Analyzing Personalized Walking in Smart Cities Through a Multi-Modal Transportation Simulation Environment

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Abstract— **While current transportation simulations can be used to evaluate vehicle trips or neighborhood walkability, none is able to evaluate trips that require multi-modal transportation when walking is always one mode. In this paper, we address this gap by the Multi-Modal Transportation (MMT) with Multi-Criteria Walking (MMT-MCW) simulation. MMT-MCW simulation can be used to evaluate various aspects of smart cities, such as walkability. The premise of MMT-MCW is based on the observations that: (a) walking can be performed for other purposes besides merely reaching destinations, such as to maintain or improve health and (b) traveler's characteristics and preferences play an important role in determining optimal route choices. Selected MMT-MCW scenarios were simulated to evaluate walkability of several cities with respect to three criteria: inter-modal transfer locations (parking lots and bus stops) elevation of walking routes, and walking distance. The simulation results show that: (a) despite similar elevation range, cities may contain walking routes with significant different average calories burn and (b) walking paths connected to parking lots and bus stops are not necessarily correlated to number of routes, amount of calories burnt, and elevation.**

Keywords-smart cities; walkability; multi-modal transportation; routing; multi-criteria walking.

I. INTRODUCTION

The concept of Multi-Modal Transportation with Multi-Criteria Walking is discussed in [1]. MMT-MCW is based on information and communication technologies and is designed to offer personalized transportation services. In its initial version, MMT-MCW is built as a simulation environment to analyze scenarios where walking is always one mode and for various purposes (multi-criteria). Two sets of factors impacting MCW are environmental factors and traveler factors. Environmental factors, compared to driving cars or riding public transportation, may have a greater impact on walking. For example, people may prefer driving cars or riding buses over walking due to rain, snow, hilly terrain, or air pollution. Location is also an environmental factor that influences walking, for instance, fastest walking routes may be based on flat and short routes, which take priority over steep and long routes. However, when walking is for exercise, the steeper and/or longer route may be preferred. Traveler factors, such as individuals' characteristics, also have an impact on choosing walking routes [2]. Several studies, such as [3], reported a correlation between individual behaviors and walking. Studies by Leslie et al. [4] and Ewing et al. [5] are examples related to the urban area evaluation in terms of neighborhood walkability. Factors, such as land use and urban design [6], [7], aging [8], air pollution [9], body mass index [10], preference for passive transport [11], and pedestrian's preference [12], that influence walking have been studied. The findings of various research projects highlight the benefits, such as weight loss [13], of replacing short motorized trips with walking. In other studies, the relationship between the built environment and walking has been studied. A longitudinal analysis is discussed in [14], itineraries to destinations is considered in [15], level of service of urban walking environment and its influence are investigated in [16], GPS-measured walking, bicycling and vehicle time in adolescents are analyzed in [17].

In this work, MMT-MCW is built as a simulation environment to find connections between different modes of transportation by utilizing public transportation infrastructures (road networks and sidewalk networks) and provide the residents of smart cities with flexible and personalized walking places. The following two example simulation cases show how MMT-MCW can be used for smart cities.

By simulating various walking scenarios in MMT-MCW, walking clusters ("walking hotspots") in a city can be identified; these walking hotspots would help urban designers and planners determine locations where new information and sensors would benefit the residents. For example, by knowing locations of walking hotspots in a city, real-time information about activities and traffic on sidewalks of those hotspots can be made available on a website, or directly be sent to the residents. Similarly, appropriate sensors, such as those that can assist pedestrians with safety issues on sidewalks, can be installed. An example sensor could be one detecting within a specified range a sharp elevation change between two adjacent sidewalk segments.

In another simulation through MMT-MCW, various connection scenarios between road networks and sidewalk networks for driving first and then walking (driving-walking) can be analyzed in a city in order to identify most usable transfer nodes ("transfer hotspots"). By knowing locations of transfer hotspots, which could be parking garages or street parking places, sensors can be installed to detect transfer node availability and inform the residents, through a website or notifications on mobile devices, in real time. An example sensor could be video images of specific parking places. Such video images when collected over a period of time can be mined so that transfer node (parking space) availability can be predicted and communicated to interested residents.

Despite the benefits of MMT-MCW for evaluating transportation options in smart cities, currently there is no research that is focused on evaluation of city' transportation infrastructures and utilities (e.g., parking locations and walking routes). To fill this gap, MMT-MCW simulation is proposed to evaluate three basic options: (a) inter-modal transfer locations (parking lots and bus stops); (b) elevation of walking routes; and (c) walking distance. The first option is related to MMT, and the last two are related to MCW.

