Effects of Built Environment and Weather on Bike Sharing Demand: Station Level Analysis of Commercial Bike Sharing in Toronto

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ABSTRACT

Bike Share Toronto is Canada's second largest public bike share system. Bike Share Toronto provides a unique case study as it is one of the few bike share programs in a North American city that experiences severe cold climates and operates throughout the entire year. Using year-round real time trip data, this study analyzes the factors affecting Toronto's bike share ridership. A comprehensive spatial analysis is performed and three regression models are developed at the station level. Results of the trip attraction and generation models provide meaningful insights on the influence of socio-demographic attributes, land use and built environment, as well as different weather measures on bicycle share ridership. The developed models can be used to assist policy makers and city planners to predict the monthly trip activity at potential station locations. A station pair (origin-destination) regression model is developed based on station to station paths' level of service attributes along with other zonal level factors. Results show that station-to-station distance and the number of intersections with major roads have negative impacts on bike share ridership. In addition, for a given origin-destination pair, the higher the percentage of bicycle infrastructure with respect to the total route length, the higher the corresponding ridership. This model can be used to predict the trip distribution between station pairs based on the total trip activity at each station. The model can also be used to assess potential bike infrastructure development based on expected bicycle routes from/to potential station locations.

INTRODUCTION

Over 400 cities around the world have implemented or are planning to implement a bicycle share program [1]. This reflects a growing concern for both environmental and personal health. The economic benefits of bicycle use may also be a contributing factor. The City of Toronto introduced its Bike Share as an active and sustainable mobility option for the citizens of Toronto as well as for visitors to Toronto. The program aims to complement the existing transit system. It provides a relatively quick means of travel within the Toronto downtown core area. The bicycles are readily identifiable as belonging to the Bike Share program, thereby eliminating the concern of bike theft or vandalism for the bicycle user. Bicycling, in general, has numerous benefits. Counted among those benefits are: decreasing CO_2 emissions; reducing various diseases such as diabetes and obesity; reducing traffic congestion and noise pollution by providing alternatives to auto-commuting; and increasing public transit use [2].

The first public bicycle share system was introduced in Amsterdam, Netherlands, in the 1960s. The “White Bikes” were distributed around the city for the public’s use. The program was aborted as the bicycles were repeatedly stolen and vandalized. In 1996, Portsmouth University in England, introduced IT based public bicycle share systems [3]. The program’s users accessed the bicycles using electronic swipe cards. This new generation of bicycle shared systems allowed the operator to identify the customer and provided him or her with the ability to track the use of the bicycle. This addition to the bicycle share concept led to a significant reduction of bicycle thefts as well as vandalism. Today, we witness the evolution of “Multi-modal Systems” that provide: GPS tracking of bicycle use; real time ridership data; moveable bike stations; and system integration with public transit modes [2]. Typically, public bicycle share systems consist of both devoted users who pay annual subscription fees as well as casual users who can pay on a month to month or on a per trip basis. The user can ride the bicycle for a maximum of 30 minutes and then return it to the nearest station [2]. If the user was to exceed his or her allotted 30 minutes, extra charges may be incurred, depending on the company’s rules of use and operation.

Bike Share Toronto was established in 2011 as part of the City of Toronto’s Bike Plan [4]. Currently, the bicycle mode share for the City of Toronto is estimated to be 1.2% [5]. However, the mode share increases substantially in Toronto’s downtown core area to 17% [6]. It is important to note that the above percentages focus on bicycling for commuter purposes and they do not include utilitarian or recreational bike trips. Thus, it is important to note that the overall actual bicycle mode share may differ from the above mentioned shares.

Currently, Bike Share Toronto operates a system composed of 80 stations and 1,000 bicycles. The existing stations are distributed in the Toronto downtown core with plans to expand the bicycle’s network and system capacity to a total of 3,000 bicycles [4]. In the first 18 months since its inception, Bike Share Toronto facilitated over 1,000,000 trips and attracted 4,743 subscribers [7]. Unlike other North American public bicycle share systems, Bike Share Toronto operates 24 hours per day, and is available 365 days a year.

