HOW ACTIVE MODES COMPETE WITH MOTORIZED MODES IN HIGH-DENSITY AREAS: A CASE STUDY OF DOWNTOWN TORONTO

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Introduction

Active transportation modes, namely: walking and biking, are the most sustainable travel modes in the context of urban transportation systems. As such, the use of active modes for different activity purposes has been under investigation by travel demand researchers (1-5). This is due, in part, to the potentially significant positive impacts of active modes on trip makers as well as urban transportation systems. Previous research efforts showed the various benefits of active modes with respect to the environment, public health, social equity, and traffic congestion (6-8). In terms of environmental benefits, walking and cycling produce nearly zero air and noise pollution compared to motorized modes. This has a direct effect on public health in addition to other benefits that an individual can achieve by using active modes such as fighting obesity and chronic illnesses. Active modes offer independent mobility for individuals who cannot drive or take transit due to inaccessibility issues (e.g. children and low-income families).

Depending on the quality of the pedestrian and cycling networks, active modes can provide a viable substitute for motorized modes especially for short distance trips. High density, mixed-use, and well-connected neighbourhoods encourage individuals to walk and/or bike instead of relying on motorized modes (9). Empirical evidence from a study conducted on 90 of the 100 largest cities in the United States shows that areas with improved cycling infrastructure have higher commuting bike mode shares which contributes partially to the reduction of traffic congestion (10). Similarly, another study showed that a modest shift in short trips (less than 5 miles) to active transportation modes could significantly reduce the annual vehicle-miles driven (11). This explains the drive behind promoting for the development of active communities in large cities throughout the last few decades and the corresponding action plans of expanding pedestrian and cycling infrastructures.

Weather conditions and the built environment along with other several factors may affect individuals' decisions of choosing active modes as their commuting travel modes. For instance, Canada has a relatively cold climate in comparison with the United States and some European countries. Nonetheless, Canadians tend to cycle more than their American counterparts. This is partially due to land-use policies that target: higher percentages of short distance trips by developing mixed-use neighbourhoods, safer cycling conditions by improving cycling infrastructure, and lower driving mode shares by introducing higher costs of owning, driving and parking a car (12). Overall, active modes of transport are on the rise in North American cities; Toronto is no exception (13). The City of Toronto has embarked on an ambitious plan to expand its bike network along most of the major routes in the downtown core (14). In order to test the effectiveness of such policies on maintaining as well as encouraging the use of active modes, an in-depth understanding of individuals' travel behaviour and how active modes compete with motorized modes in high-density areas is essential. That is, transportation planners can develop efficient policies and/or programs that promote for the increase of active modes usage.

This paper is organized as follows. A review of the literature on the current investigation of short distance trips in dense neighbourhoods is presented. The following sections present a description of the dataset used in the analysis, the econometric modelling framework, and the development of the empirical model. Finally, key findings and possible implications for developing effective policies for active modes are identified.

Literature Review

Studying commuters' mode choice behaviour has been under continued investigation by transportation planners. Nonetheless, few studies focused on studying commuting mode choice behaviour for short distance trips in cases where active modes are competitive options (9), especially within the North American Context. In this section, relevant research efforts to the current investigation's context are presented.

A recent study in the Greater Copenhagen Area analyzed mode choice behaviour for trips shorter than 22 km (15). A dataset including travel diaries and socio-economic variables of a representative sample of the population was used for the analysis. A mixed-logit mode choice model was developed to investigate the effect of travel modes' level of service attributes and trip makers' characteristics on their mode choices. The study concluded that the use of active modes of transportation is positively correlated with temperature and short trip distances. However, while there is no distance threshold defined for active modes, considering walking or biking for commuting trips that are more than 10 km is not realistic in most cases (6). Further, the study did not investigate the effect of pedestrian and cycling infrastructures on selecting active modes as a mode of transportation. Another study on short distance trips was conducted in the Netherlands, examining the effect of personal and neighbourhood characteristics on active modes choice in comparison with motorized modes (9). A multilevel logistic model is developed using a dataset that included travel records with various trip purposes with a maximum trip length of 7.5 KM. The results indicate that educated middle age urban residents are more likely to use active modes of transport. Nevertheless, similar to the Copenhagen study, the built environment characteristics were not considered.