MMT-MCW may be implemented in several ways for smart cities, for example, as a new service for individuals interested in finding routes that include walking components. [18] developed a prototype service (called Route2Health) that recommends walking sessions, if feasible, for any trip. By taking origin, destination, and traveler's conditions as input, Route2Health recommends a sequence of transportation modes along with specific details about each mode that is most optimal (personalized). MMT-MCW can also be implemented to simulate the design of smart cities.

The paper's contribution is a novel integration of new and existing Web techniques and technologies for evaluating and analyzing transportation options for smart cities. A Web-based tool (simulation) is developed to analyze mushing up data and find transportation solutions based on existing Web services (Google Map APIs). The rest of the paper is organized as follows. Section II describes MMT-MCW. Sections III and IV discuss MMT-MCW simulation and example scenarios and their results. The paper ends with a summary and suggestions for future research in Section V.

II. MMT-MCW

MMT-MCW is designed to find: (a) multi-modal transportation routes with walking as one mode and (b) optimal walking paths by considering multiple criteria. Walking transfer node and route score are the two factors that MMT-MCW considers in finding optimal solutions (routes).

Three modes of transportation are considered in MMT-MCW: walking, driving, and riding (bus). We define "walking transfer node" as a location where travelers switch from a pedestrian network to a vehicular network, or vice versa. In MMT-MCW, walking transfer nodes play an important role in finding suitable (personalized) routes. For example, change of one parking lot to another (as a walking transfer node) may result in a different (and desired) solution. With respect to public transportation, the choice of a bus stop (as a walking transfer node) determines a specific bus route. To identify a suitable walking transfer node, traveler's desired walking distance is separated into estimated upper and lower limits. The upper limit excludes walking transfer nodes that are located beyond a traveler's maximum preferred distance. The lower limit excludes walking transfer nodes that are located closer than the desired minimum walking distance. Accordingly, one or more suitable walking transfer nodes are identified.

Route score is used to quantify the suitability of a walking route in meeting traveler's criteria. To compute a route score, a relevant criterion must be identified and used to formulate a suitable metric function. Examples of route score criterion are: (1) traveler's desire to burn a specific amount of calories by walking and (2) traveler's preference for a certain level of elevation variation. The route score for the first criterion should reflect calories burnt on walking and for the second criterion should reflect elevation variation.

To calculate calories burnt on walking, the ACSM walking equation [19] can be used:

$$EE = (0.1 \cdot S + 1.8 \cdot S \cdot G + 3.5) \cdot BM \cdot t \cdot 0.005 \qquad (1)$$

where EE is walking energy expenditure (kilocalories), S is walking speed (meters/minute), G is grade (slope) in decimal form (e.g., 0.02 for 2% grade), BM is traveller's body weight (kilograms), and t is walking time (minutes). The constant 0.005 is the amount of energy expenditure burnt per one kilogram per one minute.

To calculate elevation variation, walking surface roughness is used. The walking surface roughness refers to the standard deviation of the elevations along an entire walking route. The standard deviation of a flat walking route is zero, and the higher value of walking surface roughness refers to higher variation of elevations along the walking route.

III. SIMULATION AND DATA COLLECTION

Several cities within the United States were used in the simulation. Twelve cities were selected based on three attributes: population, body mass index (BMI), and elevation range. The US Office of Management and Budget uses population to define a statistical area. A statistical area contains one or more cities (and/or counties) and can be classified as metropolitan (high-density population) or micropolitan (low-density population). Metropolitan has population greater than 50,000 and micropolitan has population between 10,000 and 50,000. The US Center for Disease Control and Prevention's definitions and categories were considered for normal weight (18.5<BMI<24.9) and obese (BMI>30.0) where individual's BMI is calculated by dividing the individual's weight (kilogram) by the square of the individual's height (meter); $BMI=weight/(height)^2$. BMI statistics are from the year 2012 provided by the CDC. Elevation range was classified into hilly (elevation range ≥100 meters) and flat (elevation range ≤ 50 meters), where elevation range is the difference between maximum and minimum elevations of the area. The elevations of 100 randomly selected positions within the city of interest were used to calculate the elevation range. The two threshold values (50 and 100 meters) were chosen for separating between hilly and flat terrains. The purpose of using the three attributes (population, BMI, and elevation range) is to explore their influence on walking routes and walking transfer nodes.

For simulations, cities were selected based on statistical areas (ranked in descending order) and on BMI statistics (percentage of normal weight and obese people). To have realistic representatives for each BMI category, city selection was based on rank; a higher rank has a higher priority. To include as many states as possible in simulations, if the second city is located in the same state as the first one, then the next city that is located in a different state is selected. The selected cities are categorized and shown using a tree diagram in Figure 1. There are six possible combinations based on the three mentioned attributes (population, BMI, and elevation range), and up to two cities were selected for each combination.

