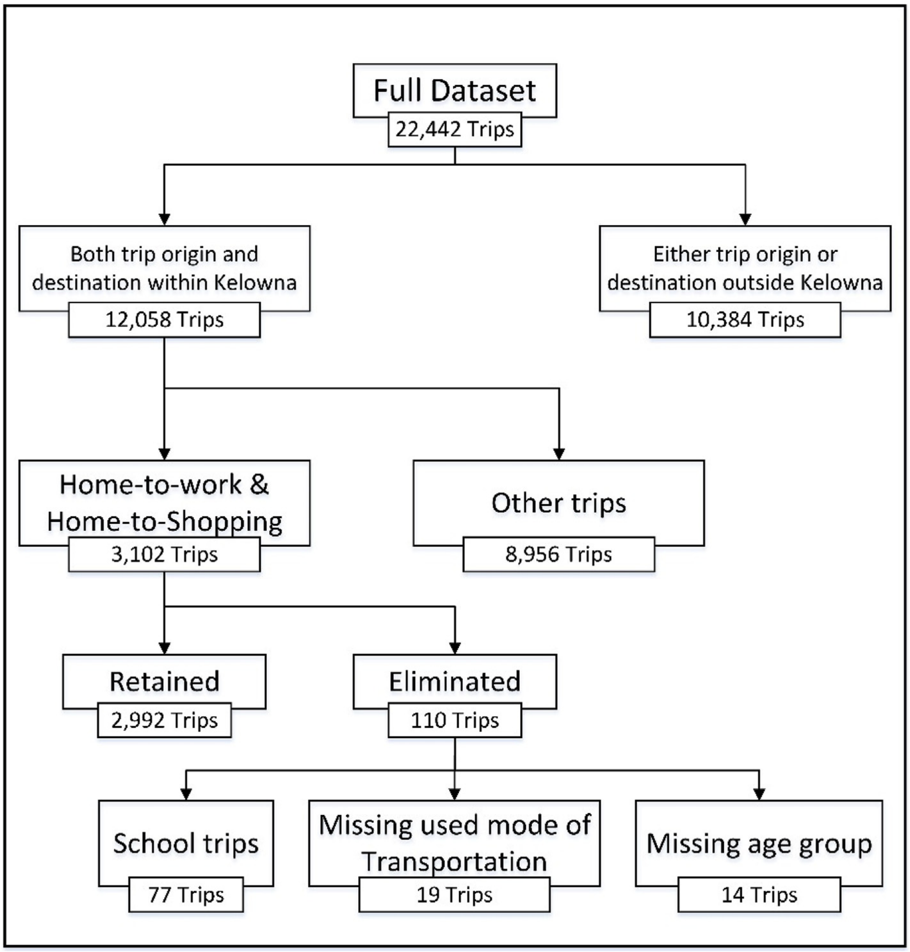

Fig. 5. Description of the dataset.

Once the subject neighbourhood was chosen, the second step was to randomly generate 1000 trips within the neighbourhood. This was done because there were few actual trips (three trips) in the survey data where both trip ends are located within the neighbourhood. Third, the arithmetic average of trip distance and travel time by each mode was estimated in the existing neighbourhood for these randomly generated trips using the OD cost matrix solver in the Network Analyst tool in ArcGIS. Travel time was estimated assuming that vehicles travel at free-flow-speed (i.e. congestion effect was not taken into consideration), as shown in equation (3) below:

$$\mathrm{TT_i} = \sum_{l \in C_i} \frac{D_l}{S_l}, \tag{1}$$

where:

TT_i: Travel time for trip (i)
D_l: Length of the link
S_l: Posted speed of the link
C_i: Set of links that are part of trip (i)

Fourth, the neighbourhood road and non-motorized network (i.e. connectivity) was retrofitted using the fused grid design principles. Fifth, the third step was repeated to estimate the average travel distance and time for the retrofitted neighbourhood design. Finally, the change in average travel distance and time was translated in terms of mode choice using Multinomial Logit (MNL) models. The hypothesis set in this investigation was that a change in trip distance and time due to connectivity changes in the FG neighbourhood design would cause a shift towards greater non-motorized modes use. Mode shift is a desirable end goal of FG neighbourhood designs, and such comparison is common and generally seen as a reasonable measure of effectiveness of sustainable community designs.