Using data of individuals' travel diaries, a similar study assessed the competitiveness of biking and driving alongside other modes in the City of Ghent (16). The study concluded that cycling might only be competitive within a range of 5 KM, while walking was only competitive within a 1 KM range. In addition, Kim and Ulfarsson conducted a study on trips that are less than 2.25 KM in Washington D.C. (17). The results indicated that individuals are more likely to drive if they can or are accustomed to. Moreover, the authors indicated that individuals are less likely to walk or bike as they age. Nonetheless, the study did not consider the effect of bike infrastructure and street walkability on individuals' mode choices for such short distance trips.

Over the past decade, a significant amount of research on studying individuals' behaviour of choosing biking as their commuting travel mode has been conducted. Heinen, van Wee and Maat (18) discussed the role of personal attitudes and built-environment on commuters' mode choice decision. The study showed that "safety" and "awareness" are strong determinants for the choice of biking as a travel mode. Xing, Handy and Mokhtarian (19) provided an extensive investigation of factors associated with commuters' choice of biking as a mode of travel in six cities in the United States. The study revealed that short distances to destinations and supporting biking infrastructure are key factors that explain the higher bike mode share among commuters. Similarly, Pucher, Dill and Handy (20) studied the effects of bike infrastructure and bike programs on bike usage as a travel mode. Habib et al. (5) investigated biking behaviour in terms of choice of biking for utilitarian and/or recreational purposes as well as bike ownership level for the City of Toronto. Howard and Burns (21) examined the effect of bike infrastructure, distance travelled and safest routes on biking route selection. The results indicate that cyclists tend to alter their routes to maximize on the utility of the aforementioned variables.

Similarly, research efforts on studying individuals' behaviour of engaging in physical activities such as commuting by bike or on foot with respect to the built environment have been investigated (7, 9). Empirical evidence from 36 environmentally diverse but equivalent-sized neighbourhoods showed that individuals walk more for activities in high-density areas (22). Another group of studies targeted the effect of land-use, the built environment and neighbourhood characteristics on the use of active modes of transportation. Cervero and Radisch compared the effect of suburban and neo-traditional neighbourhoods on the use of non-motorized mode for different activity purposes (23). The results showed that neo-traditional neighbourhoods have a stronger effect on selecting active transportation modes specifically for shopping purposes. Guo, Bhat and Copperman investigated the effect of the built environment on motorized and non-motorized trip making behaviour (24). A bivariate ordered probit model was developed. The model accounts for complementary and synergistic relationships between motorized and non-motorized modes. The study concluded that business density, street connectivity, and bike lane density are positively correlated with the use of active modes of transportation.

Other studies focused on studying the effect of weather conditions on transportation. Saneinejad, Roorda and Kennedy (25) developed a series of models to explore the effect of weather on home-based work trips in the City of Toronto. Results from their study showed that weather conditions including temperature and precipitation have a significant impact on all travel modes and more specifically on active modes of transportation. Another study on the effect of climate and weather on bike use in Melbourne City confirmed the negative correlation between cycling and precipitation (26).

Recently, bike sharing as a competitive active mode of transportation in urban centres have been under investigation. Habib et al. (27) investigated the determinants of bike share demand in Toronto. The study considered weather effects, socio-demographic variables, and built environment attributes on bike share trip activity. Results indicated that bike share ridership is positively correlated with temperature while being negatively correlated with snow on ground, humidity and precipitation. In addition, the study concluded that bike share users preferred to use routes that exhibit a high density of bike lanes. Finally, Mahmoud et al (28) examined the "mode culture" in the City of Toronto with a particular focus on the factors that influence the cycling culture. The results showed that individuals who lived and worked in the downtown core of Toronto were more likely to be rely on biking as their mode of travel.

This paper focuses on studying short distance commuting trips in high-density neighbourhoods, in particular, investigating on how active modes of transportation compete with motorized modes. Lessons learned from the literature are included and investigated in this study. Data on trip makers and their household attributes, trip characteristics, land-use and built environment attributes, and weather conditions are used to develop a nested logit mode choice model for commuting trips in the downtown area of the City of Toronto. The developed model reveals meaningful insights that answer the research question of this study.

