GREEN BIKE TRANSPORTATION SYSTEM FOR THE CITY OF VANCOUVER[1]

The City of Vancouver endeavors to implement a public bike transportation system in order to promote a greener city with lower carbon emissions, lower traffic density, free up vehicle parking, and provide a cost effective and sustainable mode of transportation to the residents. The City Council approved a proposal to conduct a pilot study at a smaller scale. The expected outcome from the pilot study is to determine the demand for the new bike system and to find the minimum number of bike terminals needed, where to locate those terminals and the availability of bikes at these terminals. The present paper essentially achieves some of these objectives using a set covering linear programming approach and the center of gravity method.

Background & Introduction

The City of Vancouver is trying to promote itself as a greener city by introducing new green initiatives. One of these initiatives is encouraging residents to use emission free bike transportation. The City of Vancouver is not only increasing bike lanes to make bike transportation convenient, but is also looking at the possibility of introducing a public bike transportation system. The system will include bike terminals where bikes can be rented or dropped off. Under the proposed system, a customer can go to a terminal and use a credit card or membership card that will be charged for $1.50 rental and a $200 deposit which is refundable when the customer returns the bike. The membership card is a monthly payment option. After the payment, one of the bikes will be unlocked for the customer and then the customer can drop it off at another terminal or back to the original terminal. The customer will be charged an additional $1 for every half hour after the first hour. The public bike transportation is better suited for short commutes. This model was first introduced in Paris and now several cities are using this model. Vancouver is the latest city to consider this option. Currently Paris brings in revenues of over $20 million a year from bike rentals. While revenue is a secondary consideration, the main thrust of this project is the green initiative to lower carbon emissions, lessen traffic density and free up parking space.

Vancouver has remarkable resemblance to Paris in terms of average summer temperatures of 20C and winters at 3C; total length of bike lanes are 371 Km and 300 Km for Paris and Vancouver respectively; and both cities have a flat topography. According to the Vancouver Cycling Statistics (2009 a, b), in 2006 approximately 4% of the commuting trips in Vancouver were made using bikes. Currently, there are over 60,000 trips made by bike per day in Vancouver, but mostly by people who own bikes. More than 3,500 cyclists commute to work downtown every morning which is the

[1] Acknowledgements. Authors are grateful to Sustainable Transportation Program Manager and the Community Outreach Coordinator at City of Vancouver, for their help and cooperation.

equivalent to 65-75 full transit buses. Overall, 15.9 % Vancouver residents cycle or walk to work whereas 41.4 percent in the Downtown and West End cycle or walk to work. Furthermore, almost half of all Vancouver residents commute less than five km to work and more than 80 percent commute less than 10 km – making these relatively short distances ideal for cycling. Currently, there are over 180,000 daily sky train users in Vancouver who can potentially benefit from this initiative. Based on the stats, the city has every reason to believe that the public bike transportation would be successful, but would like to conduct a pilot run in downtown Vancouver.

While the public bike program in Paris is highly successful, the system does have its issues. For example, some terminals are always short of bikes because of their popular locations and trucks are utilized to re-distribute the bikes to even out the allocations amongst terminals. Occasionally, bikes are not returned in proper condition, or the bike return is not acknowledged by the system and it continues to charge the customer with the possibility that someone else can take that bike. While most of these problems are operational issues that can be avoided using technology or manual solutions, a good bike distribution network with adequate number of bikes at ideal terminal locations is certainly the most desirable objective.