In this paper, we attempt to examine the effect of weather, land use, socio-demographic variables, and built environment attributes on Bike Share Toronto throughout the entire year of 2013. Using real time bicycle ridership data provided by Bike Share Toronto, factors affecting trip attraction and trip generation are investigated. Further on, the shortest and most bicycle friendly routes between each station pair in the system are generated and, through utilizing a station-to-station origin destination model, levels of service attributes are then calculated. The objective of the study is to provide a planning tool that can be used by transportation planners and city officials to predict the total monthly trip rates generated at or attracted to potential station locations and/or assess the effect of potential bicycle infrastructure development on bicycle share ridership.

LITERATURE REVIEW

Research on public bicycle share systems is on the rise. Previous research showed that public bike share users tended to be less experienced than regular bike users and therefore had different characteristics than that of bicycle riders for whom bicycle use is part of established behaviour and routines [8]. That is, studying public bicycles share users' behaviour is required to fill this gap in the literature, and is likely to provide pertinent information in regards to policy development for bicycle use in urban settings.

Few of the studies used data from customer satisfaction surveys to analyze users' socio-demographic and ridership characteristics. Bachand-Marleau et al. (2012) used data on BIXI users in Montreal, Quebec, (Canada) to conclude that the location of docking stations close to the origin of potential users can increase ridership [8]. Other studies attempted to understand the feasibility and potential of bicycle share systems. North American cities such as Ottawa, Vancouver, Seattle, and New York, through the help of and/or collaboration between consulting firms and government institutions, conducted several feasibility studies on public bicycle share systems. These studies hypothesized several potential station locations and determined, using intuition and previously published studies on cycling behaviour, the various factors that can promote systems' bicycle ridership. Factors such as population and employment density, bicycle infrastructure, socio-demographic characteristics, land use as well as the built environment were investigated [9-12].

A third category of studies used ridership data from systems that are currently in operation to predict and hypothesize the number, location and distribution of stations in other cities worldwide. For instance, Krykewycz et al. (2010) used ridership data from peer European cities to estimate demand for a hypothetical bicycle share ridership system in Philadelphia, Pennsylvania (USA) [13]. In addition, Maurer (2011) used a pair-wise suitability analysis to understand the effects of variables such as job density, household income, and alternative commuters on public bicycle share ridership to propose the locations of bicycle stations in Sacramento, California (USA). Ridership data from the Nice Ride in Minneapolis-Saint Paul, Minnesota (USA) was used to perform the analysis. In this research the time period for the study was narrowed down to the month of August. The analysis showed a positive correlation between the number of docks per station and users' ridership. On the other hand, higher proximity to railway stations was negatively correlated with station use [14].

Recently, a few studies used real time bicycle ridership data to examine factors that affect public bicycle ridership demand. Gebhart and Noland (2013) used real time ridership data for Capital Bikeshare in Washington D.C. (USA) to investigate the impact of weather variables and proximity of bike share stations to metro stations on ridership levels. Reduced ridership was correlated with cold temperatures, rain, and high humidity levels [15]. Buck and Buehler (2012) investigated the influence of bicycle infrastructure, population density, land use mix around stations, and the number of households without a car using bicycle share systems using ridership data from Capital Bikeshare [16]. The study was conducted using data gathered during the months of September to March. Buck and Buehler concluded that locating stations near bicycle lanes may increase ridership. In addition, Daddio (2012) performed a regression analysis on the usage of Capital Bikeshare stations during the month of October. The study concluded that proximity to retail outlets and the metro rail was positively correlated with trip generation while locating stations away from the centre of the bicycle share system tended to reduce ridership [17]. Socio-demographic factors were also investigated and results showed that a bicycle share system was predominantly used by white, middle-aged riders. Wang et al. (2012) conducted a similar study using data from Nice Ride, Minnesota, which only operated from the months of April to November. The study evaluated the effect of socio-demographic, land use, built environment and transportation infrastructure variables on bicycle share ridership [18]. Station proximity to high job density and food serving enterprises was found to be correlated with higher ridership levels. Rixi (2013) explored the influence of socio-demographic characteristics such as education, income, and employment and population density on monthly ridership data from three United States based operators [19]. Built environment factors such as proximity to colleges and parks were included in the analysis. Nair et al. (2013) studied Paris's public bicycle share system. The study investigated system characteristics, temporal flows and intermodal use [20]. Hampshire (2013) used real time data from the months of May to September for Barcelona's and Seville's bicycle share systems [21]. The ridership data was aggregated on the sub-city district (SCD) level and the analysis of ridership use was conducted on an hourly level. Population and employment density as well as land use attributes were found to be correlated with higher public bicycle use. In addition, higher ridership levels were correlated with the increase morning work-oriented trips.

