GPS-BASED OPTIMIZATION OF PHEV RECHARGE INFRASTRUCTURE IN WINNIPEG, CANADA

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ABSTRACT

Global Positioning System receivers are used to monitor the parking behaviour of 76 Winnipeg-area residents to determine the most suitable parking lots in Winnipeg for plug-in hybrid electric vehicle (PHEV) recharge infrastructure. Optimizing the location of this infrastructure will help maximize the environmental benefits of PHEVs while minimizing the economic costs. Using a Geographic Information System (GIS) parking events were superimposed on a high-resolution aerial photograph of the city to identify the most potentially suitable parking lots in the city. A parking lot suitability index was then developed to quantitatively rank parking lots in the city based on the parking events associated with them. Variables derived from these groups of parking events include: 1) the number of unique participants that used the parking lot, 2) the median parking duration, and 3) the ratio of parking events that occur during off-peak vs. on-peak electric demand times. The most suitable parking lot as determined by this index was surprising as it would not be considered a ‘major parking lot’ by the majority of Winnipegers, suggesting that this kind of study reveals information about parking lots that would not otherwise be apparent. Thus, future studies are recommended. Such studies would benefit from adapting their methodologies based on the strengths and weaknesses of this study, a discussion of which are provided in the last section of the report.
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1. INTRODUCTION

Society in North America and much of the developed world is highly dependant on personal vehicles. There were 557 personal vehicles per 1000 people in Canada in 2005, an 11% increase from 2000 (Transport Canada, 2006). The number of personal vehicles on the road in the United States has increased from just over 61 million in 1960 to nearly 136 million in 2007 (US Department of Transportation, 2009). Recent estimates indicate that private vehicle trips make up nearly 90 percent of individual trips in the United States (Murakami, Wagner & Neumeister, 2001). Currently, nearly all vehicles in the Canada and the United States are powered by fossil fuels which, when combusted, release pollutants such as volatile organic compounds (VOCs) and greenhouse gases (GHGs). Indeed, the transportation sector is the second largest contributor to GHG emissions in Canada and road transportation makes up the majority of transportation emissions (Figure 1). The estimated contribution of motor vehicles to the total VOC emissions during the summer months in the United States was 25% in 1991 (EPA, 1991). Motor vehicles also contribute up to 42% of the total United States carbon monoxide emissions (EPA, 1991; EPA, 1993). Overall, this means that personal vehicles are one of the most important contributors to pollution and climate change. Meanwhile, gasoline prices have spiked in recent years and smog is becoming a major issue in large urban centres, and the United States Environmental Protection Agency recently announced that greenhouse gases are a threat to human health (EPA, 2009). All these factors have increased the pressure on auto manufacturers to develop more fuel-efficient vehicles.

In response to the demand for higher-efficiency vehicles, auto manufacturers have begun selling hybrid-electric vehicles (HEVs) and, more recently, plug-in hybrid electric
vehicles (PHEVs). Though these vehicles are still powered by fossil fuels (entirely in the case of HEVs and partially for PHEVs), they are much more efficient than typical internal combustion vehicles. This means they use less fossil fuels and produce fewer pollutants and GHGs. HEVs have been publicly available for a number of years, and are powered entirely by gasoline, therefore they do not require any new infrastructure to support. PHEVs, on the other hand, are only becoming available for public purchase in 2010 in Canada and because their batteries can be recharged directly from the electric grid they have the potential to be even more fuel efficient than HEVs. However, taking full advantage of PHEVs’ added efficiency requires them to be recharged regularly by plugging them in to electrical outlets. This begs the question: where and when can the average person access a plug to recharge their PHEV?

PHEV batteries are large, and as such they can take several hours to fully recharge through a typical electrical outlet, so for the PHEV infrastructure to have any value it must be in places where people typically park for long periods of time. This may not seem like a problem when one considers the staggering amount of time the average personal vehicle spends parked – on average just over twenty-three hours per day (Jakle and Sculle, 2004). However, not all parking spaces provide access to an electrical outlet, and the large parking lots which have electrical outlets in each parking space (typically only found in cold-climates where they are used for powering block-heaters during winter months) are usually not capable of handling a large electrical load such as the one needed to recharge several PHEVs at once. Additionally, electricity is not unlimited in supply, so if people are to plug in their PHEVs in public parking lots a mechanism must be in place that enables car-owners to pay for the electricity they use, and this price will likely need
to be adjusted based on whether it is being purchased during peak electric demand times or not.

Conveniently, the place where most people park most frequently and for the longest period of time is their homes. Recharging at home effectively addresses all the problems listed above. People would likely recharge overnight, which is off-peak electric demand in most areas, and they would pay for the electricity they use (assuming they live in a house with a garage or private parking space). It is safe to assume that the next best recharge site for the typical driver is at their workplace, but employers would likely be hesitant to install recharging infrastructure for their employees until a large proportion of employees actually own PHEVs, and this could take several years or even decades. However, additional recharge opportunities exist in public parking lots where people park while doing errands or engaging in social activities. There may be value in placing designated parking spaces for PHEVs with recharging infrastructure in these locations because they are visited by a higher number of people than a workplace, and therefore there is a greater likelihood that they will be used by PHEV drivers. By taking advantage of these recharge opportunities the typical PHEV would not have to be driven as far between charges. This could allow for reductions in the battery capacity of PHEVs, and thus their cost, without reducing efficiency. In other words, increasing the number of recharging opportunities has the potential to reduce the cost of PHEVs without compromising their environmentally friendly image. The major limitation to this is that, due to the cost of upgrading or installing the necessary electrical infrastructure, it is not feasible to service every public parking lot in a city.
To maximize the benefits of installing public recharge infrastructure, it is necessary to optimize where they are located. This is the primary purpose of this study. Determining the most ideal places to install PHEV recharging infrastructure can be done by monitoring a sample population’s driving and parking habits. Before doing this, however, it is useful to understand the costs and benefits of PHEVs versus other technologies such as hybrid-electric vehicles, and to provide a background of how driving-behaviour research evolved to the point where this type of study is required.

Figure 1: Canada’s GHG emissions from 2002 by sector (left) and the GHG emissions of the transportation sector (right). (Matin et al., 2004).

1.1. Plug-In Hybrid Electric Vehicles

Plug-in hybrid electric vehicles evolved from hybrid electric vehicles (HEVs). HEVs such as the Toyota Prius and Honda Insight have increased fuel economy by supplementing the normal internal combustion engine (ICE) of typical gasoline-fuelled
vehicles with an electric motor powered by electric energy stored in on-board, rechargeable batteries. The batteries are charged by capturing energy from the brakes and the ICE, which acts as a generator (Kelly, Mihalic & Zolot, 2001; Electric Power Research Institute, 2007). When there is excess power available in the batteries, they supply power to the electric motor to propel the vehicle until the state-of-charge (SOC) in the battery is depleted to a minimum level, which is typically around 20% of the total battery capacity, or until the demands placed on the vehicle are greater than the electric motor can supply alone (e.g., during aggressive accelerations) (Axsen, Burke & Kurani, 2008; Electric Power Research Institute, 2007; Kelly, Mihalic & Zolot, 2001). HEVs also reduce wasteful emissions by shutting off the ICE when the vehicle is stopped (Gonder & Markel, 2007; O’Keefe & Markel, 2006). Finally, HEVs supplement the ICE with the electric motor, allowing for downsizing of the ICE (Gonder & Simpson, 2007). While HEVs achieve higher fuel economies than their non-hybrid counterparts, they still rely on a single energy source: petroleum fuels.

Plug-in hybrid electric vehicles (PHEVs) present a solution to this problem. They are similar to HEVs, except that they have higher capacity batteries (i.e., they store more energy) and can be plugged in to standard household 120V 15A electrical outlets. Using electricity from the electric grid to charge the batteries reduces the amount of fuel needed to power the car, potentially reducing vehicle-related emissions, depending on the type of electricity generation in the region (Gonder, Markel, Thornton & Simpson, 2007; Gonder & Markel, 2007; Hadley, 2006). The relative impact of PHEVs on GHG and tailpipe emissions depends largely on the type of electric-generating facilities used in the area. For example, in California, where renewable energy sources and nuclear power plants
generate 45% of electricity, a PHEV is estimated to produce 30 percent less CO2 and 40 percent less NOx than a similar HEV. On the other hand, in the eastern United States, where coal-fired power plants generate the majority of electricity, a PHEV may not affect CO2 or NOx emissions, and may actually triple the amount of SOx emitted (Kliesch & Langer, 2006). PHEVs also offer benefits over Battery Electric Vehicles (BEVs) – which rely solely on batteries and an electric motor to power the vehicle. These include being equipped with less powerful and therefore less expensive batteries, shorter charging times and increased range of travel (O’Keefe & Markel, 2006).