Study Area and Data Description

The City of Toronto is located in the heart of the Greater Toronto and Hamilton Area (GTHA) which forms Canada's largest urban region (29). Figure 1 shows a map of the City of Toronto with a detailed section of the city's Planning District 1, featuring the downtown core area. In addition, the map shows the distribution of trip origins categorized by distance travelled.

Figure 1 Study Area and Distribution of Trip Origins by Distance Travelled

Trip characteristics and socio-demographic attributes of the study were extracted from the 2011-2012 Transportation Tomorrow Survey (TTS) dataset. The TTS is a trip-based household survey that is conducted every five years in the Greater Toronto and Hamilton Area (GTHA) among 5% of its population. This study focuses on short distance commuting trips in which active modes are truly competing with motorized modes. In order to account for short distance commuting trips, only home-work trips with both trip ends in the downtown Toronto area are considered in this analysis. This subset of trips represents around 10% of the total commuting trips in the City of Toronto. The dataset provides detailed disaggregate individual trip records with geo-coded locations of individuals' households (to the nearest midblock), places of employment and their observed travel mode. The total number of complete trip records used in this study is 1,956.

Four travel modes are considered in this analysis, namely auto driver, transit, bike and walk. The four modes are assumed to be available to all individuals in the dataset. Travel distances and times for the auto driver mode were obtained from the 2012 EMME traffic assignment network model of the GTHA. However, for the transit mode, travel distances and times were obtained from Google Maps® Application Programming Interface (API) based on the General Transit Feeds Specifications (GTFS) data. Data obtained from the EMME assignment model and Google Maps API consider the interactions between transit and traffic to generate realistic mode-specific travel times that take into account traffic congestion. Similarly, for the bike and walk travel modes, mode-specific paths were generated using Google Maps® API. Suggested bicycle paths were generated such that the travelled distance was minimized and percent of bicycle infrastructure along the route was maximized. Accordingly, walk and bike travel distances and times were obtained for each individual using the locations of individuals' trip origins and destinations.

Travel costs for the auto driver mode were obtained based on the distance travelled and average parking costs at the traffic analysis zone of the trip destination. The average parking cost in the downtown area of the City of Toronto is $23 per day and $8 per hour (30). As such, the relatively low-cost car trips (due to the short distance travelled) are offset with high parking cost. On the other hand, transit cost is defined based on the fares set by the Toronto Transit Commission (TTC), the public transport agency that operates transit services in the City of Toronto, of $3 for adults or $2 for seniors (+65 years old) and students (13 to 19 years old) as a flat fare per trip[i]. In addition, hourly weather data collected at the Billy Bishop Toronto city airport (also known locally as the 'Toronto Island Airport') weather station was provided by Environment Canada. The data included weather temperature, wind speed, precipitation, and snow on ground. The average weather temperature for the trip records in the dataset during the fall season is 7.4oC. Further, using an updated version of a street network with details on bicycle infrastructure types, the suggested bicycle paths were used to generate the percent of bike facility length compared to the total trip distance. In addition, the total number of intersections with major roads was determined. The spatial analysis was conducted in ArcMap® 10.2.

The TTC provides extensive transit coverage in the downtown core area of the City of Toronto. Within the study area, the average airline distance from any household location (in the dataset) to any transit stop/station is 100 m signifying the ease of transit access. In addition, the study area is considered to be a walkable/bikeable neighbourhood that has well-developed pedestrian paths and cycling infrastructure including bike racks, bike lanes (separated bike lanes), sharrows (marked bike lanes), park roads, signed routes and multi-use pathways. One of the unique features of Toronto's downtown pedestrian network is the "PATH" - an underground walkway that connects more than 50 buildings/office towers, 20 parking garages, six subway stations, Toronto Coach Terminal, and Union Station. As the largest underground shopping complex in the world with a network length of 30 km (31), the PATH accommodates more than 200,000 business-day commuters and thousands of tourists and residents in weatherproof comfort. Figure 2 shows a heat map of the Walk Score® for the City of Toronto as an index of public access walkability. The average Walk Score® in the City of Toronto is 71 and it goes up to 100 in the downtown area (32). Similarly, Figure 3 shows the density of bike infrastructure in the neighbourhoods of the City of Toronto. Clearly, the downtown area is more walkable and bikeable than the surrounding areas of the city. That is, the study area with such compact, mixedused, and well-connected pedestrian and cycling network provides a perfect case to study short distance commuting trips in which active modes are truly competing with motorized modes.