Imani et al. [22] investigated factors affecting bicycle share demand at the station level using real time ridership data from the BIXI bicycle share program in Montreal, Quebec (Canada). A linear mixed modelling was developed and the results showed that stations close to major roads had lower trip activities compared to stations that were situated around minor roads and bicycle lanes. A number of land use and built environment variables, temporal characteristics and weather variables such as temperature were investigated. The study concluded that the installation of a greater number of stations in proximity to existing stations rather than increasing existing stations' capacities would have a greater impact on bicycle share ridership. However, that bicycle share system only operated during summer months and thus, similar to many previously mentioned studies, the study did not provide a full understanding of bicycle share ridership levels in different seasons during the year. In this paper, data from Bike Share in Toronto, Ontario, Canada is used. This system operates year round. It provides, therefore, rich data on seasonal bike demand by investigating the effects of detailed weather variables on bicycle ridership use.

STUDY AREA AND DATA DESCRIPTION

To investigate the factors affecting public bicycle trip generation and attraction, weather information, bicycle ridership data, socio-demographic characteristics, land use and built environment attributes were amalgamated to create a complete and all inclusive dataset.

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 database included temperature, wind chill, humidex (humidity index), snow on ground, wind speed, precipitation and relative humidity. Subzero temperature values were adjusted based on wind chill measures that combined the effect of wind speed and measured temperature. Similarly, above zero temperature values were adjusted using humidex levels that combined the effects of humidity and the reported temperature values. Using the formulas for wind chill and humidex [23], the perceived temperature was estimated. The perceived temperature is the amalgamation of humidex and wind chill with the above zero and the below zero recorded temperatures respectively. The perceived temperature is a better indicator of the overall feel of the bike user, and therefore, the perceived temperature is used in this analysis.

Real time ridership data for the year of 2013 was made available for this study by Bike Share Toronto. The dataset included trip start time and date, trip end time and date, trip duration, start station, end station, number of docks per station and bicycle number. This allowed for a comprehensive temporal analysis based on the date and time of each trip as well as spatial analysis based on the number of trips generated to and attracted by every station. The availability of data in such a form eliminated possible errors incurred due to rebalancing operations. The bicycle ridership data was analyzed on the station level and trips were aggregated on a monthly basis to account for the variability of weather effects. Figure (1) shows the distribution of the 80 bicycle share station, street network, and bike infrastructure network.