The time it takes to fully recharge the battery will depend on the total capacity of the battery, how depleted the battery is, and the voltage and amperage of the outlet the vehicle is plugged in to. Fully recharging PHEV batteries that have been depleted to the minimum level (20% of battery capacity remaining) takes between 3.9 and 8.2 hours (Figure 2) (Hadley, 2006; Duvall, 2006). Once fully charged, PHEVs can operate all-electrically until the battery is depleted to the minimum level SOC or when the vehicle requires more power than the electric motor can supply alone. When the SOC is depleted to the minimum level, the ICE turns on and the vehicle operates in Charge Sustaining Mode, which is essentially how HEVs operate all the time (Figure 2) (Axsen, Burke & Kurani, 2008; Heffner & Turrentine, 2007; O’Keefe & Markel, 2006). The distance a PHEV can travel before switching to Charge-Sustaining Mode is referred to as the Charge-Depletion Range, which typically ranges from 32 to 64 kilometres (Axsen, Burke & Kurani, 2008; Gonder, Markel, Thornton & Simpson, 2007).
Table 1: Charging Requirements of PHEVs. Battery capacity tends to increase with vehicle size. The charge duration would decrease as the Voltage (VAC) and Amperage (A) of the outlet increase. (Duvall, 2006).

<table>
<thead>
<tr>
<th>PHEV 20 Vehicle</th>
<th>Pack Size</th>
<th>Charger Circuit</th>
<th>Charging Time (20% SOC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compact Sedan</td>
<td>5.1 kWh</td>
<td>120 VAC / 15 A</td>
<td>3.9 - 5.4 hrs</td>
</tr>
<tr>
<td>Mid-size Sedan</td>
<td>5.9 kWh</td>
<td>120 VAC / 15 A</td>
<td>4.4 – 5.9 hrs</td>
</tr>
<tr>
<td>Mid-size SUV</td>
<td>7.7 kWh</td>
<td>120 VAC / 15 A</td>
<td>5.4 – 7.1 hrs</td>
</tr>
<tr>
<td>Full-size SUV</td>
<td>9.3 kWh</td>
<td>120 VAC / 15 A</td>
<td>6.3 – 8.2 hrs</td>
</tr>
</tbody>
</table>

Figure 2: Battery Discharge pattern for a typical PHEV. (Axsen, Burke & Kurani, 2008; Adapated from Kromer & Heywood, 2007).
There are a number of barriers to the widespread public adoption of PHEVs. For one, they are projected to cost between USD$12,000 and $18,000 more than their non-hybrid counterparts, which is significantly more than the additional USD$2,000 - $6,000 people pay to own a HEV version of a given vehicle (Markel & Simpson, 2006). Secondly, the increased demand placed on the electric grid by recharging a large number of PHEVs – especially during periods of peak demand – can outstrip the total supply of electricity, or the ability of existing transmission lines to deliver sufficient power to a given area (Hadley, 2006). However, PHEVs have the potential to supply power stored in their batteries to the electric grid during peak demand periods, at a profit to the vehicle owner. This concept, known as Vehicle-to-Grid (V2G), requires additional hardware in the vehicles and at the location of electric outlets (Hadley, 2006).

To maximize the benefits of PHEVs, it is important to maximize the amount of time the vehicle operates in Charge-Depletion Mode and minimizing the duration of Charge-Sustaining Mode operation (Gonder, Markel, Thornton & Simpson, 2007). To do this, it is imperative to understand the characteristics of typical drivers, including the potential timing, duration and locations of recharge opportunities, that is, when, how often, for how long, and where people are able to recharge their vehicles (Axsen & Kurani, 2008). Also, it is important to determine how far people typically drive before their next recharge opportunity. This will enable engineers to design batteries for PHEVs that can be recharged between the trips of a typical driver, while rarely depleting the battery SOC to the minimum level. For example, if the typical person drives an average of 12 kilometers to and from work, and their vehicle remains parked for 8 hours a day at work and 12 hours a night at home, then the battery for PHEVs could be designed to
power the vehicle for 12 kilometres before recharging, and the recharge should take less than 8 hours (assuming they have access to an electrical outlet both at home and work). Axsen and Kurani (2008) found that while over half of new-car buyers in the United States would be able to charge a PHEV at home, only a small percentage have the ability to recharge at work and other locations away from home. Identifying the areas most frequently visited by typical drivers in a given city could be used to determine the locations most suitable for developing infrastructure capable of recharging a large number of PHEVs. Examples of these locations include large shopping centres or office buildings. Ideally, this type of information would enable the design of a PHEV that could be operated in Charge-Depletion Mode by the majority of drivers, for the maximum proportion of time possible.

1.2. Driving Behaviour Research

Extensive research has been done to understand driving behaviour. The research varies with respect to the purpose of the research, type of monitoring, sample size and selection procedure and the duration of monitoring. The following section is loosely grouped based on type of monitoring and chronology. In general, driving behaviour research has evolved to become more accurate and incorporate a greater amount of information about driving behaviour, although some shortcomings still exist. Almost all of the research has been conducted in the United States.
1.2.1. Instrumented Vehicles

Some of the earliest research in the United States was carried out by the State of California’s Vehicle Pollution Laboratory in the mid-1960s to measure vehicle exhaust emissions over a typical urban driver’s daily route (EPA, 1995). For example, the researchers outfitted a 1964 Chevrolet with instruments to measure manifold vacuum and revolutions-per-minute (RPM) ranges within the vehicle’s engine. The vehicle was then driven from work to home and back by several employees of the laboratory. A specific test route was then selected that, when driven with the instrumented vehicle, closely matched the average vehicle speed/load distribution from the sample of home-work commutes. The speed/load distribution recorded along this route became known as the Federal Test Procedure, or FTP (EPA, 1995). The route, which was 19.3 kilometres long, became known as the “LA4” (EPA, 1995).

In 1970, researchers from the Environmental Protection Agency’s (EPA) improved on the FTP by recording speed-time distributions (instead of manifold vacuum pressures and engine RPMs) of six different drivers along the LA4 (EPA, 1995). The variables recorded included idle time, average speed, maximum speed, and total number of stops per trip. One of the six participants’ data set was discarded because it demonstrated significantly greater speed variation than the others. The speed-time trace that most closely matched the average of the five samples was then chosen to be the representative drive-cycle, and became known as the Urban Dynamometer Driving Schedule (UDDS). The trip length of the UDDS was 12 kilometres and the average duration of the trips was 37.6 minutes (EPA, 1995). Since 1972, it has been used to certify that light-duty vehicles and light-duty trucks meet emissions standards in the
United States, to consistently and repeatedly measure exhaust emissions such as NO$_x$, CO, and CO$_2$ from simulated trips and to measure vehicle fuel economy (EPA, 1993).

A number of limitations with the UDDS have been identified, such as the relatively low top speed (92 km/h), the fact that acceleration rates were artificially reduced due to limitations of the monitoring equipment, road grades were not accounted for, small timescale changes in speed were not measured, and the lack of representation of a wider range of drivers (EPA, 1995). Under the Clean Air Act, the EPA is responsible for ensuring that vehicles are tested according to realistic driving patterns (EPA, 1993). As a result, in 1992, the EPA, the American Automobile Manufacturers Association (AAMA) and the California Air Resources Board (CARB) collaborated on a large-scale survey of driving behaviour in four United States cities: Baltimore, Maryland; Spokane, Washington; Atlanta, Georgia; and Los Angeles, California. The study recorded data from 395 instrumented vehicles as well as records from chase-car studies (where an instrumented vehicle driven by researchers closely followed a participant vehicle along a designated route) along 249 routes for a total of 17,672,166 seconds of second-by-second driving data (EPA, 1993). The researchers proved that the UDDS failed to capture a large proportion of typical driving behaviour (nearly 13 percent of total in-use vehicle time). For example, the average speed from the instrumented vehicle data was 41.7 km/h, more than 8 km/h faster than the average speed in the UDDS (EPA, 1995; EPA, 1993). The results of this study also showed differences in driving behaviour between trucks and cars; manual vs. automatic transmission; high vs. low performance vehicles; old vs. new vehicles; time of day; and day of week (EPA, 1993).
The EPA constructed three representative driving cycles from this data to compare exhaust emissions to the UDDS. The first cycle, the Start Driving (ST01), was constructed solely from driving segments that occurred within 80 seconds from the initial vehicle turn-on and idle period. The second cycle, the 1400 second REP05 or Aggressive Driving cycle, was constructed from idle-to-idle segments of data that contained a high proportion of speeds and/or accelerations above those found in the UDDS. This was intended to represent aggressive driving behaviour. Finally, the 1237 second Remnant Cycle, or REM01, was constructed from segments of data that were largely not covered by either Start Driving or Aggressive Driving cycles (EPA, 1993).

Joumard et al. (2003) instrumented 39 light-duty goods vehicles to monitor driving behaviour to construct a drive cycle for measuring emissions. They recorded vehicle speed, engine speed, various temperatures once per second, as well as the mass of the load carried by the vehicle over a one month period. In a method similar to that of EPA drive-cycle construction methodology, they selected trip segments that most closely matched the average values of the entire dataset, and then pasted them together to generate a cycle that was the same duration as the average duration of trips in the dataset. Hung et al. (2007) opted to use both instrumented vehicles and chase-car data to construct a drive cycle for Hong Kong. However, their drive cycle was constructed from vehicles driving along a specific route, which was chosen due to the fact that it had the heaviest traffic volume.