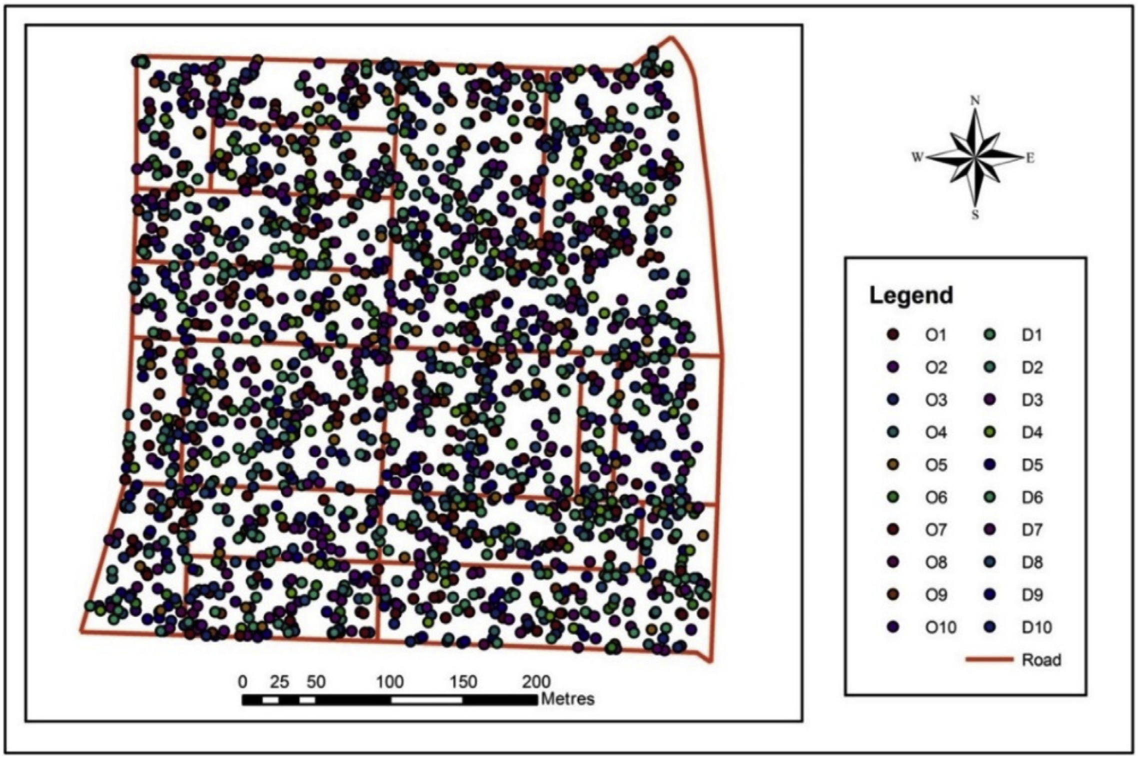

Fig. 6. Randomly generated origins and destinations scenarios.

One could argue that the great effect of retrofitting the road network on mode choice compared to retrofitting the non-motorized network might be due to the fact that there were more opportunities available in the study area to make changes to the road network compared to the non-motorized network. To eliminate this bias, mode shift was re-estimated based on a new design where the change in the average auto travel distance was set to be equal to the change in the average walking and cycling travel distance (i.e. 10 percent, as shown in Fig. 6). This exercise was done mathematically only (i.e. there is no FG design that reflects this change). Since the utility for the auto mode in the developed mode choice models is function of travel time (not distance), auto travel time was estimated as a function of travel distance using the regression models presented by equation (4) for work trips and equation (5) for non-work trips. Note that average travel time could not be estimated using ArcGIS Network Analyst, as done earlier, because there is no actual FG design that reflects the 10 percent reduction the in average auto travel distance. The preliminary analysis suggested using a linear function for relationship between travel time and distance; however, the residual chart revealed a non-linear behaviour which could be observed clearly looking at very short and very long trips (i.e. less than 2 km and longer than 16 km). Thus, two models were developed using quadratic functions for home-to-work trips (equation (4)) and home-to-shopping trips (equation (5)); the R-squared value is 0.96 for both models.

