Analysis of a Potential Hydrogen Refuelling Network
Using Geographic Information Systems:
A Case Study of the Kitchener Census Metropolitan Area

by

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis provided, including any required final revisions, as accepted by my examiners.

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ABSTRACT

This thesis provides macro-, meso- and micro-level analyses of a potential hydrogen refuelling network with a case study for the Kitchener census metropolitan area in Canada. It provides recommendations on the appropriate number of stations required to meet estimated demand for hydrogen refuelling. Furthermore, scenarios are produced using geographic information systems (GIS) to show possible networks. Micro-level analysis brings in the planning aspect of hydrogen specific zoning codes and the possible impacts of citizen and stakeholder resistances to hydrogen.

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1. INTRODUCTION

1.1 Research Problem and Context

The citizens of many cities, especially those in North America, are largely dependent on private automobiles for transportation. With the spread of suburbanization, cities and people are becoming ever more reliant on the car for transportation. Currently, the vast majority of vehicles on the road are fuelled by fossil fuels. This presents a multitude of problems. The transportation sector accounts for 33% of total carbon emissions in the United States (Melaina, 2003). Within Canada, personal transportation is the second largest source of greenhouse gas (GHG) emissions, behind industry, with the vast majority produced by private vehicles (Poudenx and Merida, 2007). In addition, the transportation sector is one of the most rapidly growing sources of anthropogenic GHG emissions. As such, emission reductions in this sector have the potential to significantly reduce overall GHG emissions. This is of particular interest to national governments as there is increasing pressure to improve air quality and mitigate climate change. Air pollution is responsible for 5,900 deaths annually in Canada alone (Judek et al., 2004). Additionally, many Western countries are dependent on foreign oil. There is a need for energy security as 65% of the global petroleum supply is located within the politically unstable Middle East (Melaina, 2003). Among the solutions to the above problems is the adoption of alternative fuelled vehicles.

Imagine a world where personal transportation vehicles produce zero greenhouse gas emissions. This future may not be far away. As global concerns over air quality, climate change and energy security intensify, there is increasing pressure to develop alternative fuels for use in the transportation sector. The decline of the fossil fuel age is approaching: What type of fuel will replace the current fossil fuel economy? This question is critical to national governments as they

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attempt to maintain competitive advantages in the energy market while addressing climate and air quality concerns. Hydrogen fuel cell vehicles (HFCVs) are an attractive option because they have the potential to produce zero emissions except for water. While this technology is currently more expensive than conventional fossil fuel combustion engines and faces challenges to becoming commercially viable, further research and development will enhance its viability. Hydrogen fuel cell vehicles have the long term potential to reduce GHG emissions (Cuda et al., 2012; Li et al., 2012; Johnson, 2008). If hydrogen is produced from renewable sources such as wind, hydropower or solar energy, true zero emission fuel use can be achieved. Even if fossil fuels are used in the production phase, emission reductions can be achieved when compared to the burning of gasoline in the conventional combustion engine vehicle (Waegel et al., 2006). Canada is well-positioned to be a global supplier of hydrogen due to its wealth of natural resources.

One of the most important issues relating to the use of HFCVs that needs to be addressed is the deployment of hydrogen infrastructure. This is required in order for mass commercialization of HFCVs to occur. The deployment of hydrogen infrastructure is one of the strategic priorities of Canada's Hydrogen Economy Initiative (Government of Canada, 2008). The term infrastructure encompasses the production, delivery, storage and use of hydrogen fuel. This infrastructure is related to the 'chicken-and-egg' problem whereby consumers are reluctant to purchase vehicles without supporting infrastructure, manufacturers will not produce vehicles without a market for them, and fuel providers will not deploy the required infrastructure without vehicles on the road. Research is needed on how the initial hydrogen infrastructure should be deployed to satisfy demand and help overcome this problem (Nicholas, Handy and Sperling, 2004). Analysis of potential hydrogen infrastructure deployment will help with this challenge

and consequently help in meeting long term goals of improved air quality, mitigating climate change and improving energy security.