1.2.2. Travel Surveys and Activity Diaries

The common shortcoming with the instrumented vehicle studies is the lack of data about destination choice and parking characteristics, such as duration of parking at
different locations. This problem can be addressed by travel surveys, which capture a large number of drivers typical travel habits. These typically require participants to record every trip origin and destination they undertook for a given day, including the start and end times for each trip and the trip purpose, and also include information about the households, people and vehicles (Stopher & Greaves, 2007; Hu & Reuschler, 2004). The first National Person Travel Survey (now known as the National Household Travel Survey or NHTS) was conducted in the United States in 1969 by the Department of Transportation. The survey has been performed numerous times since then. The data captured by the NHTS includes information about household demographics, individuals, vehicles, and travel by all modes (not just personal vehicles) for all purposes (Hu & Reuschler, 2004). Examples of the data collected include relationship of household members, income, housing characteristics, education level, vehicle make, model and year, work-related travel, and detailed information about the start time, end time, and length of each trip in a given 24-hour period. Data is obtained from a random sample selected by random-digit dialing via Computer Assisted Telephone Interviews (CATIs). The 2001 NHTS included 69,817 households (Hu & Reuschler, 2004).

Travel surveys were originally conducted in person, using sample sizes as large as 3% of the population. However, due to the high costs of in-person surveys, computer-assisted telephone interviews (CATI) have largely replaced them in North America. At the same time, sample sizes have reduced to less than 1% of the total population in an area (Stopher & Metcalf, 1996; Cambridge Systematics, 1996; Stopher & Greaves, 2007). Additionally, there are a number of disadvantages to conducting travel diary surveys such as a lack of data reliability, especially underreporting of a portion of trips,
which can lead researchers to conclude typical drivers travel less often and for shorter durations than they do in reality (Wolf, Oliveira & Thompson, 2003).

Several reasons have been suggested for respondents’ trip underreporting: 1) lack of care on the part of the respondent due to fatigue from reporting trips over multiple days; 2) forgetting about trips or failing to report them because they consider them to be redundant; 3) deliberate decisions to not report trips; 4) the trip was considered too short or unimportant, and; 5) reporting trips was too time-consuming (Brog et al., 1982; Pendyala, 1999; Richardson, 2000). However, recent modifications in the survey collection procedures by some researchers have improved the accuracy of the data recorded by travel surveys. An example of an improvement is the providing of participants with a diary so they can record their trip information directly after each trip, as opposed to recalling the information for a number of trips from a previous day. The product produced is called a trip diary, or activity diary. Also, by changing the order of the questions from “1) Where did you go?” and “2) Why did you go there?” to “1) What did you do?” and “2) How did you get there?”, the number of trips reported increased, especially for short trips that people previously neglected to include in the survey (Stopher & Greaves, 2007).

1.2.3. Global Positioning Systems-Based Research

In spite of the improvements made to travel surveys and activity diaries, some researchers suggest that it is imperative for travel surveys to record trip information over a longer period of time, while maintaining accurate trip records and minimizing the burden on respondents (Yen et al., 2006). Long reporting periods are necessary to capture temporal differences in driving behaviour resulting from day-to-day or seasonal factors.
Richardson, Seethaler & Harbutt, 2003). The most promising solution to this problem in trip reporting came with the integration of Global Positioning Systems (GPSs) into travel surveys and activity diaries (Yen et al., 2006).

1.2.3.1. GPS Background

The GPS was developed by the United States Department of Defense beginning in 1973. The primary objective was to allow the United States military to easily and accurately navigate anywhere on Earth by calculating position (latitude, longitude and elevation) to within a 5-10 metre range, while keeping accurate time for the purpose of navigation. Although designed for the military, anyone with a GPS receiver could use the system. However, until the year 2000, the GPS signal was encrypted with Selective Availability, which introduced errors of 30 to 100 metres in location determination for anyone not affiliated with the United States military (Hoffman-Wellenhof, Lichtenegger & Collins, 1994; Kaplan, 1996; Wagner, 1997). Selective Availability was de-activated by President Clinton in the year 2000, allowing all GPS users access to the same level of precision of between 5 and 10 metres.

GPS consists of a space segment, a control segment and a user segment. The space segment consists of 24 active satellites (plus spares) orbiting the Earth such that at least four satellites are at least 15 degrees above the horizon at any given time and any location on the surface of the Earth, not accounting for barriers such as topography and man-made structures. Each satellite orbits at an altitude of approximately 20,200 km and completes a full revolution around the Earth every 12 hours. Each satellite is equipped with four highly precise atomic clocks (accurate to within one second every 70,000
years), two cesium and two rubidium clocks, and a computer containing information about the satellite’s precise location in orbit (Hoffman-Wellenhof, Lichtenegger & Collins, 1994; Ashby, 2002). The satellites continuously transmit the time and orbital location information via radio waves at specific frequencies which can be picked up by the control segment and the user segment on the Earth’s surface.

Although the clocks are very precise, they are affected by special relativity, which causes time to pass more slowly for objects moving at relatively high speeds; a clock on the surface of the Earth will tick faster than a clock orbiting at high speeds around the Earth (Langley, 1991; Ashby, 2002). The trajectories of the satellites are also affected by the same gravitational forces that cause tidal action (i.e. the Sun and Moon) (Langley, 1991). Furthermore, satellite signals can be refracted when passing through the atmosphere, which dilutes the precision of locating GPS receivers (Langley, 1991; Hoffman-Wellenhof, Lichtenegger & Collins, 1994). Therefore, it is necessary to continually monitor atmospheric conditions and the trajectories of the GPS satellites, which is the responsibility of the control segment (Kaplan, 1996; Hoffman-Wellenhof, Lichtenegger & Collins, 1994).

The control segment consists of a master control station in Colorado Springs, Colorado, and several additional monitoring stations dispersed around the world, the positions of which are precisely known (Kaplan, 1996; Hoffman-Wellenhof, Lichtenegger & Collins, 1994). The primary task of the control segment is to track the satellites’ precise orbital trajectories and atmospheric conditions and to transmit error corrections back to the satellites. Each monitoring station is responsible for tracking the positions of the satellites in view, and transmitting this data, along with atmospheric
conditions, back to the master control station. The master control station then calculates the appropriate error corrections and transmits them back to the satellites (El-Rabbany, 2001).

The user segment of GPS consists of GPS receivers, which are mobile, electronic devices carried by individuals. To determine the position of the receiver on the Earth’s surface, the receiver must pick up (via an antenna) at least four different satellite radio signals containing the precise locations of each satellite and the precise time on the clock of those satellites. Because the radio signals travel at a constant speed (assuming they are not refracted by the atmosphere), the receiver can calculate exactly how far away it is from each satellite and triangulate its position on the surface of the Earth (Figure 3). Speed is most often calculated by the receiver using the Doppler Effect, which is the process by which the frequency of a signal changes due to the relative motion of the transmitter (satellite) and the GPS receiver (Figure 4) (Kaplan, 1996; El-Rabbany, 2001; Hoffman-Wellenhof, Lichtenegger & Collins, 1994). Frequency is raised when the transmitter moves towards the receiver, or if the receiver moves towards the transmitter. Therefore, the change in frequency of the satellite signal is directly related to the velocity (speed and direction) of the satellite and the velocity of the receiver. Because the position and velocity of the satellites is known relative to the position of the receiver, and the frequency of the signal can be measured by receivers, it is possible to calculate the change in frequency resulting from the velocity of the receiver alone (Langley, 1991; El-Rabbany, 2001; Hoffman-Wellenhof, Lichtenegger & Collins, 1994).
Figure 3: Illustration of triangulation being used to determine the location of a GPS receiver. If the distance between the receiver and 3 satellites is known, the intersection of the spheres of radii $r_a$, $r_b$ and $r_c$ around the three satellites gives two possible locations of the receiver. Knowing the distance from a fourth satellite will yield one possible location. (Short, 2009).