Literature Review

There have been three generations of bike-sharing systems over the past 35 years (DeMaio 2003, 2004). The first generation programs began in 1968 in Amsterdam where ordinary white colored bikes were provided for public use. However, the bikes were stolen and the program collapsed within days (Associated Press 1998). In 1995, in Copenhagen, a second generation of bike-sharing programs was launched with improvements. These bikes were specially manufactured and could be picked up and returned at specific locations throughout the central city with a coin deposit. However, theft of bikes in second generation programs continued to be a problem, which gave rise to the smart bike or third generation bike-sharing programs equipped with customer tracking GPS systems, anti-theft devices, electronic locking racks and bike locks, telecommunication systems, smartcards, mobile phone access and sometimes on-board computers. Paris launched its bike sharing program Vélib' with about 7,000 bikes in July 2007 and has expanded to 20,600 bikes with 1,450 terminals or one every 300 meters, making it the largest initiative of its kind in the world (Vélib' 2008). Vélib’ has made an improvement in this area with the launch of its “V+” concept. As it requires more physical effort and time for customers to reach uphill stations, V+ gave additional 15 minutes to access 100 designated uphill stations. These extra 15 minute credits may be saved up and used for other trips (Vélib’ 2008). According to Matsuura (2003), two models of bike-sharing exist—one for community use and the other for residential use. In the community bike-sharing model, an individual checks out a bike from one of many locations and returns it to another location. The residential bike-sharing model requires bikes to be returned at the same location from where they were checked out (usually apartment buildings). Pucher and Buehler (2006) mention that in recent years, cycling levels, public transport and bike-and-ride trips have risen sharply in the U.S. and Canada. Marten (2007) discusses the challenges faced in promoting bike and ride transportation in Netherland. Pucher and Buehler (2009) provide an overview of bike-transit integration in large American and Canadian cities. Midgley (2009) reviews the state of the art of bike-sharing systems based on experiences in selected European cities and suggests that the basic premise of the smart bike-sharing concept is sustainable transportation providing fast and easy access, using diverse business models and making frequent use of applied technology. Besides the technological aspects, business models and consumer trends in bike-sharing, the literature on mathematical models dealing with the system design and its cost-effective operations, is almost non-existent. The present paper essentially contributes in this direction.

Problem Description

Before the pilot run can be undertaken, the City of Vancouver has to consider many factors such as the number of terminals needed, the location of the bike terminals and how many bikes will be made available at each terminal. Addressing the first two issues is the main focus of the present paper and the paper employs linear programming and center of gravity approach to decide the minimum number of terminals and their locations. The third issue of bike stock levels or terminal capacity would require a comprehensive simulation model and is the subject of authors' ongoing study. The long term goal is to cover all of Vancouver, but for the first phase (i.e. pilot stage) the area of focus is Downtown, West end, Coal Harbour, Yaletown, Gastown, Mount Pleasant, Kitsilano, and some of East Vancouver. These locations are heavily populated and have a high density of daily bike riders. As the project moves further, other areas and sky train locations can be added. The following map shows the percentage of trips to work using a bicycle. The highest percentages fall within the area of concentration as shown on the map (Figure 1).