1.2 Previous Studies

One of the major barriers towards achieving a hydrogen economy is the lack of existing hydrogen infrastructure (Farla et al., 2010; Huétink et al., 2010; Government of Canada, 2008; Agnoluccia, 2007; Joffe et al., 2004; Melaina, 2003). Previous analysis of refuelling infrastructure can be divided into three categories: macro-level, meso-level and micro-level (Nicholas, 2004). Many studies have made macro-level estimations of the total number of refuelling stations sufficient to meet projected demand. These approaches often use the existing gasoline station network as a base for the alternative fuel infrastructure. Findings indicate that a range of 5-25% of the existing gasoline station network is sufficient to meet early demand for alternative fuels (Melaina, 2007; Greene, 1998; Kurani, 1992; Sperling and Kurani, 1987). Meso-level studies aim to develop infrastructure networks through the placement of refuelling stations. This relates to the form that networks may take. Most assume that people tend to refuel near their home or workplace (Greene et al., 2008; Nicholas and Ogden, 2006; Nicholas et al., 2004; Kitamura and Sperling 1986). The literature also reveals that GIS is an effective tool to assess hydrogen infrastructure needs within geographic areas. There have been very few micro-level studies on the exact placement of hydrogen refuelling stations. This is important from a planning perspective as it relates to zoning codes and the potential locations for refuelling infrastructure.

There are several deficiencies within the existing literature that need to be addressed. First, previous studies focused mainly on macro- and meso-level analysis of infrastructure

networks; they do not account for micro-level placement considerations specific to hydrogen. Micro-level considerations are vital because they produce site constraints on where hydrogen infrastructure can be located. They include minimum station area, zoning and safety codes and guidelines for hydrogen infrastructure. Many studies use the existing gasoline network as a base. It is often assumed that gasoline station siting involves zoning, safety codes and standards that are comparable to hydrogen. Thus, micro-level considerations are indirectly taken into account. However, it is important to consider the impacts that hydrogen specific zoning codes may have on a refuelling network.

Secondly, existing studies are focussed within a handful of geographic pockets. Within North America, most of the hydrogen research comes out of California.. As such, future studies outside this pocket will add significantly to the academic knowledge in the field. Canada has the potential to be a major player in a future hydrogen economy; it is internationally known for its expertise in the industry and it is a leader in R&D activities (Government of Canada, 2008). Canadian companies are involved in hydrogen production and demonstration projects worldwide. Furthermore, British Columbia has one of the largest hydrogen fuel cell industry clusters in the world. Canada also took the progressive step of developing a national code of standards in the Canadian Hydrogen Installation Code. Therefore, Canada has great potential in the industry and this research can help facilitate the deployment of hydrogen infrastructure.

Thirdly, most studies do not use socio-economic characteristics, such as income or education, in the demand estimation process. If these factors were included in an assessment, developed infrastructure could be geared towards and encourage potential adopters. Future studies will need to address these gaps to add to the knowledge in the field and facilitate the roll-out of hydrogen infrastructure. This study will address these gaps by providing micro-level

analysis within a non-American study. Furthermore, socio-economic variables will be included within the hydrogen refuelling demand estimation to target potential HFCV adopters.

1.3 Research Objectives

This exploratory study will provide insights on the development of hydrogen refuelling infrastructure by providing macro-, meso- and micro-level analyses. There are very few hydrogen infrastructure studies which encompass all three levels of analysis. This study will shed light on refuelling station roll-out by exploring the number of stations required to meet potential demand and their best locations within the study area. In terms of the planning aspect, the study explores possible impacts of hydrogen specific zoning codes and related restrictions on the refuelling network. While the chicken-and-egg problem of hydrogen development will still exist, this research produces knowledge that may encourage the actual deployment of alternative refuelling infrastructure and the commercialization of hydrogen fuel cell vehicles. Additionally, this study will help expand the knowledge outside of the United States as it presents a case study of Waterloo Region, Canada. It will also inform and educate other Canadian regions on the deployment of hydrogen infrastructure.

The primary objective of this research is to understand options for introducing hydrogen refuelling infrastructure in Waterloo Region, Ontario, Canada. A GIS-based model is used to perform location-allocation analysis and determine potential hydrogen refuelling sites based on the existing gasoline network and estimated hydrogen demand.   Different scenarios are analyzed based on different numbers of hydrogen stations. The outcome is the development of a strategic planning tool and case study results for other communities considering the adoption of

hydrogen technology and infrastructure. This study entails specifying a location-allocation model, exploring scenarios and providing recommendations.

2. THEORETICAL FRAMEWORK

The theoretical framework guides the research of a study. Thus, it is important to understand and consider those theories that apply to one's topic. With respect to location-allocation models and multi-facility problems, theories of interest include location theory, central place theory and choice behaviour theory. Brief overviews of these theories and their applicability to the study are provided below.