Figure 4 shows the travel mode shares within the study area. One of the major factors that affect individuals' mode choice is travel cost. The average cost per unit distance for transit users in the downtown area is $1.15 per KM. In addition, as explained earlier, parking costs are relatively higher in the downtown area. Further, the average trip length of trips that originate from and destined to the downtown area is 2.25 km. That is, shorter trip distances, higher parking costs, and the flat transit fares are important factors that explain the dominance of the active travel mode with more than a 50% modal share. Figure 5 shows the average observed travel distances by each mode. The average biking distance is shorter by only 0.1 and 0.4 KM compared to the average driving and transit distances, respectively. Figure 6 shows a density chart of observed walking and biking trips distributed by travel distance. This distribution suggests that walking commuting trips are often shorter than 5KM, while biking commuting trips can be longer. Similarly, Figure 7 shows the average generated travel time by mode for all trips (i.e., travel times by each mode for the same origin-destination (O/D) pair) in the sample data. Figure 7 shows that on average for the same O/D pairs, the bike mode is 5 minutes shorter than the transit mode. In terms of the effect of the built-environment on bike trips, Figure 8 shows a density chart of biking trips distributed by percent of bike facility length (e.g., bike lanes) to the total travel distance. Clearly, higher percent of bike facility length compared to the total travel distance is a significant factor that motivates individuals to bike.