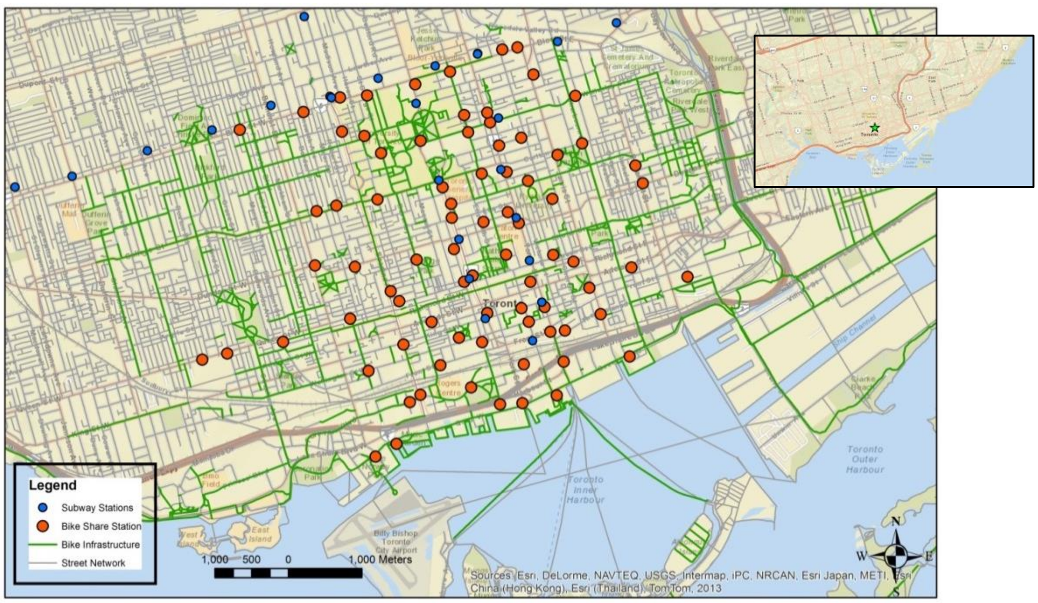

FIGURE 1 Study Area

After “cleaning” the data set to remove invalid trip records, the total number of trips completed using Bike Share Toronto in the year of 2013 was 623,649. The average number of trips generated per station on a monthly basis was 649 ranging from 60 trips to 2,072 trips per station per month. Similarly, the average number of trips attracted per station was 650 with a minimum of 82 trips and a maximum of 2,218 trips. Figure (2) shows the trip attraction as well as trip generation at the station level.