$$TT_i = 61.84 + 84.75D_i - 0.98D_i^2 \quad (4)$$

$$TT_i = 43.40 + 91.42D_i - 1.72D_i^2 \quad (5)$$

where:

TT_i: Travel time for trip (i) in second
D_i: Travel distance for trip (i) in kilometer

4.1. Mode choice modelling

Mode split models estimate the probability of choosing a certain alternative based on its utility value compared to other alternatives' utility values. This approach is derived from utility maximization principles, which assume that the trip maker is rational and will select the alternative that maximizes his/her utility (benefits). Mathematically speaking, this can be written as shown in equation (2) below (Meyer and Miller, 2001):

$$U_{im} = V_{im} + \varepsilon_{im}, \quad (2)$$

where:d.

U_{im}: Utility that individual (i) obtains from mode (m)
V_{im}: Deterministic component of utility
ε_{im}: Error term or random utility

The deterministic portion of the utility function is simply the additive of three components that represent: 1) characteristics of the individual (e.g. income, sex, etc.), 2) attributes of alternative modes (e.g. travel distance, cost, etc.), and 3) the interaction between the characteristics of the individual and the attributes of alternatives (Koppelman and Bhat, 2006). The random/error portion of the utility function accounts for all errors from different sources that affect the accuracy of estimating an individuals' utility function, such as omission of explanatory variables, inaccurate data, etc. (Koppelman and Bhat, 2006). The assumption about the distribution of the random error term determines the mathematical representation of the model. One of the most common assumptions is that the distribution is Independently, Identically, and Gumbel (Extreme Value Type I) distributed (Ben-Akiva and Lerman, 1985). These assumptions lead to the Multinomial Logit (MNL) Model formulation as shown in Equation (3).

$$P_{im} = \frac{e^{(V_{im})}}{\sum_{m \in C_I} e^{(V_{im})}} \tag{3}$$

where:

P_{im}: Probability of individual (i) selecting mode (m)
V_{im}: Deterministic utility that individual (i) obtains from mode (m)
C_I: Set of alternative modes available for individual (i)

In this study, MNL models were used to investigate the relationships between different LOS attributes (and socioeconomic variables), and transportation mode choice behaviour (i.e. the effect of travel distance/time on modal share among City of Kelowna residents). Two MNL models for travel mode choice were estimated according to trip purpose: a home-to-work trip model and a home-to-shopping trip model. For variable selection, stepwise selection was used with two criteria for keeping a variable in the models: (a) statistical significance (i.e. t-statistic greater than 1.96), and (b) intuitively proper parameter sign. For instance, a positive sign for travel cost parameter would imply that the probability of choosing an alternative will increase as travel cost increases, which is contrary to expected travel behaviour and thus should be eliminated. Three utility functions were estimated using Biogeme (Bierlaire, 2003) as follows: 1) automobile, 2) transit, and 3) non-motorized modes.

4.2. Modelling results and discussion

Ten scenarios of 100 random origin-destination points (ODs) were generated within the neighbourhood boundaries, as displayed in Fig. 6. The generated OD matrix was used to calculate the average travel distance for the 1000 simulated trips by each mode using the respective transportation network in both the existing neighbourhood and the proposed designs.

The results, as displayed in Fig. 7, show that the FG design, when applied to the road network keeping the non-motorized network intact (i.e. Alternative 1), increased average auto trip distance by 46 percent. This increase is due to the series of local road closures proposed in the design. On the other hand, the FG design, when applied to the non-motorized network keeping the road network intact (i.e. Alternative 2), decreased average walking trip distance by 10 percent. This small reduction is attributed to the existing condition of the neighbourhood, which provided only few opportunities to introduce walking and cycling cut-throughs at dead ends (i.e. culs-de-sacs) without acquiring access to private land for public use. Moreover, transit was not affected in any of the design alternatives as transit routes run at the periphery of the neighbourhood.

Similar to travel distance, the proposed fused grid design alternatives increased average auto travel time by 57% and decreased non-motorized modes average travel time by 10%. Importantly, non-motorized modes travel distances/times could have been influenced to a greater benefit had the FG designs included private property acquisitions (or trade-offs for closed street segments) to create walking and cycling short-cut routes and increased non-motorized modes connectivity; however, to maintain a conservative analysis this was not included in this study.