Figure 2 shows the maximum, minimum, and average elevations of the selected cities, and the following abbreviations are used: Micropolitan (Mi), Metropolitan (Me), Obese (O), Normal weight (N), Hilly (H), and Flat (F).

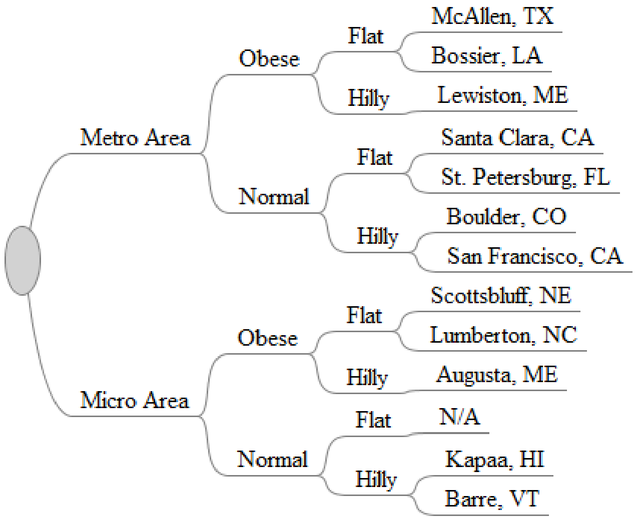

Figure 1. City and state selected for each category.

Two different MMTs were simulated: driving-walking and riding-walking. A driving-walking trip usually comprises (in sequence) driving, parking, and then walking, and return in the reverse sequence. Unlike driving-walking, travelers do not have to begin with riding (public transportation) in a riding-walking trip. The trip may start by walking from origin to a nearby bus stop then taking bus to destination. Walking can also be in the middle to connect two different bus routes, and the return trip can be in any sequence. For simplicity, the return trips were not considered and walking was assumed as the mode connecting the walking transfer nodes and destinations. To this end, walking transfer nodes and walking routes were simulated. Note that the vehicular route computation between origin and walking transfer node was not considered since it is not the MMT-MCW's main contribution. Parking lots, bus stops, walking routes, sidewalk slopes, and points of interest (POIs) were other data considered for simulations.

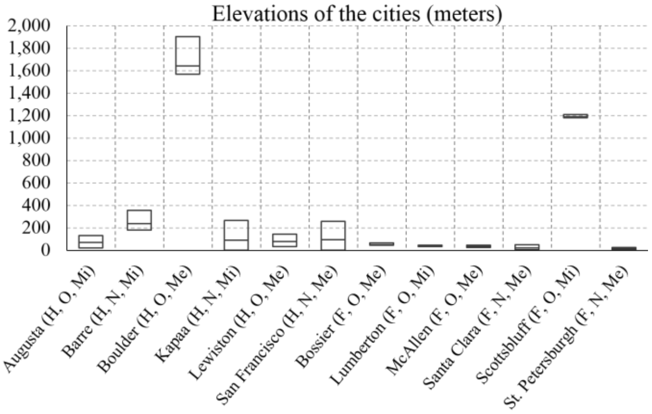

Figure 2. Maximum, minimum, and average elevations of the selected cities.

TABLE I. SIMULATION PARAMETERS

Parameter Names	Values	Units
1. Desired walking distance	1.0	kilometer
2. Inner radius	0.5	kilometer
3. Outer radius	1.5	kilometer
4. Maximum number of suitable parking lot locations	20	-
5. Maximum number of suitable bus stop locations	No limit	-
6. Body weight trial values	60, 80, 100, 120	kilogram
7. Walking speed trial values	60, 80, 100	meters/minute

The walking distance between a walking transfer node and a destination was assumed to be one kilometer. POI locations were selected from OpenStreetMap [20] and 100 destinations within each city were randomly selected (in case the number of POIs in a city was less than 100, all POIs were used). To identify suitable parking lots, a buffer (inner radius: 0.5 kilometer; outer radius: 1.5 kilometer) around each destination was created. For each destination, up to 20 parking lots within a buffer were selected as suitable walking transfer nodes (note that 20 is an arbitrary number and each destination may have a different number of parking lots). Bus stops and bus routes data were collected from Google Transit Feed Specification [21]. For each suitable parking lot and bus stop, up to three candidate walking routes were generated (ordered by travel time). Parking lot locations and walking routes were retrieved from Google Place API and Google Direction API, respectively. Once all candidate routes were computed, elevation of points along the walking route of interest was retrieved from Google Elevation API, and then Equation (1) was used to calculate calories burned for each candidate walking route. Walking surface roughness was also calculated using the elevations of route segments. To reflect multiple traveler's characteristics, four body weights (60, 80, 100, and 120 kilograms) and three walking speeds (60, 80, and 100 meters/minute) were simulated. Note that these walking speeds are for experimentation; see [22] and [23] for research on walking speed. Table I summarizes the simulation parameters.