Figure 2 Walk Score Map of the City of Toronto *(32)*

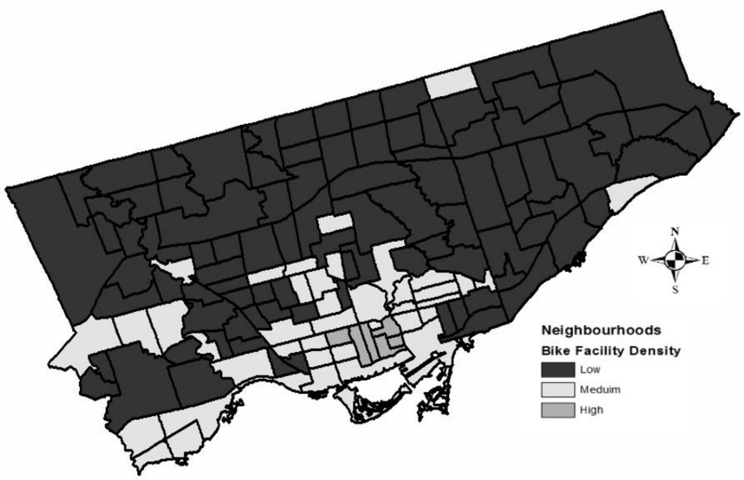

Figure 3 Bike Infrastructure Density in the City of Toronto

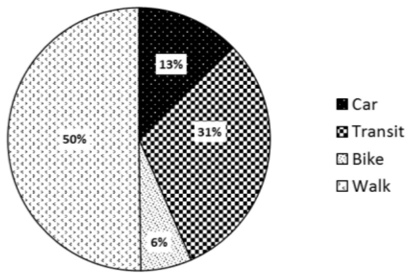

Figure 4 Travel Mode Shares

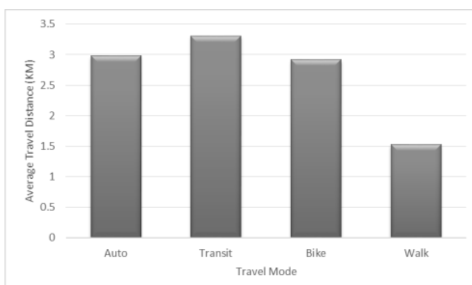

Figure 5 Average (Observed) Travel Distance by Mode

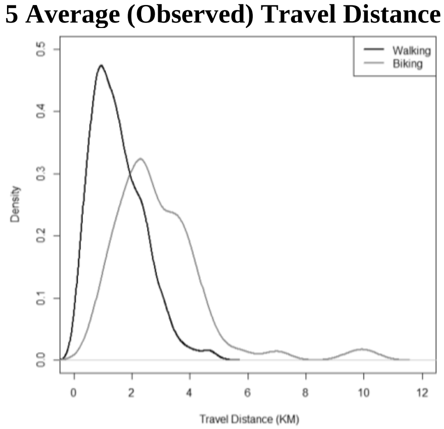

Figure 6 Density of Walking and Biking Trips by Total Travel Distance

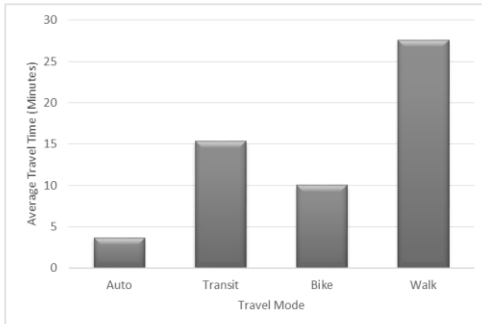

Figure 7 Average (Generated) Travel Time by Mode

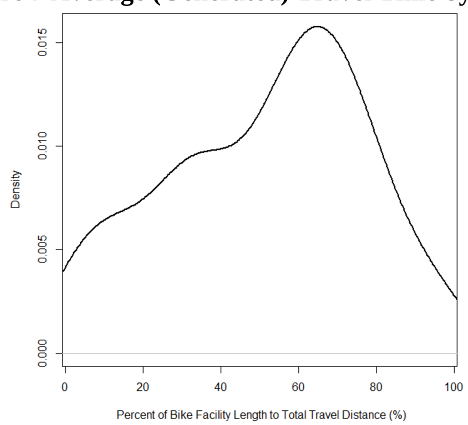

Figure 8 Density of Biking Trips by Percent of Bike Facility Length to Total Travel Distance

Econometric Model

This section presents the econometric model formulation of the Nested Logit (NL) model. The NL model formulation allows for relaxing the assumption of independence of irrelevant alternatives (IIA) and capturing preference heterogeneity among respondents. The model formulation categorizes common alternatives in "nests". The NL model formulation considers partially common error term component for within-nest alternatives. Individuals are assumed to gain a certain level of utility by choosing one travel mode over the other three available modes. The utility function (U) for each mode consists of systematic and random components. The error term component of nested alternatives can be divided into two portions to adopt nesting structures; within-nest and alternative-specific error terms. Based on the the fundamental Random Utility Maximization (RUM) Theory, trip makers are assumed to be rational in selecting their travel modes by choosing the alternative with the highest utility value (*33*, *36*):

$$U_{m|n} = V_m + \varepsilon_m + \varepsilon_n = (\beta \cdot X)_m + \varepsilon_m + \varepsilon_n \qquad [1]$$

Where the subscript "m" indicates one of the travel modes in a choice set of "M" modes, "X" is the observed variables and their corresponding coefficients "β", "ε_m" is the alternative-specific random error term, and "ε_n" is the within-nest random error term. As such, the conditional probability that a person "i" selects a mode alternative "m" from a nest "n" follows the logit formula of:

$$\Pr(m \mid n) = \frac{\exp(V_m / \lambda_n)}{\sum_{m'=1}^{M} \exp(V_{m'} / \lambda_n)} \qquad [2]$$

Where "Pr(m|n)" is the conditional probability of choosing mode "m" from nest "n" and "λ_n" is a measure of the degree of independence in the unobserved utility among alternatives in nest "n".