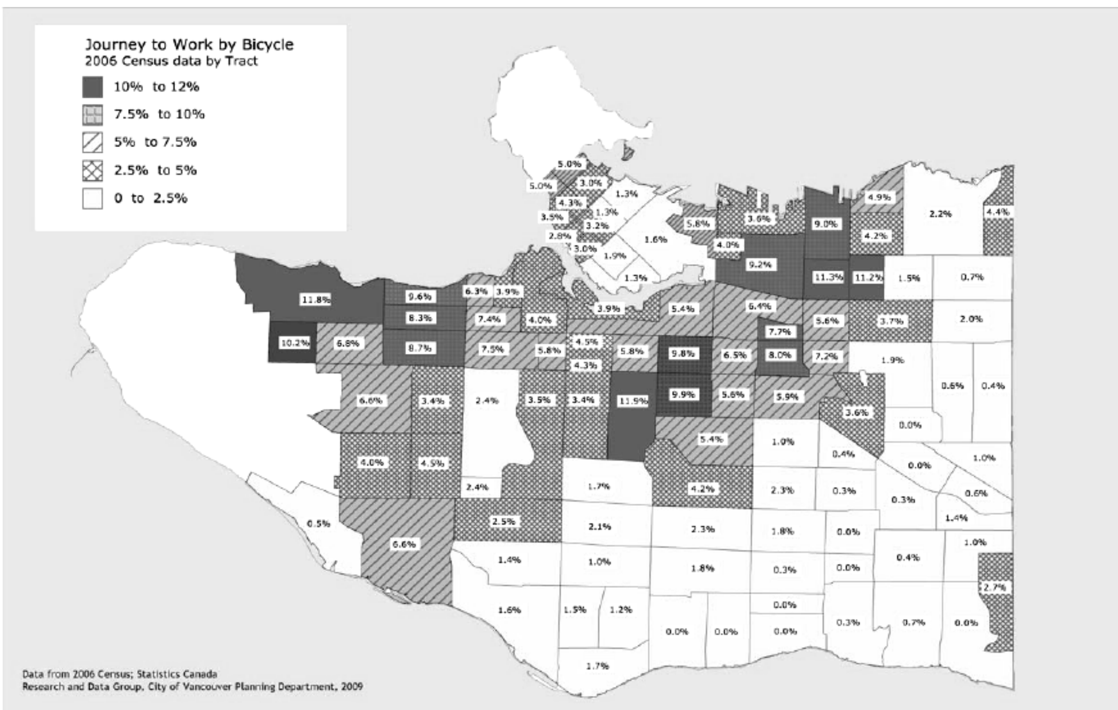

Figure 1. Concentrations using Bike Trips to Work Commute

The City of Vancouver had to establish the maximum distances between the terminals as people will only use the system if the terminal locations are closer and convenient. For the first phase of the public bike transportation system, bike terminals ware decided to be no more than 1km apart. Demand and ideal locations have been determined using the following data (Figure 2) taken from summer of 2008 at peak bike transport hours.

The numbers in Figure 2 represent how many bikes passed going each direction. The black lines illustrates bike paths and the thickness of the lines show the demand; the thicker the line the higher the demand. Before being able to design a mathematical model, the points of interest had to be determined. After much deliberations and discounting some points due to their infeasibility, fifty three points were selected based on the peak hour bike counts in summer 2008. This fared well since those locations did contain high density and sky train locations. Next task was to find the distances between all pairs of these 53 points. The following Table 1 lists the chosen locations showing how many bikes passed that location and the percentage of work commutes with bike from that location. Due to confidentiality reasons, we assign letter names to locations.