Figure 4: Illustration of the Doppler Effect. The waves in front of the moving red dot are compressed (higher frequency) relative to the waves behind it (lower frequency). The differences in frequency are used to measure the speed and direction of the source. (http://upload.wikimedia.org/wikipedia/commons/f/f7/Doppler_effect_diagrammatic.png).
GPS errors can also occur in the user segment. One example is multipath error, which occurs when the satellite signal bounces off large or reflective objects such as buildings or metal surfaces before it reaches the receiver, giving false locations and distances from the satellite (Langley, 1991; Hoffman-Wellenhof, Lichtenegger & Collins, 1994). For example, a vehicle may appear to drive off the road or through buildings when its position is mapped. Additionally, large objects, dense tree canopies, bridges and even car roofs can completely block the signal from one or more satellites such that the signals do not reach the receiver at all (signal-loss). If this reduces the number of satellite signals picked up by the receiver to three or less, no positional data can be recorded (Du & Aultman-Hall, 2007). The previous two problems become prevalent in downtown areas with many large buildings. These areas are known as “urban canyons” (Murakami, Wagner & Neumeister, 2001). Another problem with GPS units is that there may be a period of time ranging from 20 seconds to five minutes during which no data is recorded directly after the receiver is turned on, or after the signal is lost due to prolonged blockages. This is referred to as a cold-start period, which occurs due to the time it takes GPS receivers to re-acquire all the available satellite signals (Wolf, Oliveira & Thompson, 2003). Furthermore, not all GPS receivers are equal. Those that are equipped with higher quality antennae are able pick up weak satellite signals, thus improving the accuracy and reliability of the data (Murakami, Wagner & Neumeister, 2001). Finally, GPS receivers are electronic devices that require a constant supply of power when in use. Power failures due to faulty connections or drained batteries will prevent the receiver from recording data.
Some GPS receivers are equipped with internal memory storage hardware and the data they store can often be transferred to computers. This enables GPS-based driving behaviour studies to be conducted over long periods of time. GPS data recorded and stored by receivers always contains latitude, longitude, time and date, and can include additional information such as speed, altitude, trip number, number of satellites used, and the serial number of the receiver (Table 1). The volume of data recorded can often be adjusted, so that data is recorded at set time intervals, such as once per second. GPS trip information can accumulate into a very large amount of data. Therefore, the duration of the study is limited by the memory capacity of the GPS receiver, unless data is uploaded to computers periodically. Additionally, the large volume of data recorded by a GPS receiver can be difficult to transform into meaningful information (Grengs, Wang & Kostyniuk, 2008). However, by uploading the data to computers it can be filtered to include only pertinent data (and to exclude erroneous data), then mapped and analyzed using computer software programs, including Geographic Information Systems (GISs) (Yen et al., 2006; McNally et al., 2002; El-Rabbany, 2001). Finally, researchers must take extra precautions to ensure the confidentiality of participant data. A person’s travel record could easily be used to identify where participants live, work and spend free time (Grengs, Wang & Kokstyniuk, 2008).

GISs are capable of geocoding (plotting latitude and longitude on maps) spatial data (such as GPS data) and layering it over digital maps, including road maps, land-use maps, aerial photographs, hydrographic maps, and topographic maps. Each data point from a GPS data set is plotted on the map according to its latitude and longitude, but it can also be linked to additional information such as the date and time at which the point
was recorded, the speed of the receiver at that point, the altitude of the point, or any other information the researcher wishes to add, such as demographic information about the person using that particular receiver. For this reason, integration of GPSs and GISs has the potential to be a very useful tool in conducting driving behaviour research.

Table 2: Example GPS data record. Each row represents one data point recorded.

Computer programs allow additional information to be added to the table such as acceleration, distance travelled since last point, day of week, etc. (Blair, Smith & Capelle, 2009).

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<th>LONGITUDE</th>
<th>SPEED LIMIT (KM/H)</th>
<th>TYPE</th>
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1.2.3.2. GPS-Assisted Travel Behaviour Research

Several studies have compared the accuracy of travel surveys to GPS-assisted travel behaviour research. Wagner (1997) equipped a number of participants’ vehicles with a GPS receiver for a six day period, after which the participants were asked to report their trip information for one of the six days. Wagner encountered difficulties in matching unreported trips with GPS-recorded trips due to a combination of inaccurate trip-reporting (e.g. rounding-off departure and arrival times) and GPS inaccuracies such as signal loss. The GPS data was especially difficult to analyze because the study took place
while selective availability of GPS signals was still in effect. Therefore, no comparisons could be made regarding the accuracy of one method over the other (Wagner, 1997; Wolf, Oliveira & Thompson, 2003). Wolf (2000) had some success comparing the accuracy of activity diaries to GPS data recorded from participants’ vehicles. She found that GPS-equipped vehicles recorded more trips than participants recorded in activity diaries, particularly shorter trips. However, she noted that GPS receivers often failed to capture data points at the start of trips, due to cold-starts or to temporary signal-loss as a result of blockages lasting longer than 30 minutes. This problem can be partially resolved by using the previous trip-end as the following trip-origin (Wolf, Oliveira & Thompson, 2003; Yen et al., 2006). However, even though a GPS may record trips more accurately and consistently than travel surveys and reduce the burden on respondents, it does not provide any information about the household, drivers, or trip purpose. Therefore it seems that a combination of GPS and travel surveys are necessary for conducting travel behaviour research.

One such study combined GPS data collection with activity diaries using Personal Digital Assistants (PDAs) (Murakami, Wagner & Neumeister, 2001). The researchers conducted bench tests of different GPS receivers along a specified route through a variety of areas to select the most reliable and accurate receiver for their study. The route was selected such that the vehicle would pass through a wide variety of neighborhood types to expose the receivers to all kinds of potential error sources such as tall buildings, tree canopies and underpasses. One hundred vehicles from 100 households were recruited, and it was assumed that only one driver from each household would drive the vehicle. The drivers, who were well stratified by age, gender and whether or not they had
children, were given a PDA and a GPS receiver which was installed on the roof of their vehicles. The participants were asked to fill out selected information about each vehicle trip they took over a six day period by entering it into data fields on the PDA. The PDA was pre-configured to be as user-friendly as possible to minimize the burden on participants. For example, trip purpose and number of occupants in the vehicle could be selected from drop down menus, and the GPS automatically recorded trip start time, end time, duration, route, and speed. The vehicle’s cigarette lighter supplied the power for the GPS unit and PDA. Therefore, the researchers had to calibrate the units to shut off soon after the vehicle was turned off so the car battery was not depleted. This study allowed for the collection of travel survey data with minimal burden on the respondent, while simultaneously taking advantage of GPS to ensure that minimal trip underreporting occurred. The GPS receivers were instrumented to record data once-per-second, but generally only recorded once every two seconds. A small portion of the GPS units were returned with no data recorded, for unknown reasons, while a few others appeared to have experienced power supply issues due to faulty connections with the cigarette lighter. The results showed that overall the combination of GPS and user-friendly activity diaries are more effective than travel surveys alone, though still not perfect.

1.2.4. Parking Research

As noted earlier, PHEVs can be recharged during parking events by plugging in to electrical outlets. Thus, it is important to develop an understanding of peoples’ parking behaviour. The previously mentioned studies have focused primarily on determining trip purposes, frequencies, and durations – but have not paid much attention to analyzing
parking events. Studies related to this aspect of driving behaviour are less common. A few of these are reviewed in the following section.

Schonfelder et al. (2005) used GPSs to monitor 450 vehicles on a second-by-second basis in the Atlanta metropolitan area for the purpose of identifying an individual’s destination choice behaviour and activity spaces (the area containing places that individuals regularly visit). Individual vehicles were monitored for periods ranging from 6 to 367 days. The sample was selected using a random stratified sampling framework to get a representative variety of vehicles and household characteristics. In addition to vehicle type and household characteristics, the researchers also asked participants to supply their workplace locations. Because of the large dataset, they were able to filter out trips shorter than 120 seconds in duration as well as trips whose origins did not closely match the previous trip end. Multiple trip-ends within a 200 metre radius were grouped together and classified as a single destination (Schonfelder et al., 2005). They were able to calculate the average number of trips per day (4.1) as well as the mean daily travel duration (74.4 minutes) and mean daily distance travelled (49 km). While the number of unique destinations visited by each participant never stopped increasing with the number of trips (Figure 5), the top three most visited destinations made up over 30% of the total destinations over the entire study period (Figure 6).
Figure 5: Relationship between number of trips and number of unique locations. The number of unique locations appears to increase steadily with the number of trips taken. (Schonfelder et al., 2005).

Figure 6: The number of trips taken to each of the top ten destinations for the sample. The top three destinations make up over 30 percent of all destinations. (Schonfelder et al., 2005).
Grengs, Wang & Kostyniuk (2008) devised a method for associating multiple trip-ends clustered within a threshold distance from each other with a single nearby destination. They collected GPS data from 78 participants for a one month period. When multiple trip-ends were recorded within a 30 metre distance of each other, the researchers associated these trip ends with a single location, such as a nearby shopping mall. The algorithm used to associate multiple trip-ends with a single location is known as a union-find algorithm which groups points by solving a maximal clique problem (Grengs, Wang & Kostyniuk, 2008).

Ashbrook and Starner (2003) also devised a model to identify important locations frequented by individuals based on GPS data. They defined a place as a GPS coordinate with an interval of at least ten minutes between it and the previous point. The ten minute interval was used because it was determined to be long enough to eliminate any time intervals that resulted from GPS signal loss. The researchers then used a clustering algorithm to determine the significance of the places. First they chose one place point and a radius r, flagging all the points found within the radius around the original point. The mean of these flagged points was then used as the new centre point and the process was repeated until the mean no longer moved. Once the mean stopped moving (panel e of Figure 7), all the points inside the radius were placed in a cluster and were no longer considered. The cluster then becomes a location, which is assigned an ID such as home or work. This process is repeated until no places remain, only locations. To determine the ideal radius r, the algorithm was run numerous times with varying radii, and the number of clusters was plotted against the radius r (Figure 8). The ideal radius corresponded with the point on the curve just before the number of locations begins to converge on the
number of places. To find this point in the curve (the so-called kneepoint) the researchers found the average of each point on the graph and the next n points to the right of it, beginning from the right side of the graph. The kneepoint occurs when the current point exceeds the average by a threshold value, or when the slope of the curve changes significantly. A similar technique was then used by the researchers to determine important sub-locations for each location, for example, the math and physics buildings on a university campus. The only shortcoming of this method is that it may not be useful in identifying irregularly-shaped clusters.