A home-to-work and a home-to-shopping trip mode choice models were developed in this study, with model specifications shown in Table 2, and Rho-squared values of 0.62 and 0.71 for the home-to-work and home-to-shopping trips models, respectively. The developed models show that the number of vehicles per person in the household is positively associated with auto use and negatively associated with transit use. Though this result is consistent for both home-to-work and home-to-shopping trips, it is more pronounced for latter. Similarly, the number of bikes per person in the household has a significant negative association with auto use for home-to-work trips, while it is not statistically significant for home-to-shopping trips. In addition, the model shows that travel distance and time have negative signs, as one would expect. For auto mode, the increase in trip time is associated with less driving. The influence of trip time on choosing auto mode is much stronger and more significant for home-to-work trips, as shown by the coefficient of trip time being −0.177 for home-to-work trips compared to −0.053 for home-to-shopping trips. For the non-motorized modes, travel distance has a relatively very strong negative correlation with non-motorized use for both trip types.

The effect of fused grid on mode choice behaviour was then quantified using the developed MNL models. The developed mode choice models were used to translate the changes in average travel distance and time to mode choice. However, modal shares could not be estimated for the study area as there was a small set of trips where both trip ends are located within the neighbourhood. To

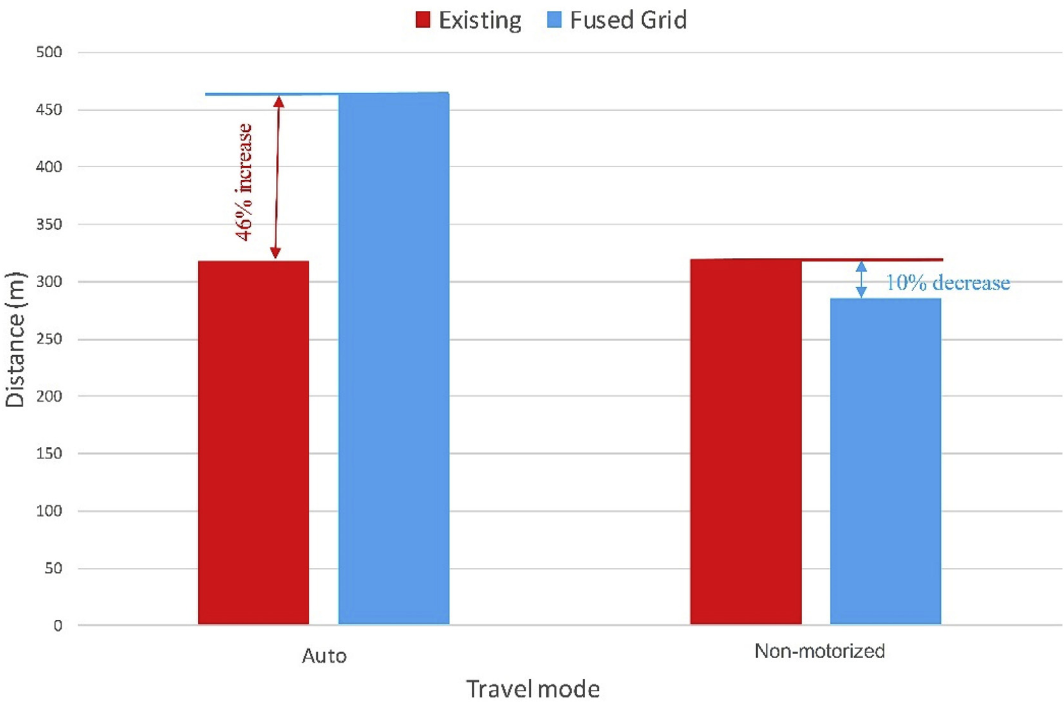

Fig. 7. Change in average travel distance.

Table 1
Characteristics of the sample.