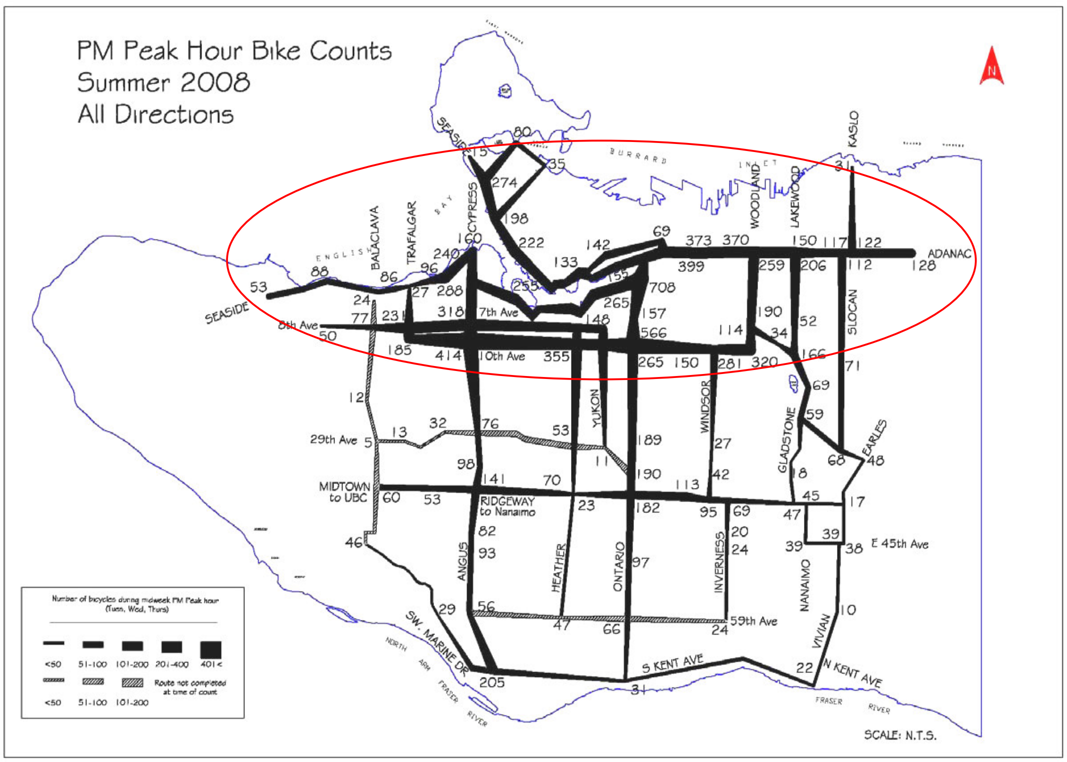

Figure 2. Peak-Time Bike Counts in Summer 2008

Table 1. Points of Interest for Bike Terminals

Point	Bike count	Percent commute to work	Point	Bike count	Percent commute to work	Point	Bike count	Percent commute to work
A	53	11.8%	T	150	6.5%	L1	69	4.0%
B	88	11.8%	U	281	8.0%	M1	399	9.2%
C	86	9.6%	V	320	7.2%	N1	373	9.2%
D	27	9.6%	W	114	7.7%	O1	370	9.0%
E	96	6.3%	X	566	9.8%	P1	259	9.0%
F	240	3.9%	Y	157	5.4%	R1	150	4.2%
G	160	3.9%	Z	708	6.4%	S1	117	2.2%
H	288	3.9%	A1	265	5.4%	T1	31	2.2%
I	318	4.0%	B1	155	5.4%	U1	122	2.2%
J	231	7.4%	C1	133	1.3%	V1	128	2.2%
K	77	8.3%	D1	255	3.9%	W1	112	0.7%
L	24	9.6%	E1	222	3.0%	X1	206	11.2%
M	50	6.8%	F1	198	2.8%	Y1	190	5.6%
N	185	8.7%	G1	274	3.5%	Z1	34	7.2%
O	414	8.7%	H1	15	5.0%	A2	52	1.9%
P	355	5.8%	I1	80	5.0%	B2	166	3.6%
R	148	5.4%	J1	35	3.0%	C2	71	1.9%
S	265	9.8%	K1	142	1.6%			

The Mathematical Model

To meet our objectives and make the problem manageable, we used three mathematical models in a sequential manner. A set covering linear program model has been used to determine the minimum number of bike terminals required. Once the minimum number of terminals is determined, we formed clusters of neighboring terminals around those locations using an allocation procedure. Clusters are groups of locations that can be serviced with one terminal because the distance between them falls below the 1km requirement. Once we find the clusters, they are used in the center of gravity model using the peak hour bike counts as the weights. The center of gravity method essentially determines the exact location of the bike terminal for a cluster. Since the peak hour bike count is used as a weight for a demand point, a higher bike count has a stronger gravitational pull on the bike terminal and the terminal tends be relatively closer to this point. Alternative methods for determining terminal locations instead of the mathematical models given in this report may include primary research such as surveying residents on preferred locations; assess the interests among local businesses to sponsor the bike system which will establish a bike terminal next to their businesses.

Notation

Let,
y_j = 1 if location j is selected for terminal, 0 otherwise.
d_{ij} = the distance between points of interest i and j; for i, j=1,2,3,....,53.
$\alpha_{ij} = 1$ if $d_{ij} \leq 1$ Km or 0 otherwise; $\forall$ i, j = 1,2,3,....,53.
Based on the maximum distance of 1 Km, α_{ij} essentially develops a binary coefficient matrix to be used as an input to the mathematically programming model.