![Figure 7: Illustration of location clustering algorithm. Solid circle represents the cluster boundary, X is the center of the cluster, and the dotted circle represents the previous cluster boundary. The hollow points are the data-points that are within the cluster.](image)

(Ashbrook & Starner, 2003).
Figure 8: Relationship between number of locations found and radius used in clustering algorithm. The arrow indicates the location in the curve that was used to determine the ideal radius to use. (Ashbrook & Starner, 2003).

Figure 9: Comparison of clusters identified by the CLARANS (top) and DBSCAN (bottom) algorithms. The DBSCAN clusters coincide with what intuitively appear to be clusters, while the CLARANS does not. (Ester et al., 1996).
After assessing various clustering algorithms, Ester et al. (1996) concluded that it would be useful to devise a new clustering algorithm that could identify irregularly-shaped clusters using large spatial datasets. They called this clustering algorithm DBSCAN. The algorithm method that DBSCAN uses to find clusters of points is very complex. However, when compared to the often-used CLARANS clustering algorithm, DBSCAN was more effective at identifying irregularly shaped clusters (Figure 9).

DBSCAN was also used by Griffin, Huang and Halverson (2008) to perform a cluster analysis on GPS data tracking personal vehicle trip endpoints, due to its ability to identify irregularly-shaped clusters (Figure 10). The authors chose DBSCAN over the K-means clustering approach, which tends to select symmetrical clusters. After clustering points, the authors developed a set of criteria to classify the clusters (points of interest) based on attributes such as time of arrival and duration of stay. For example, for a trip endpoint to be considered a person’s home, three criteria must be met: 1) the destination must be visited at least 15 times in a four week period; 2) the average duration of parking at the destination must exceed eight hours; and 3) the destination must be located in a residential land-use area of the city. The researchers developed similar criteria to classify participants’ work/school locations. This was made easy by the fact that the researchers collected information on the participants’ occupation and employment status. The criteria for full-time workers were slightly different than for students, due to the decreased amount of time students are required to attend their learning institution. The researchers were unable to reliably classify locations other than school, work, and home, however. This was due to the fact that a variety of businesses were located in close proximity to each other, and would require a similar amount of time to visit. For example, it would be
difficult to distinguish between going to a fast-food restaurant and grocery shopping.

Figure 10: An example of an irregularly shaped cluster of parking events. (Griffin, Huang & Halverson, 2008).

1.3. Objectives

Although home and work will likely be the most suitable locations for recharging PHEVs, it would be beneficial to take advantage of additional recharge opportunities in public locations. The availability of public recharge locations is expected to reduce battery size and therefore initial cost, while not compromising the environmental benefits of PHEVs. At this point, little or no research has addressed the need to optimize the locations of these recharge stations, which is necessary due to the high cost of installation. Accordingly, the objectives of this study are twofold: 1) to develop a GPS-based methodology of determining the most suitable parking lots for re-charging PHEVs in the City of Winnipeg, and; 2) to evaluate the efficacy of this methodology and its potential application in other jurisdictions.
2. METHODS

To meet the objectives of the study efficiently and effectively, it was necessary to study the parking behaviour of a sample population of Winnipeg drivers for an extended period of time. Prior to the start of this project, GPS data collection from a sample of Winnipeg drivers was underway for a study on driving behaviour for the purpose of optimizing PHEV batteries. The GPS data collected was made available for this study by the head researchers at the Universities of Winnipeg and Manitoba. Although the data collection procedures for driving behaviour research are not optimal for parking behaviour research, they are very similar, and collecting a separate data set would have been too expensive and time consuming to stay within the limits of this project. Therefore, the data collection procedures outlined below are not necessarily those that would have been used in ideal circumstances, they are merely a description of the procedures used by the researchers involved in the driving behaviour research project.

2.1. GPS Receiver Selection

The GPS receiver used to record driving data in this study was Persentech Inc.’s Otto Driving Companion. This receiver has several features that make it suitable for this study. It is compact (12.8cm X 7cm x 3.2cm), lightweight (320 g), and powered by plugging in to a vehicle’s lighter socket (Figure 11). The units each came with a mounting bracket that attaches to the windshield using suction cups and a gel pad that sits on the dashboard which helps ensure that the units get a clear view of the sky through the windshield without damaging the vehicle (Figure 12). The unit turns on and off automatically with the vehicle, which minimizes the responsibility placed on participants.
(i.e. they do not have to remember to turn the unit on and off). The Ottos also have the ability to record data at one-second intervals and store up to 300 hours of data before running out of memory. The Otto records trip number, date and time in Greenwich Mean Time, latitude and longitude to five decimal places, and the speed of the vehicle once per second when the vehicle is on. Other features of the Otto include the ability to warn drivers when they are speeding (when they are within the city limits), approaching red-light cameras, crosswalks, and school zones; and a feature that allowed participants to later view a map and summary of their driving on their personal computers.

Figure 11: The Otto Driving Companion (Persentech Inc., 2009).

Figure 12: Mounting bracket and gel pad for use with Otto Driving Companion. These features ensured the GPS receiver got a clear view of the sky. (Persentech, Inc., 2009).
2.2. Participants

Volunteer participants were largely recruited on a first-come first-served basis using a ‘snowball’ method. Recruitment notices were sent out through local media outlets including radio and television. New participants were encouraged to invite their friends and relatives to participate as well. In all, 93 participants signed up for a one-year period, though some dropped out prior to the end of the study and were replaced by later recruits. In the end, a total of 76 households supplied driving data. No financial incentives were offered to the participants; however, many expressed enthusiasm for the added features of the Otto such as viewing their driving records on their home computers and receiving warnings when they were speeding or approaching red-light cameras.

The participants were asked to fill out a short survey prior to participating in the study. The information collected included home address and contact information, number of drivers that would likely operate the vehicle, age group, sex, employment status, and education level of each driver, and the gross annual household income. Participants were also asked to identify all of the reasons for using the vehicle, such as driving to work/school, running errands, work-related driving and shopping. General vehicle information was also collected including make, model, year, fuel type, average frequency of use, and approximate odometer reading. Due to the information collected, an ethics form was appended to the survey assuring the participants that their personal information would be kept confidential.

Participants were asked to use the mounting bracket during all trips so that the Otto would have a clear line of sight through the windshield. They were also requested to place the Otto out of sight when parking outside to reduce the chance of theft. When the
memory neared capacity (usually once every three months) participants were required to upload the data to their computers and email it to the researchers, then clear the memory before returning the unit to their vehicle. Participants also had the option of having their unit picked up by a researcher, who would upload the data, clear the memory and return the unit to the participant. This was helpful for those participants who either did not have access to a PC or who were not computer-savvy.

2.3. Resulting Data Set

A total of 76 participants submitted a data set containing at least one parking event, although it should be noted that most participants’ vehicles were driven by more than one person over the study period. The total number of data points collected from all participants was approximately 44 million, including 39,749 parking events of at least 30 minutes. The largest data set for a single household vehicle was recorded between May 20, 2008 and March 31, 2009, and consisted of 2,447,722 data points including 1,583 parking events. The smallest data set was collected over a period of 27 days consisting of 36,408 data points and 30 parking events. Sixty percent of all identified drivers were male, and drivers between 46-55 years and 26-35 years accounted for nearly half of all drivers in the study (Figure 13). The vast majority of drivers were employed on a full-time basis; the most common household income ranged from $70,000 CAD to $99,999, while 6% of households earned less than $40,000 CAD and 18% earned more than $150,000 CAD (Figure 14). This suggests the sample bias occurred, with more affluent, wealthier households being over-represented by the sample. However, because of the additional cost of PHEVs versus standard vehicles, it may be suitable to have some sample bias towards wealthier individuals as they may be more likely to purchase PHEVs.
than less-wealthy individuals. Cars made up the vast majority of vehicle-types in the study (70%) while sport-utility vehicles and mini-vans accounted for 15% and 11% of the total vehicle-types, respectively. Other vehicle types included vans and light-duty trucks.

Figure 13: Age groups of drivers in sample population.

Figure 14: Participant household incomes.
2.4. Data Processing

Due to the large volume of data collected (more than 40 million data points) it was necessary to process it using a Visual Basic 5.0 (VB) program. The first step in data processing was to convert the time from GMT to Winnipeg time, which is Central Daylight Savings Time (UTC -5 hours) between the second Sunday in March and the first Sunday in November and Central Standard Time (UTC -6 hours) during the rest of the year. Secondly, because of participant drop-outs and late applicants, several of the Ottos were used by more than one person over the study period. To distinguish between participants who had used the same GPS unit, unique participant IDs were added to the appropriate data points.