IV. SIMULATION RESULTS

The simulation results are related to four entities: suitable parking lots, suitable bus stops, walking routes that connect parking lots and destination (PK routes), and walking routes that connect bus stops and destinations (BS routes). Suitable parking lots and suitable bus stops are the parking lots and bus stops that are located within a ring buffer (inner radius: 0.5 kilometer; outer radius: 1.5 kilometer) around each destination. All 12 cities contain suitable parking lots and acceptable PK routes, but only two cities (San Francisco and Santa Clara) contain suitable bus stops and acceptable BS routes (these are the only two cities, among the selected cities, that provide coordinates of their bus stops). PK and BS routes are considered acceptable if their distances are within 0.9 and 1.1 kilometer from destinations. Based on these four entities, results are separated into three sub-sections: (A) suitable parking lots and acceptable PK routes, (B) suitable bus stops and acceptable BS routes, and (C) acceptable PK routes vs acceptable BS routes.

A. Suitable Parking Lots and Acceptable PK Routes

Figure 3 shows the selected cities (on x-axis), the numbers of destinations (on y-axis), and the counts of destinations that have suitable parking lots (on y-axis). The following abbreviations are used in the figure: Micropolitan (Mi), Metropolitan (Me), Obese (O), Normal weight (N), Hilly (H), and Flat (F). Most cities in metropolitan areas have a large number of destinations with suitable parking lots except Bossier (1 out of 72) and McAllen (4 out of 99). Four cities (Barre, Kappa, Scottsbluff, and Bossier) have zero or only one destination with at least one suitable parking lot, which are considered outliers and excluded from the analysis. From the figure, both obese and normal weight groups fall within cities with both small and large number of destinations with suitable parking lots. This indicates that there is no obvious separation between the two groups with respect to number of destinations.

Figure 4 shows maximum, minimum, and average number of calories burned (top left) and walking surface roughness (lower left) for walking routes that connect to parking lots (PK routes). On x-axis, the first four cities are hilly and the latter four are flat. The graphs indicate that hilly cities have wider ranges of both calories burnt and walking surface roughness. This is because both calories burnt and walking surface roughness are directly related to the elevation range of hilly cities and the walking routes. An interesting observation is that most cities (except Boulder) in the left figure have a similar average calories burnt regardless of the elevation range. Although Boulder has a similar walking surface roughness compared to other hilly cities, its average calories burnt is significantly higher than the others. This indicates that walking routes in Boulder are better in terms of burning calories.

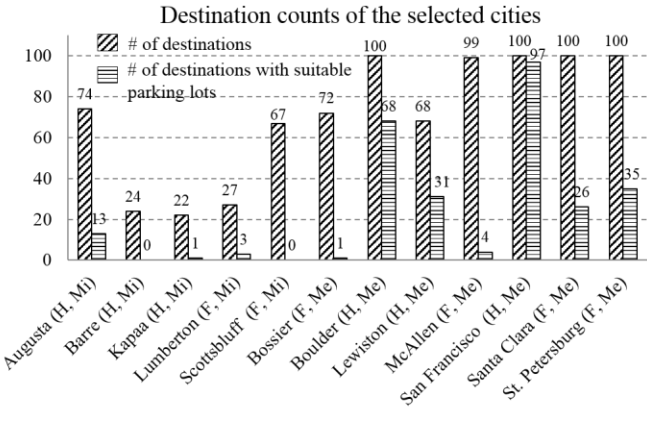

Figure 3. Number of destinations and counts of destinations that have ≥ 1 suitable parking lots.

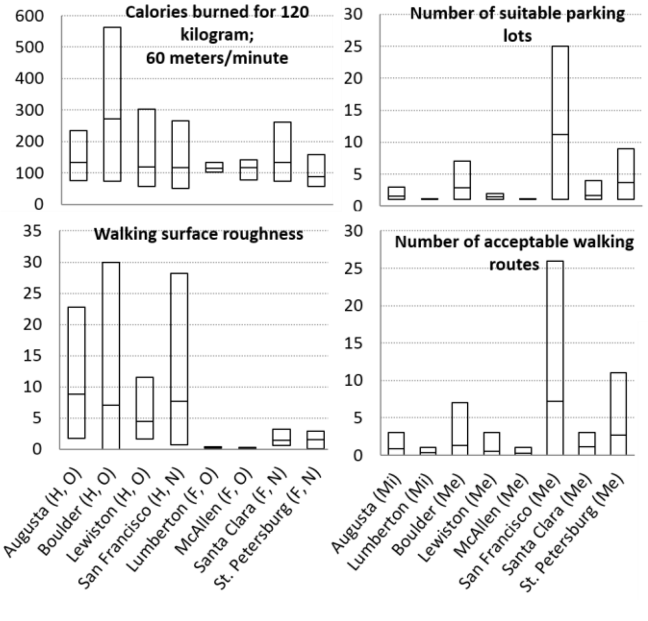

Figure 4. Comparison of attributes related to PK routes in different cities.