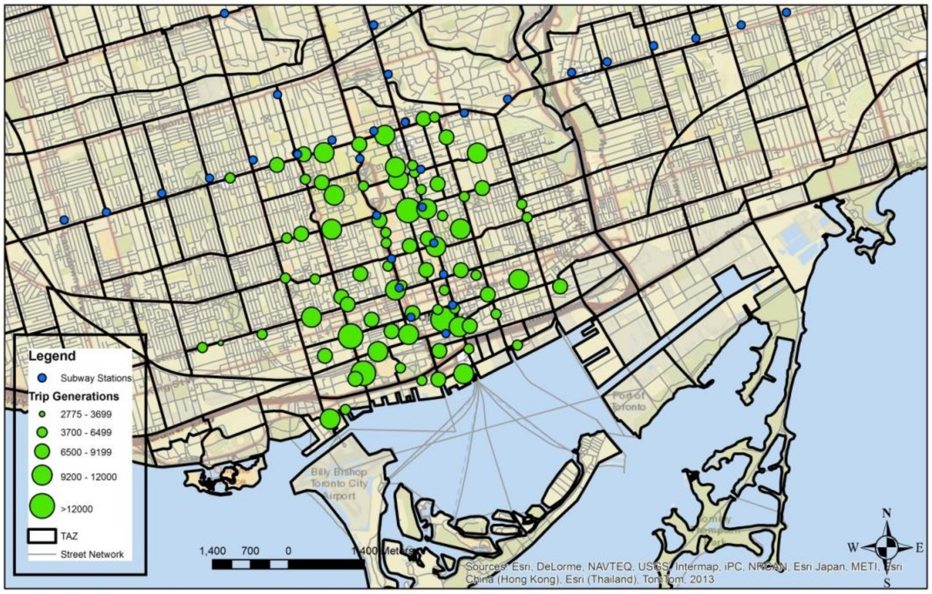

FIGURE 2-a Trip Generations at Bike Share Stations

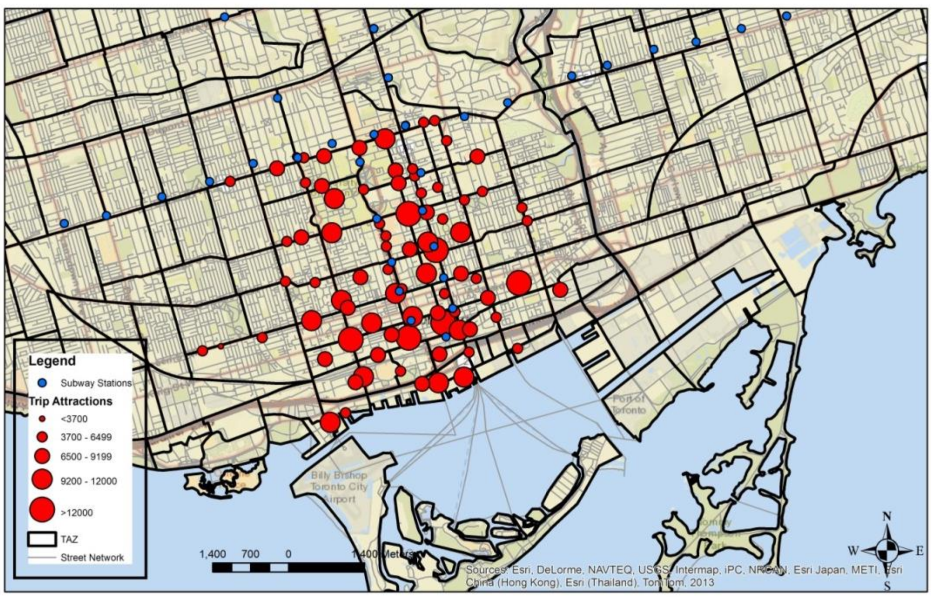

FIGURE 2-b Trip Attractions at Bike Share Stations

FIGURE 2 Trip Activity at Bike Share Stations

Using the start and end stations of the trips, hypothetical bicycle paths were generated using Google Map's Application Programming Interface (API). Bicycle paths were generated such that the travelled distance was minimized and percent of bicycle infrastructure along the route was maximized. Bicycle lanes provide one of the safest means for cyclists to travel in the City of Toronto. The route selection hypothesis is supported by a study conducted by Winters et al on bike route safety and bike user preference in Toronto, ON and Vancouver, BC (Canada). The authors concluded that bike friendly routes – routes that exhibit some form of bike infrastructure - are safer, and are generally preferred by bike users [24]. Therefore, they were included in our study's criteria for path selection. Bicycle users were assumed to be rationale (i.e. pragmatic), in choosing the shortest and safest path to travel on. Travelled distance and trip durations were determined based on the suggested routes. The average actual trip durations between each station pair were compared against the estimated durations. Results showed consistency of station-to-station trip duration. The spatial analysis was done in ArcMap® 10.1, using an updated version of a street network with details on bicycle infrastructure type, if any. The suggested bicycle paths were used along with the street network to generate the percent of bicycle path length compared to the total path length and the total number of intersections with major roads.

Socio-demographic characteristics including employment density and percent of male population were also considered. The data was extracted from the Transportation Tomorrow Survey (TTS) to be used in the analysis. The Transportation Tomorrow Survey was chosen as it is one of the largest and most comprehensive household surveys conducted in North America [25]. Every five years, approximately 5% of all households of the Greater Toronto and Hamilton areas are randomly selected, and individuals' trip information and demographics are gathered. Data such as age, gender, home and work locations, and occupation type are aggregated on a zonal level.

In addition, the effect of bicycle share stations' proximities to subway stations and university campuses on bicycle ridership was investigated. Further on, the number of neighbouring stations within the 200 meter buffer zone was also considered as a variable in the study's analysis. Moreover, we explored the effect of numerous docks per station on trip rates.

METHODS

In order to investigate the effects of weather, socio-economic and demographic factors, as well as land use and the built environment on bicycle share ridership, a regression analysis was performed on three different levels: trip generation, trip attraction, and station-to-station trips. Accordingly, three data sets were created at the station level with zonal variables where applicable. The first and second data sets were developed based on the number of trips originating from or destined to each station on a monthly basis, respectively. The third data set was created using disaggregate trip information as such the number of trips for each origin-destination (OD) station's pair was determined. Since the number of trips was a non-negative variable (i.e., inherently skewed from the normal distribution), the natural logarithm of the trip counts was used as the dependent variable. Table (1) shows the definitions of variables considered in the analysis. The three multiple log-linear regression models are:

1. Station-level Generation Model: The natural logarithm of the total number of trips per month originating from each station is the dependent variable.
2. Station-level Attraction Model: The natural logarithm of the total number of trips per month destined to each station is the dependent variable.
3. Station-to-Station OD Model: The natural logarithm of the total number of trips between each OD pair is the dependent variable.

The three models were estimated using the Ordinary Least Square (OLS) method using the "lm" package in the statistical software "R".

RESULTS

Data from 80 stations was used to develop trip generation and attraction models on a monthly basis for a full year. The total number of observations used for the parameter's estimation was 960. Table (2) shows the estimation results of the two models. The reported adjusted R^2 values were 0.71 and 0.68 for the trip generation and attraction models respectively. In other words, more than 71% and 68% of the variation in trip generation and attraction could be explained by the variables included in the models. This is a relatively high fit considering the small number of trip origins/destinations available for this analysis.