The data was then filtered to remove any data points that were not relevant to parking-spot analysis. To do this, the VB program was designed to select only the data points associated with parking events and save them in a separate text (.txt) file. Parking events in this study were defined as periods equal to or longer than 30 minutes during which no GPS data was recorded. Parking events lasting less than 30 minutes were not considered significant to this study because it was assumed that typical driver would not bother plugging in their PHEV if they were parked for less than 30 minutes, as charging a vehicle for 30 minutes in a 120C 15 A outlet would only provide a small amount of charge to the battery. Furthermore, in order to eliminate erroneous trip-ends caused by periodic signal loss and the resulting lag in signal acquisition, it was necessary to utilize a time interval longer than most cold-start signal acquisition times, which range from 30 seconds to 8 minutes (Wolf, Oliveira & Thompson, 2003). Therefore, only data points separated by a time interval of equal to or greater than 30 minutes were selected. Each
The VB program was then programmed to calculate the duration of each parking event in minutes (rounded off to the nearest minute). The duration of each parking event was assumed to be equal to the time interval between the trip-end and subsequent trip origin. It should be noted that because of the cold-start signal acquisition time, the actual duration of each parking event was typically 30 seconds to 8 minutes shorter than the recorded time interval. However, it would have been extremely difficult to correct for this problem accurately, and so no correction factors were employed. The distance between the trip-end and the next trip-origin was also calculated and added to the output table, as was the number of parking events per day, although these were not utilized in the subsequent analysis. The program was also designed to add the month, day of week, and hour of day, of both the trip-end and subsequent trip-origin to separate columns of the output table. Original raw data calculated by the GPS receiver such as the participant ID and the date, time of day, latitude, and longitude of both the trip-end and subsequent trip-origin were kept in the output table.

The output table was then converted to a Database IV (.dbf) file so that it could be imported to ArcMap (Table 3). Unfortunately, the time values associated with the parking events were lost during the conversion, which is why it was necessary to have the VB program add the month, day of week and hour of day of each parking event to the output table. ArcMap was used to plot the locations of all trip-ends. Street maps, aerial photographs, land-use classification maps, building footprint maps, and hydrographic
maps for the City of Winnipeg and surrounding regions (supplied by ATLIS Geomatics Inc. via the University of Winnipeg Map Library) were then added as separate layers to the GIS.

2.5. Data Analysis

One of the goals of the project was to determine the most suitable locations in the City of Winnipeg for recharging PHEVs. To do this, it was necessary to decide upon ideal characteristics for these recharging locations, and to utilize these to rank potential parking areas in the city. Accordingly, the author created the parking lot suitability index. It consists of three separate variables: the number of different participants who used the parking lot, the average parking duration, and the proportion of parking events during off-peak electricity demand times relative to on-peak demand times. The parking lot should be used by a large number of people to increase the likelihood of being used by PHEVs. The average parking duration should be as long as possible to maximize the amount of electricity delivered to the batteries during use. Finally, the parking lot should be popular during off-peak electric demand times to reduce strain on the electric grid.

Because of the large number of public parking lots in the City of Winnipeg, it was not feasible to analyze every lot individually. Since one of the objectives of the study is to identify those parking lots that are used by a large number of Winnipeg drivers (as represented by the sample), it was necessary to identify these widely-used parking lots and thereby eliminate infrequently used parking lots from further analysis. ArcMAPs Neighbourhood Analysis tool was used to do this. The Neighborhood Analysis tool divides the map surface into a grid and counts the number of unique participant IDs in each rectangular grid section, then assigns a colour to each section based on this value.
(Figure 15). A range of grid-sizes was employed. Using a variety of grid sizes helps to reduce the likelihood that a parking lot will be erroneously identified as “widely used” or “not-widely used” due to its relative size. For example, a large parking lot at a major shopping centre may have been used by a large proportion of the sample population. However, if the grid size in the Neighbourhood Analysis was smaller than the area of the parking lot, each grid would under-represent the popularity of the parking lot, thus making it appear insignificant. Using a grid size large enough to capture most or all of these large parking lots helps minimize this underreporting. On the other hand, a large grid size might contain several small, unpopular parking lots, which could make the area appear very popular (Figure 16). This problem is mitigated by using smaller grid sizes.

Five different grid-sizes were used, ranging from 3,261 m² at the fine scale to 7,246,650 m² at the coarse scale. The number of unique participant IDs in a grid-section ranged from 75 at the coarsest-scale to 35 at the finest. By overlaying the five maps produced by the Neighbourhood Analysis at each grid-density and super-imposing these maps on an aerial photograph of the city, it was possible to easily identify the most popular parking lots in the city, regardless of their size. This methodology narrowed down the list of potential parking lots in the city from at least several hundred to 49. This methodology also ensured that home-parking events were filtered out from further analysis because the grid sections did not generally encompass areas containing more than one or two participants’ homes.
Table 3: Example of output table converted to Database IV file in Microsoft Excel. Note that the Times are erroneous due to an error during the conversion from .txt to .dbf format, which is why the hour of day was included in the table.

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After identifying the most widely used parking lots with the Neighbourhood Analysis tool, each parking lot was examined in greater detail. The first step was to isolate all the parking events that were associated with each lot. To do this, a polygon was digitized around the approximate outline of each parking lot using a high-resolution aerial photograph of the City of Winnipeg. The parking events that intersected each of these polygons were selected and saved as individual spreadsheets (Figure 17). Accurately capturing all the parking events associated with covered parkades required additional steps because the GPS signal was often lost as the vehicle entered the parkade. This would typically cause a number of data points to appear clustered around parkade entrances. The locations of these entrances had to be verified and all the points clustered at the entrances were captured by the polygon and included in the analysis (Figure 18). An additional challenge was that the aerial photograph were not current, and so did not include some of the more recently built parking lots and businesses in the city. To resolve this, if there was a group of parking events located on an area that did not appear to be a parking lot (Figure 19), the area was looked up on Google Earth to see a more current image. Then, if the area was determined to be a parking lot, a polygon was drawn around the cluster of points that appeared to be in the region of the lot and they were included in the next steps of the analysis. The individual analysis of each parking lot was performed using Microsoft Excel. Three variables were derived: 1) variety of use; 2) median parking duration; and 3) ratio of off/on peak electric demand parking.
Figure 15: Map output showing results of a coarse-scale Neighborhood Analysis on the wideness-of-use for parking across the City of Winnipeg.

Figure 16: The coarser-scale Neighborhood Analysis (left) suggests that both the parking lots (indicated by the upper and lower clusters of parking events (dots)) are widely used. However, the finer-scale analysis (right) reveals that only the northernmost parking lot is widely used.
To measure the variety of use of an individual parking lot, the number of unique participants that used the parking lot was counted. Lots with the highest variety of participant usage were considered the most widely used. Variety of use was considered to be more important than frequency of use, because a frequently used parking lot does not increase the likelihood that a PHEV will park there. That is, while a frequently used parking lot may seem like a suitable choice for recharge infrastructure, if the number of people who actually use the parking lot is small, there is a small probability that any of these people will actually own a PHEV, and thus a small probability that the infrastructure will ever be used. Only parking lots used by seven or more participants were included in further analyses.

Figure 17: A polygon outlines a shopping centre parking lot. The points (parking events) that intersected this polygon were selected and separated from the main data set.
Figure 18: Parking events associated with underground parkades such as this were clustered by the parkade entrances. The polygon surrounding the parkade had to capture these points.

Figure 19: Google satellite image of Richardson International Airport (left) and outdated aerial photograph with updated parking lot polygon (right).
The best indicator of average parking duration was determined to be median parking duration, due to the right-skewed nature of the data (Figure 20). A small proportion of parking events had durations exceeding 12 hours in public parking lots, which seems anomalous. The cause of these anomalously long parking events was likely receiver error or very uncommon circumstances. These anomalously long parking events could have been the product of the GPS receiver failing to acquire a signal during an entire trip. When this happens, the data record shows no difference between the parking event and the subsequent trip during which no signal was acquired. Therefore, the parking event appears to continue until the next time the GPS acquires a signal, which tends to be much longer than a typical parking event in a public parking lot. Using the median parking of the mean reduces the impact of these long-duration parking events on the results.

Off-peak electric demand parking is more desirable for utilities servicing PHEV re-charging infrastructure. This is because recharging a large number of PHEVs during on-peak electric demand hours has the potential to drain more power than available, which can lead to power outages. A crude measure of a parking lot’s compatibility with this need is the off:on peak electric demand ratio, that is, the ratio of parking events beginning during off-peak demand to the number of parking events beginning during on-peak times. Parking lots with large off:on peak demand ratios ranked higher than parking lots with small off:on ratios. Manitoba Hydro (2006), Manitoba’s electric supplier, defines on-peak electric demand as the hours between 6am and 10pm, Monday through Saturday, during the months of January, February, June, July, August, and December. All other times are considered off-peak.
Figure 20: Histogram showing frequency and cumulative percentage of parking event durations for the Grant Park Shopping Centre parking lot. Most of the parking events last less than between 60 and 90 minutes, with the majority (over 90%) lasting under 6 hours. Note the spike in parking events lasting longer than 12 hours, which are likely caused by GPS error.