Variable	Category	Home-to-Work		Home-to-shopping	
		N	%	N	%
Number of vehicles in a household	0	57	2.8	41	4.3
	1	557	27.2	295	31.3
	2	891	43.5	408	43.3
	3+	542	26.5	199	21.1
Number of bicycles in a household	0	280	13.7	229	24.3
	1	312	15.2	185	19.6
	2	506	24.7	238	25.2
	3+	949	46.4	291	30.9
Household dwelling type	Single Detached House	1394	68.1	637	67.6
	Apartment or Condo	321	15.7	162	17.2
	Townhouse or Row House	229	11.2	103	10.9
	Duplex	83	4.0	27	2.9
	Mobile Home	20	1.0	14	1.5
Age	(05–14)	288	14.1	34	3.6
	(15–24)	326	15.9	72	7.6
	(25–34)	373	18.2	124	13.1
	(35–44)	535	17.2	136	14.4
	(45–54)	363	17.7	154	16.3
	(55–64)	305	14.9	221	23.4
	65 and over	39	1.9	202	21.4
Sex	Men	938	45.8	356	37.8
	Women	1109	54.2	587	62.2
Monthly or annual transit pass	Yes	249	12.2	78	8.3
	No	1798	87.8	865	91.7
Driver's license	Yes	1644	80.3	868	92.0
	No	403	19.7	75	8.0

Table 2
Mode choice model parameters.

	Home-to-work Trips Model			Home-to-shopping Trips Model		
Loglikelihood of Mode Choice	−632.221			−250.209		
Loglikelihood of Null Model	−1916.433			−1035.586		
Rho-Squared Value	0.670			0.758		
Variable	**Auto**	**Transit**	**Non-motorized**	**Auto**	**Transit**	**Non-motorized**
Alternative Specific Constant	–	−2.73	−0.335	–	−4.74	0.4
Age						
Group 3 (15–24)	−0.99 (−3.57)	–	–	–	–	–
Group 4 (25–34)	−0.402 (−2.02)	–	–	–	–	1.30 (4.33)
Bikes/person in the household	−0.437 (−1.89)	–	0.545 (2.23)	–	–	0.501 (2.76)
Vehicles/person in the household	1.14 (4.9)	−1.06 (−2.32)	–	1.66 (4.59)	−2.32 (−2.55)	–
Gender						
Male	–	–	0.332 (1.93)	–	–	–
Monthly transit pass	−1.66 (−4.25)	3.13 (8.04)	–	−0.831 (−1.88)	4.09 (4.69)	–
Driver's license	–	−1.04 (−2.44)	–	–	–	–
Employment status						
(School full-time)	1.45 (3.73)	0.754 (2.02)	–	–	–	–
Dwelling type						
(Apartment)	–	–	–	−1.35 (−5.01)	–	–
(Duplex)	–	–	–	–	–	1.24 (2.52)
Travel distance	–	–	−0.846 (−11.52)	–	–	−0.894 (−6.55)
Trip time	−0.152 (−3.87)	−0.021 (−2.11)	–	−0.122 (−1.85)	–	–

Note: values within parenthesis () show t-stat value, — = variable is not statistically significant.

tackle this issue, it was assumed that the impact of applying fused grid principles at the entire city would give similar results to those obtained by retrofitting the study area. Hence, the change in travel distance and time in the neighbourhood can be generalized to fit the entire city. In other words, travel distance/time for each recorded observation in the retained dataset of the OTS was changed such as non-motorized modes travel distances for all observations are decreased by 10 percent while auto travel times are increased by 46%. This hypothesis means that the results presented below give a sense of the potential impact of applying fused grid principles at the city level in Kelowna as opposed to at an individual neighbourhood by neighbourhood basis. This assumption introduces a more conservative reality that the full benefits of FG design principles in any community would be maximized only when a system-wide approach to the control and design of land use and transportation is considered.

The forecasting results (see Table 3) show that retrofitting the road network has substantial impact on mode choice as auto use decreased by approximately 6 percent and non-motorized modal share increased by 24.3 percent. On the other hand, the impact of changing non-motorized network only resulted in 1 percent reduction in auto use and 10 percent increase in non-motorized modes for home-to-work trips. Combining both designs (i.e. changing road and non-motorized networks) resulted in reducing auto mode share by 8 percent and increasing non-motorized modes by 41 percent. These differences are significant at a 95% level of confidence statistical test. Similar behaviour was observed for home-to-shopping trips as changing road network had more impact on modal share; however, the results were less promising as there was minor change in modal share in general.