Model 1. Identify Minimum Terminals

Using the binary coefficient matrix as an input to the following set covering model, the best terminal locations to cover the area of focus has been identified as follows:

Find vector **y** so as to

$$Minimize \sum_{j=1}^{53} y_j \tag{1}$$

subject to:

$$\sum_{j=1}^{53} \alpha_{ij} \, . \, y_j \geq 1 \quad \forall \text{ i} = 1,2,3,....,53. \tag{2}$$

$$y_j \in \{0,1\} \quad \forall \text{ j} = 1,2,3,....,53.$$

The objective function (1) expresses the minimization of the number of bike terminal locations selected. The constraint set (2) ensures that each bike density point is covered by at least one terminal. The actual size of the problem is smaller than above as some constraints will be redundant. Furthermore, for several constraints α_{ij} will be zero if the distance is more than 1 km. For the bike terminal problem, the constraint set essentially models the situation depicted in Table 2.

Table 2. Bike Terminal Requirements

At least one terminal at locations	At least one terminal at locations	At least one terminal at locations	At least one terminal at locations
A	O, I	D1	S1, R1, W1, U1, X1
B	P, R	E1, F1	T1
C, D	R, P, S	F1, E1, G1	U1, S1, W1
D, J, C, E, N	S, R, X, Y	G1, F1, H1, I1	V1
E, D, F	T, U	H1, G1	W1, S1, U1
F, E, G	U, T, V, W	I1, G1, J1	X1, S1
G, F, H	V, U, W, Z1	J1, I1	Y1, W
H, G, I	W, U, V, Y1, Z1	K1	Z1, V, W, B2
I, H, O, R	X, S, Y	L1, M1, N1	A2, B2
J, D, K, N	Y, S, X, Z	M1, L1, N1	B2, A2
K, J, L	Z, Y, A1, B1	N1, L1, M1, O1	C2
L, K	A1, Z, B1	O1, N1, P1	
M	B1, Z, A1, M1	P1, O1, R1	
N, D, J	C1	R1, P1, S1	

Model 2. Allocation of Points-of-Interest

While the above formulation identifies minimum number the terminals, it does not allocate all points of interests to these terminals. Furthermore, it may be possible that a point of interest is covered by more than one terminal. Such a scenario is always desirable due to the additional service and options available to the commuters and our model does not discount such possibilities. For modeling purposes, we need to ensure that a point of interest is allocated to one terminal to avoid any double counting of trips. We use the following procedure for this allocation based on the proximity of a point of interest to a terminal.

Step 1. Identify a set $\theta=\{j\}$ such that $y_j = 1$.

Step 2. Consider the distance matrix $[d_{ij}]$ for $j \in \theta$, i=1, 2,...53. Here, the columns represent the terminals and rows represent points of interest.

Step 3. Set i = 1.

Step 4. Find $d_{ij}^{*} = \min(\text{vector } \mathbf{d}_{ij})$ for $j \in \theta$, i.e. the minimum entry in i^{th} row. The column index for this minimum entry is j^{*}, assign i^{th} point of interest to j^{*} terminal.

Step 5. While i < 53, set i=i+1 and repeat step 4.

The application of set covering mathematical programming (model 1) identifies 23 terminal locations to cover the entire range of points of interests and the allocation procedure (model 2) makes the clusters as given below in Table 3.

Table 3. Bike Terminals and Associated Clusters

Terminal	Cluster	Terminal	Cluster
A	A	E1	E1, F1, G1
B	B	I1	I1, G1, J1
D	C, D, J, E, N, F	K1	K1
F	F, D, E, G, H	L1	L1, M1, N1
I	H, G, I, O	O1	N1, M1, O1, P1, R1
L	L, M, K	S1	S1, R1, W1, U1, X1
R	R, P , S, X, Y	T1	T1
S	S, P , R, X, Y, Z	V1	V1
U	U, T, V, W, Z1	Y1	Y1, W, Z1, V, P1
Z	Z, Y, S, X, A1, B1, M1	B2	B2, A2, Z1, W
C1	C1	C2	C2
D1	D1		