Figure 4 (top right) shows number of suitable parking lots and (lower right) shows number of acceptable walking routes. Acceptable walking routes refer to walking routes that have their distance within 0.9 and 1.1 kilometer (±10% of the designated one kilometer walking distance) from destinations. The graphs show that San Francisco has the highest average number of suitable parking lots, the highest number of acceptable walking routes, and the largest range on both attributes (largest variation of results); this is expected for a metropolitan city where transportation infrastructures are dense. Note that San Francisco is the 13th most populous city in the United States [24].

Figure 5 shows spatial distribution of destinations that have acceptable PK routes. Destinations in Augusta and Santa Clara have a very small number (between 1 and 3) of acceptable PK routes. St. Petersburg reveals a road (northsouth direction) that has destinations with a high number of acceptable PK routes. Destinations in Boulder spatially spread across the city and do not show an explicit pattern. San Francisco has most of its destinations with a large number of acceptable PK routes. Most destinations in San Francisco cluster together in the north-east region of the city because most of the POIs (which are used as destinations) in San Francisco are also located in the north-east region.

Figure 6 shows average calories burn for the acceptable PK routes grouped by destinations. Each map has legends showing minimum and maximum values with circle sizes. All the cities (except Boulder) have their average and maximum value lower than 200.

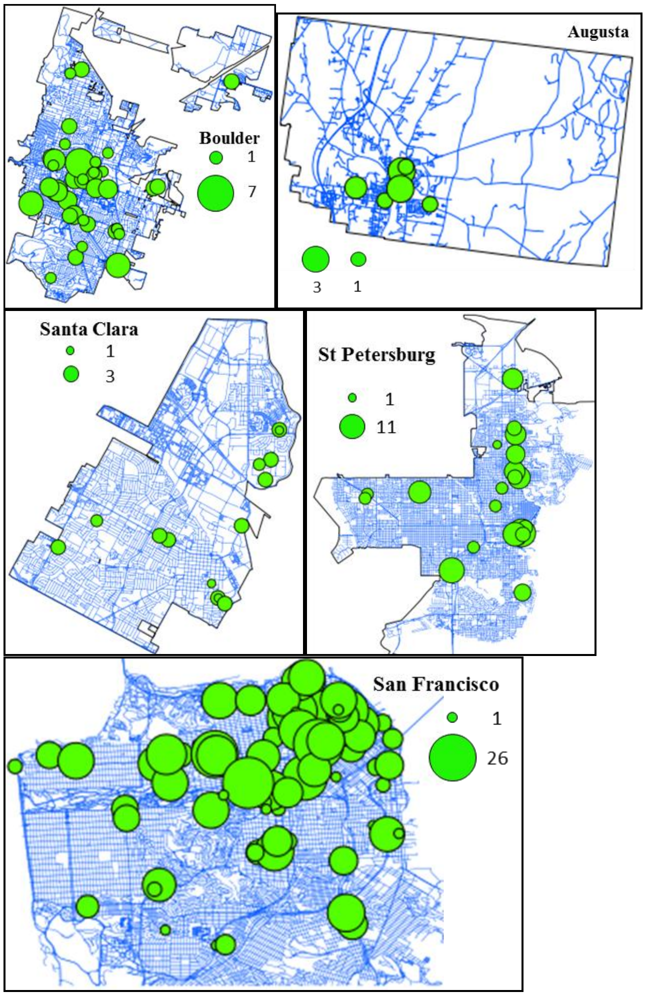

Figure 5. Destination distributions with number of acceptable PK routes.

This sub-section discusses and compares suitable parking lots and acceptable PK routes in five cities: Augusta, Boulder, San Francisco, Santa Clara, and St. Petersburg. San Francisco has the highest average numbers for both suitable parking lots (11.16) and acceptable PK routes (7.2). With similar walking distance and time, Boulder offers the best environment in terms of burning calories. Augusta has a high amount of calories burn only for destinations within the city's inner area, which has a dense road network. Even though Santa Clara is classified as a metropolitan city, it does not provide a large number of suitable parking lots. Santa Clara has 1.70 suitable parking lots on average, while Augusta (a micropolitan city) has 1.54.