The minor effect of fused grid design on mode choice for home-to-shopping trips might suggest that other built environment characteristics than connectivity might be more influential in individuals' transport decision-making process for home-to-shopping

Table 3
Mode shift.

Design	Home-to-work Trips			Home-to-shopping trips		
	Auto (%)	Transit (%)	Non-motorized (%)	Auto (%)	Transit (%)	Non-motorized (%)
Existing	79.1	9.4	11.5	92.3	3.2	4.6
Alternative 1	74.10 (−6.3%)	11.6 (+23.4%)	14.3 (+24.3%)	91.8 (−0.5%)	3.1 (−3.1%)	5.0 (+8.7%)
Alternative 2	78.2 (−1.1%)	9.0 (−4.3%)	12.7 (+10.4%)	91.5 (−0.9%)	3.4 (+6.2%)	5.2 (+13.0%)
Alternative 3	72.5 (−8.3%)	11.2 (+19.1%)	16.2 (+40.9%)	91.0 (−1.4%)	3.3 (+3.1%)	5.7 (+23.9%)

Table 4
Mode shift assuming equal change for both non-motorized and auto networks.

Design	Home-to-work Trips			Home-to-shopping trips		
	Auto	Transit	Non-motorized	Auto	Transit	Non-motorized
Existing	79.1	9.4	11.5	92.3	3.2	4.6
Alternative 1	78.2 (−1.1%)	9.9 (+5.3%)	11.8 (+2.6%)	92.1 (−0.2%)	3.2 (0%)	4.8 (+4.3%)
Alternative 2	78.2 (−1.1%)	9.0 (−4.3%)	12.7 (+10.4%)	91.5 (−0.9%)	3.4 (+6.2%)	5.2 (+13.0%)
Alternative 3	77.0 (−2.7%)	9.6 (+2.1%)	13.4 (+16.5%)	91.8 (−0.5%)	3.1 (−3.1%)	5.1 (+10.9%)

trips, such as land use density and mix, which will be the subject of future research. Or it could simply reflect a lack of data and/or modelling available at a finer/neighbourhood level. As mentioned earlier, the shift in modal share in this study is estimated only based on the change of trip distance and time. However, fused grid design includes many other elements related to the build environment, including 1) high density and mixed land use near the center of the neighbourhood; 2) increased accessibility to jobs, schools, and shopping; 3) aesthetically pleasing due to green open spaces; and 4) Increased neighbourhood safety. Including these factors in future analyses will provide a more comprehensive assessment of the fused grid design in future research. Moreover, physiological factors of perceived comfort and safety, and habit, could play a role in influencing the mode choice decision-making process. For example, the Theory of Repeated Behaviour proposes that habit is an important factor in determining repeated behaviour (Singleton, 2013). For instance, a person who always drives to the convenience store would most likely keep doing so, even if context changes and cycling/walking happen to be as fast as driving. This repeated behaviour occurs because driving to the convenience store for that person is an unconscious, habitual behaviour and will not change without mindful intention. In addition, the Theory of Interpersonal Behaviour suggests that the intention to do a behaviour is mediated by both contextual situation and habit (Idris et al., 2015). For example, various trips have different sets of needs, such as shopping trips that require transporting bulky goods.

For the forth alternative where change in the average auto travel distance was set to be equal to the change in the average non-motorized modes travel distance (numerical exercise), the results revealed that providing more accessibility to non-motorized users actually have more impact on modal share than restricting car use. As shown in Table 4; the results are consistent for both trip types. This finding suggests that providing direct routes for non-motorized users is a more effective measure to increase walking and cycling modal share in a community, compared to restricting car use.

5. Research conclusions and limitations

5.1. Conclusions

Fused Grid (Dutch Safe System) Neighbourhood Design Principles are a recent sustainable community design strategy developed by CMHC that aim to promote safer and healthier living at a high quality of life for all Canadians and globally. It combines the best characteristics of the conventional culs-de-sac and traditional grid neighbourhood patterns, and features many design elements including compact higher density and mixed land uses, car-free cores and central greens, and ubiquitous convenient smaller green spaces for restorative play/rest areas and social interaction opportunities. One main trait that differentiates a neighbourhood designed using FG principles from contemporary neighbourhood designs, is the fact that FG favours non-motorized connectivity (continuous grid to encourage local trips) over vehicular connectivity (disrupted grid to make non-motorized trips safer).