The three variables derived – number of participants who used the parking lot, median duration of parking, and off:on peak demand ratio – were used to rank the top 40 parking lots from most to least suitable for PHEV-recharge infrastructure. Lots were ranked based on each variable separately, such that the most suitable from each category were identified. Next, each parking lot’s ranks in each of the three categories were added together to determine its overall suitability score:

$$Overall\ Suitability = Rank_{\#\ participants} + Rank_{Duration} + Rank_{Off:On\ peak}$$
Parking lots were ranked according to their overall score with low scores being more desirable than high scores. The results are listed and discussed in the following chapter.
3. RESULTS AND DISCUSSION

The methodology used to assess Winnipeg parking lots yielded four groups of parking lots: 1) the parking lots used by the largest number of people; 2) parking lots with the longest median parking duration; 3) parking lots with the greatest degree of use during off-peak electric demand times, and 4) the most suitable parking lots for PHEV recharging infrastructure. The following section reviews and discusses the characteristics of the top parking lots in each of these categories and provides a critical assessment of the methodology so that future studies may build upon its strengths and weaknesses.

3.1. Parking Lots Used by the Greatest Number of People

The five parking lots used by the largest number of participants were the Polo Park Shopping Centre, Grant Park Shopping Centre, the Forks Market, St. Vital Shopping Centre, and the Richardson International Airport (Figure 21). The shopping centres are among the largest in the city, with the exception of Grant Park, and are located in the central and southern portions of the city. The lack of representation of northern shopping centres is an indication of the sample bias, as there were relatively few drivers from northern Winnipeg households included in the sample. The Forks Market is located near the centre of the city and attracts people from all over the city for food, drink and entertainment. It has both free and for-pay parking facilities, including surface and multi-level parkade parking. The Richardson International Airport also has surface and multi-level parkade parking facilities, but they all cost the same amount of money to use. The other widely-used parking lots are free and entirely surface level parking, with the exception of Polo Park, which has a second level parking lot that is free of charge. All of
the parking lots, except the airport, offer restaurants, businesses and entertainment in the form of movie theatres at the shopping centres or, in the case of the Forks, live music, skating, biking, walking along the river trail, and skateboarding. Perhaps having such a wide range of services is the reason that these locations drew such large numbers of participants.

Figure 21: Parking lots used by the largest number of participants.
3.2. Parking Lots with the Longest Median Parking Duration

The most obvious characteristic of the parking lots with the longest median parking duration is that they are all parkades where drivers are charged a fee to park. The most likely reason for this relationship between long parking duration and parkade use is a lack of alternative options (i.e. no free parking spaces are available for long-term parking within walking distance of the destination) (Figure 22). Closer examination of these parking lots revealed that although they were parked in by several participants they showed signs of being regularly used by at least one participant during working hours. This was evidenced by individual(s) parking several times in the same parking lot (much more frequently than all other individuals who used the parking lot) and these individuals having a relatively constant parking duration typically lasting around 8 hours, which was longer than the average of all other individuals using that parking lot. A number of these parking lots appeared to have several participants who parked during work, but it was impossible to verify this due to data collection inconsistency, such as failure to use the GPS receiver every day and participant drop-outs. When these participants’ data were removed from the parking lots, the median parking durations dropped dramatically, from 475 minutes to 10 minutes in the case of the airport, suggesting that these work-related parking events significantly increased the median parking duration. However, since these parking lots were nevertheless used by a large number of people, it does not seem logical to exclude work-related parking from the analysis. Work-related parking should be expected to occur in parking lots that are suitable for PHEV recharge infrastructure, and has the potential to drastically increase the suitability of a parking lot. One of the problems with this result, however, is that parking lots used by members of our sample
for work-related parking are not necessarily the parking lots used for work-related parking by the majority of Winnipeggers. The sample size is too small to provide an accurate representation of those parkades in the city that are mostly used for work-related parking. Therefore, while it is clear that work-related parking increases a parking lot’s suitability for PHEV recharge infrastructure, it is not clear which parkades in Winnipeg are actually the most suitable.

An alternative reason for parkades having such high median parking durations is that many of these are multi-level parking facilities. When leaving these parkades, the GPS receiver would have been less likely to acquire a signal, causing the receiver to switch off if it fails to acquire a signal after several minutes. When this occurs, the entire trip following the parking event in the parkade is lost from the resulting data set. The observed duration of parking events that precede these ‘lost’ trips is therefore extended until the next time the GPS receiver successfully acquires a satellite signal, which cannot occur until the next time the car is turned on. This may produce parking events lasting several days, and the locations of the start and end of the parking event may be several kilometres apart. Future studies could reduce this error by selecting a GPS receiver with a stronger antenna more likely to acquire satellite signals in multilevel parkades. Removing these parking events from the analysis is an alternative solution, but it is not immediately clear how to accurately remove only the erroneous parking durations from the analysis without potentially removing accurate ones. Supplementing the GPS data with travel diaries is certainly a possible answer, but these are also associated with reliability issues.
3.3. Parking Lot with Highest Off:On Peak Electricity Demand Ratio

The parking lots with the lowest proportion of parking events occurring during peak electric demand hours show few, if any common attributes (Figure 23). They consist of parkades and surface parking lots, free and pay-for-use parking, downtown and suburban locations. Only two of the top five parking lots currently have electrical outlets available in each parking stall, and the businesses and services provided nearby range from a university to a home building supplies centre. Because of this lack of
commonality, it would have been difficult to determine which parking lots were used preferentially during off-peak electric demand times without GPS receivers. Indeed, this result validates the importance of studying parking behaviour to optimize the location of PHEV recharge infrastructure. The parking lot with the highest ratio of off:on peak electric demand parking events was a home building centre in the southern portion of the city. It had more than eight times as many parking events occur during off-peak hours than on-peak, a far greater proportion than the next best parking lot (Figure 23).

Figure 23: Parking lots with highest off:on peak electric demand parking ratios.
3.4. Overall Most Suitable Parking Lots for PHEV Recharging Infrastructure.

As with the parking lots used preferentially during off-peak electric demand times, the overall most suitable parking lots have few common characteristics, and the parking lot that came out on top as was quite a surprise in that it is not commonly perceived as being an important parking lot by Winnipeggers. The overall most suitable parking lot as determined by the suitability index is a large surface parking lot that services three discount clothing and housewares stores and a Chinese buffet restaurant (Figure 24). It ranked in the top ten in each of the three categories of the parking lot suitability index, 

Figure 24: Suitability index values for overall most suitable parking lots.
though not in the top five of any category. Although the top parking lot was unexpected, many of those parking lots that ranked near the top are major parking lots, such as the Forks, the Millennium Library, and the Polo Park Shopping Centre. Nevertheless, the other unexpectedly high-ranking parking lots further reinforce the validity of studying parking behaviour using the methodology herein.

3.5. **Strengths and Weaknesses of Methodology**

This study faced a number of unexpected challenges. Some of these were overcome, while others arose too late in the process or were too time consuming or costly to deal with adequately. A discussion of these challenges and their possible solutions is provided below and recommendations for future studies of this nature are provided that may resolve some of the issues.

Improvements could be made with respect to the sample selection. A larger sample size would have provided a better representation of the population. The sample selection process used – the snowball method – resulted in sample bias towards higher income households concentrated in the southern half of the city, because the snowball originated in the community of the University of Winnipeg. Different sample selection methods could have reduced this bias. However, the bias towards wealthier individuals may be suitable in this instance because of the additional cost of PHEVs, which makes it less likely that PHEV owners will be in a lower income bracket. Future sample selection methods should also include a quality control component whereby participants who fail to meet minimum performance criteria (e.g. consistently maintaining the GPS receiver plugged in with a clear line of sight between it and the sky
when driving and regularly uploading their data) are replaced by new participants as soon as possible.

The GPS receivers used in this study and its parent study were not tested for their performance in the downtown ‘urban canyons’, in multi-level parkades, or for their short cold-start signal acquisition times. High performance in these areas would have reduced the uncertainties associated with parking location and duration in multi-level parkades and downtown parking lots. A more rigorous evaluation of GPS receivers prior to receiver selection would surely improve the accuracy of the results in future studies of this nature.

Hard-wiring the GPS receivers in participants’ vehicles would also have reduced data consistency issues that arose due to poor power connections and participant-related error. Furthermore, testing the GPS receiver in participants’ vehicles prior to their participation could have reduced errors that arose due to vehicle differences. For example power was supplied to the GPS receiver for a period of time after the vehicle was turned off in some vehicles, thus distorting the duration of parking events. Data reliability could also have been bolstered by requiring participants to complete travel diaries in which the purpose of each trip along and its departure and arrival times are recorded.