First, location theory seeks to understand the spatial organization of activities. In terms of this study, this relates to the questions of: Where should refuelling stations be located and why? It is based on the assumption that firms locate to maximize profits while consumers choose locations to maximize utility. Alfred Weber, a pioneer in this area, purported that industrial locations are based on and can be predicted by minimizing transport and labour costs (Weber and Friedrich, 1929). This idea can be transferred to refuelling stations and other types of facilities. With multi-locational problems, as is the case with service stations, demand considerations must be taken into account. A network of facilities must be implemented to satisfy demand.

Secondly, central place theory also seeks to understand spatial organization but focusses on settlements and the services they provide. This theory uses the concepts of range and threshold of a commodity when determining demand. In terms of refuelling, the range refers to the maximum distance a consumer is willing to travel to refuel. This is important for ensuring adequate refuelling availability. Threshold is the minimum bound, for example population or income, required for the provision of a good or service.

A third significant theory that influences this study is choice behaviour. In relation to service stations, choice behaviour is about understanding where individuals tend to refuel and

why. This knowledge can help determine the service range for an alternative fuel network. Furthermore, it helps one understand what form a refuelling network should take in order to maximize efficiency. However, there have been very few studies on refuelling behaviour. In addition, of the studies that do exist most are focussed upon gasoline refuelling as there are few alternative fuel stations in place. Kitamura and Sperling (1986) explored refuelling attitudes and the importance of fuel availability in terms of alternatively fuelled vehicles (AFVs). This study is significant as they used in-person interviews directly at service stations. Thus, answers are likely to be more accurate, as opposed to phone interviews or mail-back surveys, because consumers described their behaviour while they were in the act of refuelling. Sperling and Kitamura found that locational attributes of refuelling stations and fuel price are the most dominant characteristics that influence which fuel outlet a driver chose to patronize (1986). In their California study, drivers tended to refuel close to their home or workplace. Highway stations were also significant as some consumers tended to refuel on the commute route. Their study also determined that there are two types of drivers; deliberate and ad hoc. Deliberate drivers tend to frequent to same station regularly or search for one that is convenient. On the other hand, ad hoc drivers refuel when they are running low on fuel. As such, ad hoc refuelling behaviour is very unpredictable. One surprising result was that those who adopt AFVs first were not necessarily more tolerant of less fuel availability. This highlights the importance of deploying hydrogen refuelling infrastructure that is not too sparse. Sperling and Kitamura's study provided valuable insights on refuelling behaviour.

In summary, location theory, central place theory and choice behaviour theory are the primary theories influencing studies on hydrogen refuelling infrastructure. They form the basis for the ideas and factors influential in the design and analysis of this infrastructure.

3. LITERATURE REVIEW

After considering the relevant theories, this literature review explores the assumptions, methodologies and findings of past studies related to the research topic. Many studies have addressed the hydrogen 'chicken-and-egg' infrastructural problem. Hydrogen infrastructure refers to the production, delivery, storage and use of the fuel. Hydrogen can be produced from a variety of sources either on-site or at centralized facilities. Safety concerns and social acceptance are aspects to be addressed in terms of delivery, storage and use. Studies on hydrogen refuelling stations can be divided into macro-, meso- and micro-level analyses. These topics are addressed in the section that follows.

3.1 Hydrogen Production Considerations

3.1.1 Type of Feedstock

While hydrogen is the most common element on earth, it is rarely found as a gas and must be extracted from water, hydrocarbons or other substances containing hydrogen. A major infrastructural consideration is the type of feedstock used to produce hydrogen. Feedstock refers to the type of energy source used in the process of producing hydrogen fuel. Potential feedstocks include natural gas, coal, biomass, nuclear, wind, ethanol and water. Hydrogen fuel is often touted as a zero-carbon emitter when used in HFCVs. However, if the feedstock used in the production phase is a fossil fuel, greenhouse gas emissions are created. This is termed 'black' hydrogen as opposed to 'green' hydrogen. Presently, steam methane reforming (SMR) is the dominant path used for the production of hydrogen (Government of Canada, 2008; Waegel et al., 2006; Joffe et al., 2004; Ogden, 1999). As methane, also known as natural gas, is a fossil fuel, carbon capture and sequestration technologies must be used in order to achieve GHG reductions.