Table 4. Input to Center of Gravity Model

Point	Bike count	Location (X,Y)	Point	Bike count	Location (X,Y)	Point	Bike count	Location (X,Y)
A	53	(0.1,12)	T	150	(9.8,10.6)	L1	69	(8.9,13.2)
B	88	(2,12.5)	U	281	(10.9,10.6)	M1	399	(9.2,13.2)
C	86	(3,12.3)	V	320	(11.5,10.6)	N1	373	(10,13.2)
D	27	(3.4,12.4)	W	114	(11,11)	O1	370	(10.5,13.2)
E	96	(3.7,12.5)	X	566	(8.6,11.2)	P1	259	(11.5,13.2)
F	240	(4,13)	Y	157	(8.6,12)	R1	150	(12.1,13.2)
G	160	(4.4,13.2)	Z	708	(8.9,12)	S1	117	(13,13.2)
H	288	(4.5,12.4)	A1	265	(7.9,12.1)	T1	31	(13.2,15)
I	318	(4.5,11.6)	B1	155	(8,12.7)	U1	122	(13.5,13.2)
J	231	(3.4,11.5)	C1	133	(6.8,12.9)	V1	128	(14.5,13.2)
K	77	(2.5,11.4)	D1	255	(5.6,12.2)	W1	112	(13.2,13.2)
L	24	(2.5,12)	E1	222	(5.8,13.4)	X1	206	(12.5,13.2)
M	50	(2,11.4)	F1	198	(5.4,14)	Y1	190	(11.5,12)
N	185	(3.4,10.7)	G1	274	(5.2,14.9)	Z1	34	(11.7,11.3)
O	414	(4.7,10.7)	H1	15	(5,15.5)	A2	52	(12.3,11.5)
P	355	(6.5,10.7)	I1	80	(5.5,15.7)	B2	166	(12.5,11)
R	148	(7.6,11.5)	J1	35	(6.1,15.4)	C2	71	(13.3,10.6)
S	265	(8.6,10.6)	K1	142	(7.5,13.2)			

Model 3. Identify Centers of Gravity for Clusters

The preliminary terminal locations and clusters in Table 3 are purely based on distance considerations. These terminal locations treat all the cluster members equally so long the distance from terminal is less than 1 km. For example, whether a demand point is 100 or 900 meters away from terminal, it has the same membership in a cluster. Furthermore, these terminal locations do not take into account the fact that certain points of interests have a higher demand or bike count as compared with others and therefore the terminal should be located closer to these points. In this section, we further refine our search for terminals by considering the x and y coordinates of cluster members and treating the bike-counts as the weights that exert gravitational pull on the terminals. In the center of gravity method (Ballou 2004), we perform the following steps.

Step 1. We lay a grid with x-y axes, over the focus area of the map. Using the grid, we find the x and y coordinates of the points of interest on the map. The x-y coordinates of all the points along with their bike count weights are given in Table 4 which is used as an input to next step.

Step 2. For each cluster in Table 3, we use the following equations to determine the ideal location of the service terminal using Table 4 as input.

Let,
t = The cluster index;
k = The location index within the cluster;
l_t = Number of locations within cluster t;
X_{tk}= X-coordinate of location k within cluster t;
Y_{tk}= Y-coordinate of location k within cluster t;
C_{tk}= Bike-count weight (from Table 4), for location k within cluster t;

The x and y coordinates of the center of gravity of cluster 't' are given in equations (3, 4) as follows:

$$X_t = \frac{\sum_{k=1}^{l_t} C_{tk} \cdot X_{tk}}{\sum_{k=1}^{l_t} C_{tk}}, \quad t=1,2,......23. \tag{3}$$

$$Y_t = \frac{\sum_{k=1}^{l_t} C_{tk} \cdot Y_{tk}}{\sum_{k=1}^{l_t} C_{tk}}, \quad t=1,2,......23. \tag{4}$$

The (X_t,Y_t) coordinates given by equations (3) and (4), provide the ideal locations for the bike transportation system as given below in Table 5.