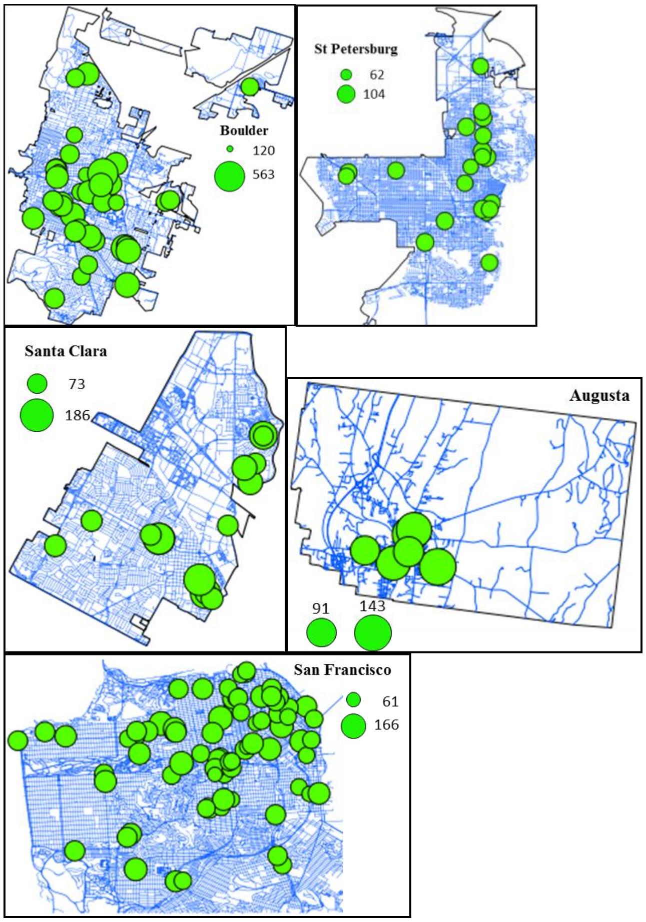

Figure 6. Destination distributions with calories burn for acceptable PK routes.

B. *Suitable Bus Stops and Acceptable BS Routes*

Figure 7 shows spatial distribution of destinations in San Francisco and Santa Clara. The destinations are classified into two groups: (1) destinations that have suitable bus stops (circle shape) and (2) destinations that have no suitable bus stops (triangle shape). According to Figure 7 (left), there is a clear distinction between the two groups in San Francisco. The first group densely clusters within the north-east region of the city, while the second group is surrounding the first group. All destinations in Santa Clara have at least one suitable bus stop.

Figure 8 shows spatial distribution of destinations with number of suitable bus stops. None of the destinations in San Francisco has more than four suitable bus stops, while the destinations in Santa Clara have much larger number of suitable bus stops. Figure 9 shows spatial distribution of destinations with number of acceptable BS routes. None of the destinations in San Francisco has more than five acceptable BS routes, while the destinations in Santa Clara have wider range of number of acceptable BS routes. Most destinations with large number of acceptable BS routes in Santa Clara cluster within the inner region of the city. A counter intuitive observation is that despite the denser road network (which means a large number of road segment connections and route choices), the destinations in San Francisco still have fewer number of acceptable BS routes compared to Santa Clara. Average number of BS routes is 2.41 for San Francisco and is 9.29 for Santa Clara. Note that destinations that do not have acceptable BS routes were not included in calculating the averages. An interesting observation related to suitable bus stops and acceptable BS routes in Santa Clara is that destinations in the lower region of the city have a large number of bus stops but have a small number of BS routes, while destinations in the upper region have the opposite numbers.

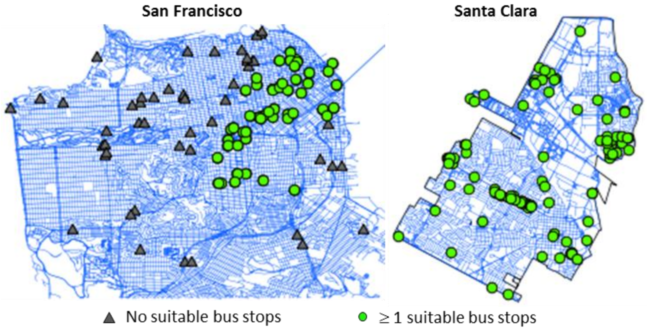

Figure 7. Suitable bus stops availability.