The marginal choice probabilities are calculated as:

$$\Pr(n) = \frac{\exp(V_n + \lambda_n \cdot I_n)}{\sum_{n'=1}^{N} \exp(V_n + \lambda_n \cdot I_n)} \qquad [3]$$

Where "Pr(n)" is the probability of choosing alternative from nest "n", "V_n" is a function of common attributes within nest "n" (if any), "N" indicates the total number of nests "n", and "I_n" is the "logsum" variable of nest "n". The logsum (also known as the "inclusive value") represents the expected utility of the within-nest alternatives as:

$$I_n = \log\left\{ \sum_{m'=1}^{M} \exp(V_{m'} / \lambda_n) \right\} \qquad [4]$$

Therefore, the unconditional probabilities of travel modes can be obtained as:

$$\Pr(m) = \Pr(m \mid n) \cdot \Pr(n) \qquad [5]$$

In this paper, the empirical models were estimated using the "mlogit" package in the statistical software "R" and using the "MAXLIK" component for maximum likelihood estimation (*34*, *35*).

Empirical Model

Previous studies showed that trip distance/time and travel cost along with personal attributes are important variables to consider while developing mode choice models (*25-27*). In addition to the typically used variables, the effect of weather conditions and built environment variables on active modes is investigated in this study. Table 1 presents definitions of variables that are used in this analysis.

A traditional multinomial logit (MNL) model as well as a nested (NL) logit model were developed. The empirical results showed that the NL model outperformed the MNL model and therefore results of the NL model are only presented herein. The NL model is developed with three nests, namely: auto driver, transit, and active modes. Different model structures and specifications were tested and the final model specifications are reported in Table 2. A total of 16 parameters were estimated using a sample of 1,956 trips that originate from and destined to the downtown Toronto area. The reported adjusted Rho-Squared value, as a measure of goodness-of-fit (*36*), is 0.36. All the reported parameters are estimated with the expected signs and found to be statistically significant (with t-statistics higher than 1.96) at the 95% confidence interval, except for the "walk score" variable for the walk mode and the "Male" variable for the transit mode which are statistically significant at the 90% confidence interval. As expected, travel modes with higher unit travel costs are less likely to be chosen over modes with lower unit travel cost or modes of no travel cost. Similarly, modes with shorter travel times are preferred more.

In terms of individual-specific variables, the increase of the car ownership level as compared to the number of persons per household has a positive effect on the probability of choosing the auto driver mode. In addition, individuals who have access to free parking at their work locations are more likely to drive to work. Similarly, holding a transit pass is a significant variable in increasing the probability of choosing transit as a travel mode. Consistent with previous research findings, the model shows that males are more likely to bike than females (37). In addition, individuals who are 35 years old or less are more likely to bike more than older individuals.

Table 1 Definitions of Variables

Variable Name	Description
Distance	Mode-specific network distance, in KM, from individuals' household location to their work location
Cost	Mode-specific travel cost, in Canadian Dollars (CAD), from individuals' household location to their work location
Time	Mode-specific travel time, in minutes, from household individuals' location to their work location
Male	=1 if individual is male; =0 Otherwise
Free Parking	=1 if individual has access to free parking at work location; =0 Otherwise
Age<35	=1 if individual age is equal to or less than 35 years old; =0 Otherwise
Transit Pass	=1 if individual holds a TTC Metro Pass; =0 Otherwise
Number of Vehicles	Number of vehicles per household
Number of Persons	Number of persons per household
Temperature	Weather Temperature, in ºC, by time of day of the individuals' trips
Number of Intersections	Number of intersections with major roads along individuals' bike path from their household location to their work location
Length of Bike Facilities	The total length of bike lanes along individuals' bike path from their household location to their work location
Walk Score at Employment Zone	The walk score of individuals' work location traffic analysis zone (measured at the neighbourhood level)

Table 2 Parameter Estimation Results – Mode Choice NL Model

Number of Observations	1956	
Log-Likelihood (Full Model)	-1399.8	
Log-Likelihood (Null Model)	-217.8	
Rho-Squared Value	0.36	
Systematic Utility Function:		
Variables	**Parameter**	**t-Stats**
Alternative Specific Constant		
Auto Drive	-4.85800	-12.069*
Transit	-0.60736	-1.975*
Bike	-2.91619	-6.519*
Travel Cost/Distance	-0.52030	-20.694*
Travel Time	-0.10242	-15.564*
Auto Drive		
Free Parking	1.91308	9.479*
Number of Vehicles/Number of Persons	2.23915	9.921*
Transit		
Male	-0.25804	-1.922’
Transit Pass	2.75873	15.447*
Bike		
Male	0.43767	2.416*
Temperature	0.02540	1.977*
Number of Intersections/Distance	-0.11461	-3.334*
Length of Bike Facilities/Distance	0.49890	2.094*
Age<35	0.32795	2.048*
Walk		
Walk Score at Employment Zone	0.39377	1.695’
Log-Sum of Active Modes Nest	0.81572	1.978*