Most of the parameters were estimated with the expected signs and were statistically significant at the 95% level of confidence. The results indicated that zones with a higher percentage of males were generating or attracting more trips. This result was consistent with previous research findings that males were more likely to take advantage of the bicycle sharing program than females [8]. Similarly, trip activities were higher in zones that had university campuses as well as transit stations, which indicated that the system users may be using bicycles to both access and egress transit stations [8, 21]. At the station level, stations with a higher number of bicycle docks were more likely to generate or to attract more trips. In general, the values of the parameters' estimates of the two models were close. However, the effect of having more than 30 bike docks at the station on trip generation was about two times its effect on trip attraction. The reason for that is, perhaps, Bike Share Toronto users tended choose stations with a higher number of bicycle docks to increase their chances in finding an available dock to return their bicycles to. Otherwise they would have to travel to a nearby station that had an available dock. The number of stations within a 200 meter buffer area was also significant and was positively correlated with the number of trip attractions. Multiple stations in close proximity provide a Bike Share Toronto user with multiple options to park his or her bicycle while reducing the inconvenience caused by the unavailability of empty docking stations. It is worth mentioning that stations with over 30 bicycle docks were located near high-rise residential towers and in densely populated and high trafficked areas.

The models also took weather effects into consideration. Weather data was prepared to enable the average monthly measures to be used for this analysis. The perceived temperature was positively correlated with the number of trip activities. The maximum reported average monthly temperature was 27.5˚C during the month of July in Toronto. Such temperature recordings did not pose an eminent risk to outdoor activities such as bicycling. On the other hand, the amounts of snow on the ground, precipitation and humidity levels presented a negative correlation with the total number of bicycle trips taken per month. Users were less likely to bicycle during snowy days or when routes were covered by snow, thus avoiding the risk of accidents and injuries. The amount of precipitation was not significant as it was aggregated on a monthly basis (to be consistent with other analysis measures). This was consistent with the findings of Imani et al. (2014).

In order to perform the regression analysis on the number of trips from/to each origin-destination pair, an OD dataset was prepared and data from 6,316 trips were used. Based on the start and end stations, bicycle routes were generated. Bicycle path measures such as distance travelled, number of intersections with major roads, and the percent of bicycle infrastructure of the total bike route were calculated. In addition, zonal attributes of the destination station zone were produced. Table (3) shows the model's results. All the estimated parameters were statistically significant and with the expected correct signs. The reported adjusted R^2 is 0.31.

TABLE 1 Definition of Variables

Variable		Definition	Unit	Aggregation Level
Socio-demographic	Male	Percent of males	%	Zonal
	Empden	Average employment density	Pers/Km^2	Zonal
Weather	Temp	Perceived Temperature; adjusted for wind chill and humidex	C^o	Monthly
	Snow	Amount of snow on ground	cm	Monthly
	Hum	Relative humidity	%	Monthly
	Precip	Amount of precipitation	mm	Monthly
Built Environment	n_stations	Number of bike share stations in 200m buffer	NA	Station
	University	= 1 if the zone has university campus; = 0 otherwise	Dummy	Zonal
	Transit	Number of subway/commuter rail stations	NA	Zonal
	distance_travelled	Distance travelled between an OD pair	km	Bike Path
	Intersections	Number of intersection with major roads between an OD pair	NA	Bike Path
	bike_infra	Percent of bike infrastructure compared to total bike path; bike infrastructure includes bike lanes, sharrows, park roads, contra-flow bike lanes, trails	%	Bike Path
	Docks	= 1 if the station has more than 30 bike docks; = 0 otherwise	Dummy	Station

The results showed a negative correlation between distance travelled and the number of trip activities between each origin-destination pair. Similarly, the increase in the number of intersections between the bike path and major roads had a negative effect on the number of trips. Major intersections inhibit heavy traffic, both automotive and pedestrian, thus bicycle users might attempt to avoid crossing such intersections due to risk of injury or accident, or time delays.

Previous research efforts obtained a significant correlation between ridership and bicycle lanes [16], while other researchers found counterintuitive results with bicycle lanes having a negative correlation with ridership [19]. However, their analysis focused on quantifying bike lanes in buffer zones around bicycle share stations. In this paper, we investigated the effect of bicycle infrastructure found along users' paths from each OD pair. Results showed that the increase of bicycle infrastructure length compared to the total bicycle path significantly encourages more bicycle trips. Bicycle infrastructure and the number of intersections can be considered as a safety proxy for bicycle users.