The parking lot suitability index is not an advanced or widely accepted way of measuring a parking lot’s appropriateness as a PHEV recharge site. The three variables that make up the index (the number of people that use the parking lot, the average parking duration and the ratio of parking events that occur during off- versus on-peak electric demand time) are important to consider when selecting the location for a PHEV recharge site, but they are certainly not the only factors to consider. Nor does it seem
appropriate to weight them equally as factors that influence where PHEV infrastructure should be located. For example, the justification for including the off:on peak electric demand ratio in the index was to compensate for potential power shortages that could result from a large number of PHEVs recharging at one time. This is not likely to be a problem in the near future as the rate of adoption of PHEVs by the general public will likely be slow. Furthermore, since the Province of Manitoba is not short on the supply of electricity – in fact it exports electricity to other jurisdictions, including the northern United States – the likelihood of experiencing a power shortage seems small. Therefore, the off:on peak electric demand ratio may not have deserved as much influence in the suitability index as the other two variables. This may not be the case in other jurisdictions that are subject to higher energy prices or the risk of power shortages, and it may also be more important as the number of PHEVs on the road increases. In future studies, it would be prudent to weight the suitability index variables based on their relative significance at the particular time and place of the study.

It might also have been useful to include additional factors in the assessment, such as who owns the parking lots, because some owners may be more inclined or financially able than others to install recharging infrastructure. Other factors such as whether there is existing electrical infrastructure in place will also affect the results. For example, it may be less expensive to install recharging infrastructure in a parking lot that already has plugs for every parking space. Inclusion of these types of cost-factors in future analyses might make the results more accurately reflect the real-world decision-making processes that govern the installation of this infrastructure.
It would also be useful to assess factors that affect individuals’ day-to-day parking decisions, to more easily predict the most suitable PHEV recharge locations in other cities. The variable costs of parking at different parking lots may be one of these factors. GPS data could be used to examine this relationship but it would be beneficial to supplement GPS data with survey questions about how the cost of parking influences drivers’ parking decisions. For example, researchers could request that participants keep a travel diary that includes descriptions of how much they paid for parking, when applicable. An additional factor that might influence parking decisions is personal safety, which might be related to factors such as lighting conditions, location, or type of parking facility. Well-lit parking lots with security cameras in neighbourhoods perceived as unsafe might be more desirable for drivers concerned for their safety, and these factors may become more important at certain times of day, such as after dark. The threat of vehicle break-ins and theft may also deter motorists from parking in certain parking lots. This too could be studied with the help of surveys or travel diaries.

Seasonal differences in parking habits may also exist. For example, large shopping centres become extremely busy in the weeks before Christmas. Accordingly, their parking lots are very often full or nearly full at that time of the year. Large events such as concerts and sporting events have similar impacts on parking. These temporal changes in parking influence parking behaviour. For one, they increase the demand for parking spaces, and thus increase the demand for PHEV recharge spaces, which might force corresponding increases in the cost of recharging or the number of recharging sites. Additionally, the more distant parking spaces that are rarely used during the year become populated with vehicles. These changes can clearly be seen with GPS data as the number
of parking events in distant parking spaces at large malls increase during the busy shopping season.

Another factor that might be assessed in future studies is the extra distance people are willing to walk from their cars to their destination in exchange for charging their PHEV. Some of the large parking lots in the study cover areas as large as several smaller parking lots in the downtown area. If recharge spaces are only located in one area of a large parking lot, PHEV drivers may be forced to park farther away from their destination than desired. If they are willing to walk this extra distance from their vehicles in large parking lots, they may also be willing to walk an extra distance when downtown to recharge their vehicles. This means that installing recharge infrastructure in one centrally located parking lot downtown could draw people away from otherwise desirable parking lots. Thus, it becomes important to determine how far out of their way people are willing to park to recharge their PHEVs, and to somehow incorporate this into the analysis of suitable parking lots, especially in areas with many small parking lots in close proximity to each other.

An additional problem associated with locating recharge infrastructure is that once the ideal parking lots have been identified, planners must then select how many parking spaces should be equipped with recharge infrastructure, where to distribute these recharge spaces throughout the parking lots, and how to control their use. PHEV recharge stalls could be used to attract customers in the future, but they surely would not be desirable if they were located far away from main entrances. It might also be harmful to prohibit parking in PHEV recharge stalls by non-PHEVs, as this might make non-PHEV drivers feel discriminated. There are already specially designated parking spaces for
people with disabilities and pregnant women. What proportion of these spaces should receive PHEV recharging infrastructure? These planning challenges are not entirely beyond the scope of this kind of study. GPS parking data overlaid on high-resolution aerial photographs clearly show the most commonly used parking spaces within a parking lot (Figure 25). This could be used to help determine the ideal parking spaces for recharge infrastructure based on their popularity.

Future developments will obviously confound the results of this study. As businesses relocate and new buildings are built, the distribution of parking lots changes,

Figure 25: Parking events show preferred parking locations at the Winnipeg airport. Each red mark indicates the location of a single parking event.
and so too will the locations of the most ideal parking lots for PHEV recharging. Since it is not feasible to try to predict future changes in parking behaviour, it may become necessary to periodically re-analyze the parking behaviour of a city’s residents.

Parking behaviour may not be the only relevant area of study related to PHEV recharging. Passive recharging in public parking lots is not the only method of recharging that has been proposed. A different option being given consideration is the construction of battery exchange sites; these are small gas-station-like businesses that replace depleted batteries with fully charged ones for a fee in a matter of minutes. Quick-charge stations are yet another recharge option (Figure 26). These are places where PHEVs plug in to high voltage electric outlets that recharge PHEV batteries much more quickly than standard outlets. These alternatives do not necessarily preclude the need for parking lot charging. In fact, the parking lots identified by the research reported here might well be ideal locations for the quick charging stations. The methodology used in future studies could surely be modified to determine the ideal locations for these types of recharge sites, possibly by basing them on the frequency and distance people travel to fill up at gas stations, since they are so similar to battery exchange sites and quick charge stations.

Figure 26: Quick charging station. Location unknown. (ESB, 2009).
One could also point out that this study did not address on-street parking as an option for recharging. PHEV recharge infrastructure could be located along streets where parking is allowed. However, for a street to be suitable it must be used by a large number of people for long periods of time. However, the majority of widely used street-side parking spaces are located downtown, where parking is limited to one or two hours at most, which is not long enough to recharge a PHEV battery using a standard 120V 15A circuit. Another problem with street-side parking spaces is that they often become no-parking zones during morning and evening rush-hours. Furthermore, the risk of vandalism to charging cables may be higher due to increased pedestrian traffic through these areas, and might deter PHEV drivers from viewing street-side recharge sites as a suitable option. Nevertheless, many cities do have on-street charging facilities, including London, England, thus this kind of infrastructure may well deserve attention in future studies of this nature (ESB, 2009; Figure 27). Some of the clustering algorithms, such as DBScan, might be ideal for quickly identifying the most suitable on-street sites for PHEV recharge infrastructure.

Figure 27: Street charging in London, England. (ESB, 2009).
3.6. Conclusion

It is clear that the widespread adoption of PHEVs would require infrastructure upgrades in most cities to provide recharge opportunities. Studying parking behaviour provides insight into which parking lots would be most suitable for PHEV recharge infrastructure. Winnipeg is an excellent location for a study of this nature. It is medium-sized with a population of just over 700,000, and many of the parking lots already have electrical outlets installed in public parking lots for engine block-heaters in the winter. Additionally, political interest in downtown parking has recently increased in Winnipeg. A parking development group was hired to assess Winnipeg’s downtown parking infrastructure and to provide recommendations about possible improvements. In the autumn of 2009 it concluded that there are too many surface parking lots and not enough parkades, and that existing parkades are aesthetically unpleasing. It recommended establishing minimum design standards for all new parking lots and the provision of financial incentives to parking lot owners to encourage upgrades. Theoretically, this may present an opportunity for the City of Winnipeg to install PHEV recharge infrastructure in newly constructed or renovated parking lots. However, since PHEVs are not yet publicly available for purchase in Canada, it is unlikely that this will happen in the near future. Nevertheless, this study has demonstrated that studying parking behaviour using GPS provides useful information that might not otherwise be apparent. For example, the parking lots that ranked highly in the off:on peak electric demand category showed no common characteristics and the overall most suitable parking lot for PHEV recharge infrastructure would not be considered a major parking lot by most Winnipeggers. Although this study is the first of its kind, it offers valuable lessons that future studies of
parking behaviour and recharge opportunities may build upon. Indeed, additional studies are necessary to adequately represent the parking behaviour in different cities.

Furthermore, studies of this kind are needed to optimize the batteries that are incorporated in PHEVs. This enables the simultaneous reduction in initial cost of PHEVs by allowing for smaller batteries, and maximization of the environmental benefits of PHEVs with minimal investment in infrastructure. These studies should be done in a timely fashion as the number of PHEVs on the road is expected to increase in the near future. Additionally, the benefits of this research are applicable to electric vehicles, which may be of value if electric vehicles become publicly available in the future.
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