* Significant at the 95% level of confidence, **’** Significant at the 90% level of confidence

While different weather variables were tested, only the atmospheric temperature showed significant correlation with bike usage. Data from the household survey was collected during the fall season (September-December) in which severe weather events were not recorded. Variables such as precipitation, snow on ground and wind speed were tested but were not found statistically significant; therefore, only the weather temperature was included in the model. During the fall season, higher temperatures are desirable for individuals who are using active modes. This explains the positive effect of the increase in temperature on the probability of choosing bike as a travel mode. The reported temperature during the analysis period over the sampled trip records ranged from -12oC to 25oC with an average of 7.5^{oC}.

The effect of the built-environment on active modes was carefully considered while developing this model. The average slope of bike routes was calculated using the digital elevation model (DEM) of Toronto. However, it did not show statistical significance when it was included in the model. This result is perhaps due to the relatively flat terrain of the downtown core area. As explained above, a detailed bike network was used to generate the percent of bike facilities (i.e., bike lanes) compared to individuals total travel distance. In addition, the total number of intersections with major roads was determined. These metrics were obtained according to the suggested bike path using Google Maps® API which considers the safest (by utilizing the surrounding bike infrastructure) and shortest bike route. Model results show that higher percentages of bike lanes compared to the total travel distance has a significant positive effect on the probability of choosing biking as a travel mode. On the other hand, higher number of intersections with major roads has a negative effect on bike usage. Similarly, data on neighbourhood walk scores were obtained at the employment zone. Higher walk score values indicates more walkable neighbourhoods. The model results suggest that individuals are more likely to walk to work if the walk score at the employment zone is high.

Model results show that females, transit pass holders, individuals who live in households with high car ownership levels, and individuals who have access to free parking at work locations are the least prone to using active modes. From a policy-making perspective, customized strategies that are specifically targeted to such markets are expected to be more efficient. For instance, policies such as restricted parking allowance per household in the downtown residential buildings, and limitation of offered free parking space within the downtown area may contribute to an overall lower driving modal share. On the other hand, seasonal marketing programs targeting the middle aged and females can be utilized to promote for sustainable commuting alternatives. The targeted market shares are potentially expected to change their culture and perception towards active modes. Moreover, the model can be used for policy analysis to investigate the effect of improving the built-environment on active modes usage. Introducing new bike lanes, enhancing intersection crossings safety, and providing protected and direct pedestrian paths are few initiatives that can contribute to a more sustainable community. The developed model can help in evaluating the effectiveness of some of the above-mentioned policies as a tool to support the decision making process.

Conclusions and Future Work

This paper studies commuters' mode choice behaviour in high-density areas. The study focuses on short distance commuting trips where active modes (i.e., bike and walk) truly compete with motorized modes. The downtown area of the City of Toronto as one of the most vibrant active neighbourhoods in North America is selected as a case study. Data from the 2011-2012 Transportation Tomorrow Survey (TTS) is used for the empirical analysis. A Nested Logit (NL) mode choice model with three nests, namely: auto driver, transit, and active modes is developed. In addition to personal and household attributes, the model includes variables that explain individuals' active mode choice behaviour such as mode-specific travel distances and times, the surrounding built environment, and weather conditions. The empirical investigation reveals useful insights that are helpful in understanding how active modes compete with motorized modes in high-density areas. The built-environment and weather conditions have a strong effect on active mode shares. In addition, shorter distances to destinations and lower travel cost per unit distance contribute significantly to the increase of bike and walk mode shares.

Next steps of this research include the application of the developed model for policy analysis. As such, the effect of different variables on short distance trips modal shares can quantified. In addition, future research may consider comparing short distance commuting trips in different planning districts of the GTHA. This will provide more insights on how the built environment affects commuters' decisions in different parts of the region.

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