This paper presents results of research on how the street connectivity aspect of the FG neighbourhood design principles would influence people mode choice behaviour in Kelowna, BC, Canada by hypothetically retrofitting an existing neighbourhood. The selected study area was a grid pattern neighbourhood with a few culs-de-sacs, in the South Central part of Kelowna. Three hypothetical alternative designs were generated through a series of local road closures and green space and pathway insertions. This is considered a conservative approach, as other factors that might affect mode choice, including perceived level of comfort and safety, and road congestion, were not taken into consideration, but are also shown in the literature as having profound influences on levels of non-motorized use.

To provide reliable empirical evaluations, two mode choice models were developed for home-to-work and home-to-shopping trips using data from the 2013 Okanagan Regional Household Travel Survey. The developed models were used to quantify the shift in modal shares by comparing mode choices associated with the hypothetical proposed designs to that of the existing condition. The results show promise, as applying fused grid principles in this hypothetical case study was successful in significantly reducing auto use and increasing the use of transit and non-motorized modes for home-to-work trips. In contrast, the results of changing connectivity on home-to-shopping trips suggest that the impact of a neighbourhood designed using FG network principles may be limited. This result will be explored in future research when changes in land use are modelled and their influence on non-motorized use is forecasted. In addition, it was found that improving non-motorized network have more influence on encouraging non-motorized use and decreasing auto use compared to restricting car use. This finding suggests that applying fused grid to a neighbourhood in Kelowna with more opportunities to increase non-motorized connectivity (e.g. cul-de-sac) will have more impact than applying it to a neighbourhood with already high non-motorized and vehicular connectivity (e.g. grid pattern). Another conclusion that emerged from the study is that planners need to focus more on providing shortest path for pedestrians and cyclists to improve transportation sustainability in a community. While this study focused on quantifying the impact of fused grid on mode choice behaviour, other benefits are expected based on the results. For example, the reduction in VKT due to the modal shift toward non-motorized modes is likely to cause improvement in transportation safety and reduction in GHG emissions. This is supported by many research that found VKT as a key significant variable for modelling road safety (Sun and Lovegrove, 2013; Masoud et al., 2015) and GHG emissions (Rahman et al., 2017). However, further investigation is required to establish these benefits.

5.2. Limitations and future research

The fused neighbourhood design put great emphasis on providing a highly connected off-road non-motorized network, which has been found in the literature to be associated with an increase in walking and cycling. Further research is needed to determine the effectiveness of the increased off-road non-motorized network connectivity in the fused grid design on encouraging more non-motorized trips. Furthermore, the fused grid design includes many other elements other than the road network layout such as intersections design, green spaces layout, and land use distribution. Including these factors in future analyses will provide a more comprehensive assessment of the fused grid design. Another limitation of this study is that the modal shift was estimated using the average change in travel distance and time of 1000 randomly generated trips, NOT actual trips in the neighbourhood.

In addition, the underlying assumption of the RUM framework is that decision makers are overly rational with unlimited knowledge of the available options and make decisions based on extremely complex computations. However, it can be argued that these assumptions do not appropriately describe a human decision-making process and fails to capture its limitations. Future research can benefit from utilizing a mode choice modelling technique that accounts for humans' bounded rationality and the influence of behavioural aspects. In addition, numerous literature suggested that accounting for physiological factors provides further insights and offers improved prediction of travel mode choice behaviour (Bamberg and Schmidt, 1998; Galdames et al., 2011; Idris et al., 2015). These factors can be accounted for by utilizing established theoretical frameworks from the social physiology literature such as the Theory of Planned Behaviour (Ajzen, 1985), the norm activation model (Schwartz, 1977), and the Theory of Interpersonal Behaviour (Triandis, 1977). In addition, in light of numerous studies suggesting non-linear relationship between non-motorized modes and their predictors (Cervero et al., 2019), future work should account for this non-linear relationship. Finally, examining if there is any variation in the influence of fused grid design on travel behaviour between weekday and weekends would be a fruitful area for further research.

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