Table 5. Ideal Bike Terminal Locations

Cluster	Terminal (x, y)	Cluster	Terminal (x, y)
A	(0.1,12.0)	E1, F1, G1	(5.4,14.2)
B	(2.0,12.5)	I1, G1, J1	(5.3,15.1)
C, D, J, E, N, F	(3.6,12.0)	K1	(6.1,13.2)
F, D, E, G, H	(4.2,12.7)	L1, M1, N1	(9.5,13.2)
H, G, I, O	(4.6,11.7)	N1, M1, O1, P1, R1	(10.4,13.2)
L, M, K	(2.3,11.5)	S1, R1, W1, U1, X1	(12.8,13.2)
R, P , S, X, Y	(8.0,11.1)	T1	(13.2,15.0)
S, P , R, X, Y, Z	(8.3,11.4)	V1	(14.5,13.2)
U, T, V, W, Z1	(11.0,10.7)	Y1, W, Z1, V, P1	(11.4,11.7)
Z, Y, S, X, A1, B1, M1	(8.7,11.9)	B2, A2, Z1, W	(11.9,11.1)
C1	(6.8,12.9)	C2	(13.3,10.6)
D1	(5.6,12.2)		

Discussion on Results

- Twenty three ideal terminal locations have been identified for the bike transportation system as given in Table 5. However, these locations are only ideal in terms of gravity model and will have to be adjusted to a nearest realistic point. For example, an ideal gravity location may fall on a building in which case, the location will need to be adjusted to the nearest available space for terminal or to a closer business who is willing to sponsor. These terminal locations will cover the area for pilot phase 1 to meet the current criteria of maximum 1km between the neighboring locations. However, if the location of interest is isolated at the edge of the map, a slight larger distance than 1km may be acceptable to the city which through visual inspection may further reduce the terminal locations from twenty three.
- A large part of the data being used relates to bike counts using rider-owned bikes. There is an assumption in our model that the current bike commuter data can be used to determine the demand and popularity of a bike rental system. Therefore, we feel that running the pilot phase is very important in gathering specific information on the acceptance of the new public bike transportation system. The model outputs are only as good as the quality of input data. We feel that further research including potential customer surveys, will enhance the value of these models. The first phase pilot experiment will generate more realistic data for the project which can not only be used to validate the above assumption, but it will also be helpful to roll out the system to other phases. Although, our recommendations for bike terminal locations are sensitive to the assumptions made, but that does not undermine the importance of our modeling approach as these models can always be scaled up or down to accommodate changes in parameters and constraints as more realistic data is made available.
- The costs of opening bike terminals are not directly considered in the model. Since we minimize the number of terminals (equation 1), indirectly the model minimize the cost of terminals under the assumption that the cost of running a terminal at each location is the same. However, if the costs of various terminals are significantly different, objective function (equation 1) can be easily modified.
- The results may also be sensitive to political agendas in terms of locating terminals in certain areas or in front of certain businesses. Therefore, an effort was made in this paper to disguise location names with letters.

Conclusion and Further Work

The City of Vancouver plans to implement a public bike transportation system in order to promote its image of a green city with lower greenhouse gas emissions, less traffic density and not-so-congested parking. The city is looking to provide an affordable and sustainable mode of transportation through a public bike rental system. The project will be implemented in phases with the first phase (i.e. pilot phase) to focus on Downtown and surrounding areas. Some of the main issues faced by the city are to determine the minimum number of bike terminals needed, identify the best locations for those terminals and assess the number of bikes to be made available at those terminals in order to meet the requirements. The present paper uses the past commute data to identify the high density points to serve, determines the minimum number of bike terminals needed and their ideal locations using a set covering technique. These locations are further refined using an allocation procedure and center of gravity approach for single facility location among a cluster of demand points. The paper suggests 23 ideal locations for the pilot phase.

The third objective of determining the number of bikes needed at each terminal is not addressed in the current paper, but the work is under progress to develop a comprehensive simulation model to set the terminal capacities in terms of number of bikes. The outcome will help to assess the investment involved in each terminal so that sponsorships could be attracted for the pilot project. Furthermore, the outcome of simulation model will also help to develop parameters for the bike re-distribution system.

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