TABLE 2 Trip Generation and Attraction Models Results

Variable	**Trip Generation Model**			**Trip Attraction Model**		
	Estimate	***t*-statistics**		**Estimate**	***t*-statistics**	
(Intercept)	6.953336	26.713	*	6.683968	22.96	*
Male	0.009689	5.508	*	0.010661	5.749	*
University	0.195252	5.947	*	0.158966	4.607	*
transit	0.143319	6.329	*	0.126535	5.308	*
Docks (>30)	0.210768	5.077	*	0.120705	2.763	*
temp	0.033687	20.725	*	0.033589	19.648	*
snow	-0.07649	-7.948	*	-0.07913	-7.784	*
hum	-0.02164	-5.762	*	-0.01803	-4.552	*
precip	-0.00867	-0.024		-0.25583	-0.711	
n_stations	0.044623	1.749		0.057974	2.153	*
Adjusted R^2	0.71			0.68		

* Significant at the 95% level of confidence.

TABLE 3 Station-to-Station Origin-Destination Model Results

Variable	Estimate	*t*-statistics	
(Intercept)	1.842000	51.737	*
distance_travelled	-0.000134	-21.372	*
intersections	-0.007579	-11.45	*
bike_infra	0.000652	4.07	*
empden	0.358100	5.531	*
Male	0.007555	11.666	*
university	0.027390	2.284	*
Transit	0.020430	1.963	*
Dock (>30)	0.037500	2.419	*
Adjusted R^2	0.31		

* Significant at the 95% level of confidence.

At the destination station zonal level, the employment density, male population percentage, presence of a university campus and transit stations, and the number of available docks had a positive correlation with the total number of trips, as was expected. A positive correlation with employment density at the zonal level suggested that users tended to use the system for commuting. This may be a natural transition in the use of bicycles as bicycle stations are heavily distributed throughout Toronto's financial district, which is a heavily populated residential and commercial/business area. The rationale behind the positive correlation with the number of docking stations, male population percentage, university campus and transit stations had been previously indicated in the explanation of the trip attraction and trip generation model results.

CONCLUSIONS AND FUTURE WORK

Previous studies on pubic bicycle share systems were concerned with identifying the factors affecting bike share demand at the system terminals. This study builds on the current understanding of different factors driving bike share ridership. Trip attraction and trip generation models were developed to study factors affecting public bike share demand at the station level. The analysis was performed on Toronto's Bike Share system that operates year round and provided rich data on seasonal bike demand by investigating detailed weather variables. Nevertheless, this study goes one step further by analyzing the variables affecting demand along a proxy path of the bike share user by developing a station pair (origin-destination) regression model. Different factors were investigated including detailed weather variables, zonal level socio-demographic characteristics, land use, built environment and levels of service attributes.

The trip generation and trip attraction model results revealed that higher temperatures, lower humidity levels, and lower amounts of ground snow were positively correlated with bike ridership. Public bicycle share stations that were located near university campuses and transit stations experienced higher trip activities. In addition, the model's results highlighted the importance of station capacity and station-to-station proximity in providing sufficient bicycles for trip generation and docking spaces for trip attraction.

The station pair (OD) regression model was developed based on station to station path level of service attributes along with other zonal level factors. The model's results showed a negative correlation between distance and bicycle ridership. A positive correlation was observed between the increases of bicycle infrastructure along the path and a decrease of number of intersections with major roads. This explained the safety perception of bicycle users. On major intersections and on roads with no marked bicycle paths cyclists would be exposed to higher risks of collisions. Similar to the results obtained from the generation and attraction models, the station pair model showed that public bike users were more attracted to zones of high employment density which potentially indicates that a significant share of users were using the system for commuting.

The developed models can be used to predict the total monthly trip rates generated at or attracted to potential station locations. This can help bicycle share systems to examine possible locations of new stations and to choose the one that maximizes the total bicycle ridership. In addition, the station pair model can be used to estimate the distribution of those trips between new and existing stations. The model can also be used to assess potential bicycle infrastructure development based on expected bicycle routes from and to potential station locations.

In this study, suggested bike paths based on the hypothesis of utilizing bike infrastructure and following the shortest paths were used to conduct the station pair origin destination analysis. Actual users' paths can be mapped *via* GPS tracking units or through the utilization of mobile applications in order to enhance the developed understanding of public bike share users' preferred routes. In addition, bike share programs are implemented in major cities around the world, thus users interact with heavy traffic and congested roads. Understanding the effect of traffic, both auto and pedestrian, can assist city planners and bike share system operators in making better decisions on station location choices.

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