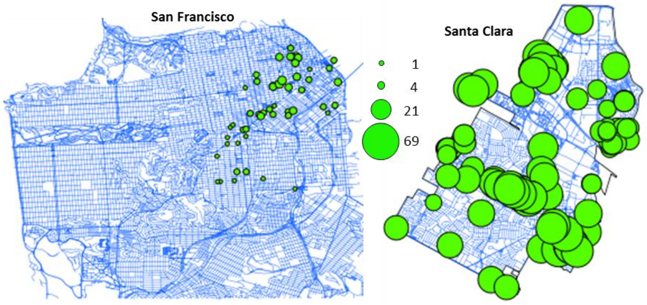

Figure 8. Number of suitable bus stops.

Figure 10 shows spatial distribution of destinations with number of bus routes. All destinations that have a suitable bus stop in San Francisco have four bus routes. Two and seventeen are the minimum and maximum numbers of bus routes for destinations in Santa Clara, and destinations in the northern region tend to have a larger number of bus routes than the others.

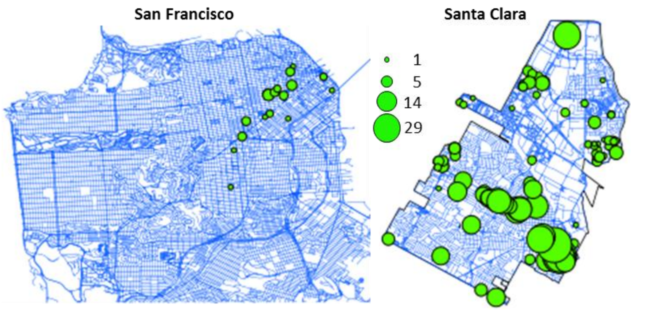

Figure 9. Number of acceptable BS routes.

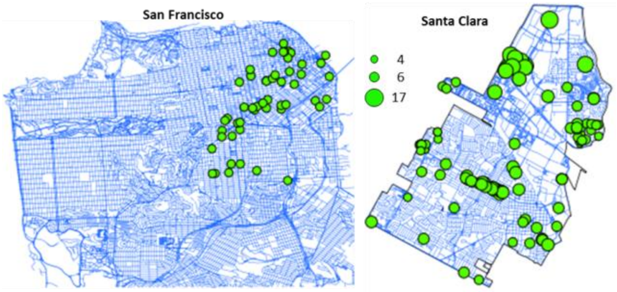

Figure 10. Number of bus routes.

This sub-section discusses and compares suitable bus stops and acceptable BS routes in San Francisco and Santa Clara. Only destinations in the north-east region of San Francisco have suitable bus stops, while all destinations in Santa Clara have suitable bus stops. Assuming a direct relationship between road and sidewalk densities, San Francisco, which has a denser road network, is expected to have a higher average number of BS routes, however, the results show otherwise. This observation indicates that road network density does not necessarily correlate with the number of acceptable BS routes.

C. *Acceptable PK Routes VS Acceptable BS Routes*

Figures 11 and 12 show the comparisons between acceptable PK routes and acceptable BS routes in San Francisco and Santa Clara, which are the only two cities (among the selected cities) that publish their bus stop coordinates. Each bar graph represents maximum, minimum, and average values. In San Francisco, PK routes have higher average values than BS routes, while, in Santa Clara, it is the opposite. This indicates that PK routes and BS routes are not necessarily correlated. Considering walking surface roughness, BS routes in San Francisco have narrower range than PK routes, meaning that BS routes are generally flatter than PK routes. This can be inferred that the acceptable BS routes are available mostly in the flat areas. However, an interesting observation is that BS routes in Santa Clara show opposite behavior such that PK routes are flatter than BS routes. It should also be noted that both PK and BS routes in San Francisco have a much larger walking surface roughness (by around 10 times) than their counterparts in Santa Clara, meaning that PK and BS routes in Santa Clara are much flatter. A counter intuitive observation from calories bar graphs in both Figures 11 and 12 is that despite different elevation range (San Francisco: Hilly; Santa Clara: Flat) and a large walking surface roughness difference, both PK and BS routes in San Francisco still have average calories close to their counterparts in Santa Clara (~120 calories for PK routes; ~140 calories for BS routes). This is because the amount of calories burn was estimated using the same walking speed (60 meters/minute) in both cities. Therefore, despite the close amounts of estimated calories burn, walking routes in San Francisco help burn more calories within the same period of time compared to the walking routes in Santa Clara.

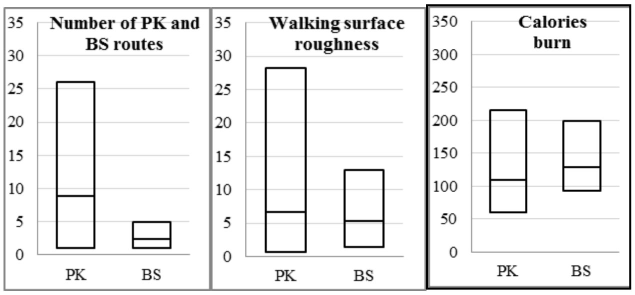

Figure 11. Comparisons between PK routes and BS routes for San Francisco.