Despite this, SMR is an attractive option because it is relatively inexpensive and the existing infrastructure for the extraction and distribution of natural gas is already in place (Waegel et al., 2006; Gielen and Simbolotti, 2005). Additionally, the existing infrastructure is likely sufficient to meet hydrogen demand during the early transitory stage to a hydrogen economy (Waegel et al., 2006). Referring to the Canadian context, the country's wealth of resources allows for the possibility of many different hydrogen production pathways. Several refuelling stations in British Columbia currently use electrolysis to produce hydrogen on-site. This method uses electricity to split hydrogen and oxygen atoms in water. It is currently unclear whether the focus should be on maintaining diverse pathways or specializing in one type of production, such as electrolysis (Government of Canada, 2005). Regardless, the use of fossil fuel feedstocks is likely to continue in the near-term (Consonni and Vigano, 2005; National Academy of Science, 2004; Romm, 2004).

3.1.2 Type of Production Facility

A second major consideration relating to the production of hydrogen fuel is the type of facility used. There is debate over what type of production plants, central or dispersed, are more appropriate for the initial provision of hydrogen infrastructure. Central plants are large-scale and located on the outskirts of urban areas while dispersed production involves smaller plants that produce hydrogen on-site of the refuelling station. Centralized plants have lower initial costs but transportation of hydrogen to refuelling stations is required (Bersani et al., 2009). On the contrary, if the fuel is produced directly at the refuelling station, there are no transport costs. However, this option faces higher installation costs for onsite production and dispensing (Bersani et al., 2009). Joffe et al. (2004) suggest that centralized production is only viable when there is

high demand for hydrogen fuel. Thus, it would be inappropriate for use during the initial

infrastructure deployment stage. According to the Oak Ridge National Laboratory report by

Greene et al. (2008), centralized production options are generally for use with fossil fuel

feedstocks. Fossil fuel feedstocks are likely to be dominant in the near-term but centralized

production plants may be inappropriate for low demand levels.   Therefore, more research is

needed on how hydrogen infrastructure should be rolled out in the early phases.

To summarize, there are many unknowns when it comes to the production of hydrogen.

As it is a developing technology, feedstocks are likely to change over time. However, fossil

fuels may play an important role in producing hydrogen in the near term. It is also unclear

whether centralized or dispersed production will be the dominant facility type.

3.2 Hydrogen Storage and Delivery Considerations

Hydrogen is well-suited for storage because there is very little degradation over time and

additional energy storage is relatively inexpensive (Waegel et al., 2006). However, there are

storage concerns associated with the delivery of fuel, at the refuelling station, and on-board the

HFCV. The main considerations for storing hydrogen relate to safety concerns and user

acceptance.

Hydrogen gas is a highly flammable substance. Thus, there are important safety

considerations relating to its storage and delivery. Centralized production methods have

additional costs due to the need for delivery of hydrogen fuel to refuelling stations. Over long

distances, hydrogen is stored in liquid form in cryogenic tanks. Pipeline transport is also an

option. With short distances and demonstration projects, tube trailers are commonly used

(Government of Canada, 2008). The Canadian Hydrogen Installation Code, implemented in

2007, provides voluntary codes and standards for the use of hydrogen and facilitation of supporting infrastructure. Canada is progressive in this matter as few countries have national standards in place. National codes and standards are important as they build consumer confidence and social acceptance of hydrogen technology, leading to additional infrastructure deployment. However, to date, very few communities have hydrogen specific zoning codes in place.

Hydrogen fuel cell vehicles and relating infrastructure face challenges relating to user acceptance of the technologies and NIMBYism (Farla et al., 2010; Roche et al., 2010; Government of Canada, 2008). This can affect the micro-level placement of individual hydrogen stations. Two examples that help perpetuate negative social attitudes towards the use of hydrogen are the Hindenburg disaster and hydrogen or H-bombs. In the former, flammable metallic paint, not hydrogen, was determined to be the cause of the fire that engulfed the airship in 1937 (Roche et al., 2010; Nicholas, 2004). In the latter, the explosive power of a hydrogen bomb is actually caused by fusion reactions, not the flammability of hydrogen (Nicholas, 2004). Thus, hydrogen's poor public image is unjustified. The introductory phase of a new technology is vital to building public support and alleviating safety concerns; despite progress in fighting hydrogen stigma, even a small accident could affect the uptake of a technology disproportionately (Slovic et al., 1987).