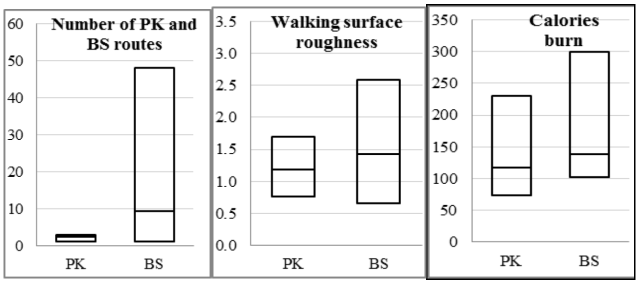

Figure 12. Comparisons between PK routes and BS routes for Santa Clara.

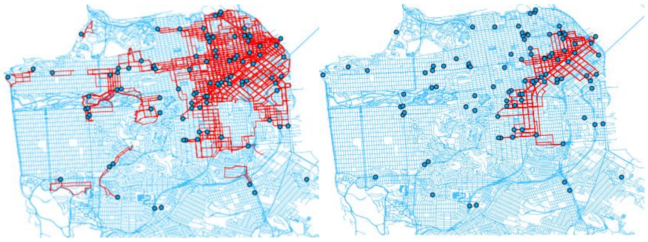

Figure 13. San Francisco: PK routes (left) and BS routes (right).

Figures 13 and 14 show the spatial distribution of destinations and the spatial coverage of PK and BS routes in San Francisco and Santa Clara overlaid on the cities' road networks. The maps indicate the inverse behavior between the two cities such that PK routes have more coverage than BS routes in San Francisco, and vice versa for Santa Clara. Figure 15 shows the comparisons of destination distributions with number of acceptable PK and BS routes in San Francisco and Santa Clara. The maps indicate the inverse behavior between the two cities such that the number of acceptable PK routes is much larger than that of BS routes in San Francisco, and vice versa for Santa Clara.

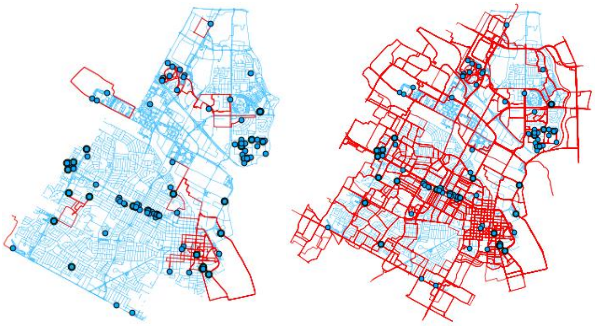

Figure 14. Santa Clara: PK routes (left) and BS routes (right).

Figure 15. Comparisons between destination distributions with number of acceptable PK and BS routes.

In this sub-section, PK routes and BS routes of San Francisco and Santa Clara are compared. The results show that PK routes and BS routes are not necessarily correlated. For driving-walking mode, San Francisco has much more parking lots and acceptable PK routes than Santa Clara. For riding-walking mode, Santa Clara has much more bus stops and acceptable BS routes than San Francisco. Both PK and BS routes in San Francisco have much larger walking surface roughness (by around 10 times) than their counterparts in Santa Clara, meaning that PK and BS routes in San Francisco have much higher elevation variations.

V. SUMMARY AND FUTURE RESEARCH

This paper presented a new simulation approach for evaluating smart cities. Scenarios in selected cities were simulated. The simulation results show that: (a) despite similar elevation range, cities may contain walking routes with significant different average calories burn and (b) PK routes and BS routes are not necessarily correlated (e.g., San Francisco and Santa Clara).

Considering that enhancing health and wellbeing of people, among other benefits, is one objective for building smart cities, our proposed approach can be used to evaluate smart cities for their environment infrastructures (roadways and sidewalks) and transportation infrastructures (different modes) and as a simulation tool to design new smart cities.

Some future research directions are:

- Investigating and developing MCW optimization algorithms for travelers, such as people with disabilities (e.g., wheelchair users and people who are blind or visually impaired), people with special physical conditions (e.g., people with joint problems), and people with health conditions (e.g., people who must be less exposed to air pollution or sun light).
- Investigating and developing a predictive MMT-MCW methodology that allows route request well in advance and can monitor the recommended route up to minutes before the route is taken and update the recommendation based on changes of environmental and individual factors.

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