Problems with social acceptance are also tied to NIMBYism behaviour with respect to hydrogen refuelling stations. One such example of local resistance to hydrogen infrastructure is the case of London, England. The city began its hydrogen demonstration project in 2003 as part of the Clean Urban Transport for Europe (CUTE) plan. Local-level resistance was experienced after the decision by BP to build a publicly accessible hydrogen refuelling station adjacent to an

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existing gasoline station in Essex (Eames et al., 2006). This resistance occurred despite approval

from the Health and Safety Executive, consent for hazardous substances and a favourable report

by a third-party safety consultant (Eames et al., 2006). Demonstration projects, occurring

globally, are a popular method used to increase public awareness and education of the benefits of

hydrogen technology. Demonstrating compatibility, whereby consumers do not have to change

behaviour from the use, maintenance, and fuel availability of conventional combustion engine

vehicles, is a significant factor to attracting consumers (Huétink, 2010; O'Garra et al., 2005;

Rogers, 2003; Bunch et al., 1993). Thus, social acceptance of hydrogen technology influences

adoption and can produce constraints on infrastructure siting.

3.3 Hydrogen Refuelling Stations

Strategies to address the 'chicken-and-egg' problem, referring to hydrogen refuelling

stations, can be divided into three categories: macro-level, meso-level, and micro-level. Macro-

level analysis refers to estimations of the number of refuelling stations recommended for a

specific area. Meso-level analysis involves the locations of stations within a network while

micro-level analysis relates to individual site evaluation (Nicholas, 2004). There are very few

micro-level based studies on the siting of individual stations. This is related to the lack of

hydrogen specific zoning codes and the lack of experience and standards for siting hydrogen

facilities. Additionally, micro-level constraints vary between regions, such as the case with

zoning. This section addresses each level of analysis separately.

3.3.1 Macro-level Studies

Macro-level analysis of hydrogen infrastructure estimates the number of refuelling stations required to satisfy demand within a certain area. Numerous studies on hydrogen refuelling networks are based on the existing gasoline station network (Huétink et al., 2010; Bersani et al., 2009; Nicholas, 2004; Kurani et al., 2003; Sperling and Kurani, 1987; Kitamura and Sperling, 1986). The gasoline network is commonly used as a base because of past experience, consumer familiarity and it is a highly developed network. In addition, hydrogen is likely to be produced with fossil fuels in the near-term. As such, petroleum companies can benefit from the involvement with hydrogen vehicles and infrastructure (Bersani et al., 2009).

Many studies based on urban and metropolitan areas recommend a percent of existing gasoline stations needed to meet estimated demand for hydrogen refuelling. Studies suggest that a relatively small portion of the existing gasoline network may be sufficient to satisfy demand for a hydrogen vehicle market. For example, studies on gasoline and diesel car owners estimated that successful market penetration would likely occur if 15% of existing stations offered diesel fuel (Sperling and Kurani, 1987; Sperling and Kitamura, 1986). Greene's findings were similar, estimating that 20% of existing petrol stations are required to satisfy alternative fuel availability based on a survey of American households (1998). Stephens-Romero et al. (2010) estimated that only eight hydrogen stations, or 23.5% of the existing gasoline stations, are required to provide adequate service in the City of Irvine, California. However, macro-level analysis methods generally do not take into account the unique characteristics of a region's transportation system, such as population type and dynamics and driving intensities.

It is important to note that a select few studies question whether existing stations are appropriate for on-site hydrogen production and refuelling. For example, Greene et al. (2008)

examined 120 existing gasoline stations and determined that only 20 were suitable for on-site steam methane reforming of hydrogen. Additionally, many studies ignore the economics of alternative fuel provision. There is a high cost associated with converting existing stations to dispense hydrogen fuel. For example, Wang et al. (1998) calculated that the conversion would cost $1.4 million US to dispense 50,000 gallons of gasoline equivalent per month. Thus, some studies suggest that relatively few existing gasoline stations are suitable for joint dispensing of gasoline and hydrogen and that conversion is expensive. Despite this concern, most studies assume the current gasoline network will be related to a future hydrogen network.

Three macro-level approaches were developed by Marc Melaina (2003) and focus on the United States: these approaches are based on 1) percent of existing stations, 2) metropolitan land area and 3) principal arterial roads. Melaina's first method estimates the percentage of existing gasoline stations required to maintain fuel availability for the alternative fuel market. Melaina's second approach, based on metropolitan land area, attempts to estimate the number of refuelling stations required such that consumers are located within a specific distance of one. Driving times can also be used instead of absolute distances to represent proximity and convenience to a refuelling station (Nicholas et al., 2006). The third approach, purported by Melaina (2003), is based on principal arterial roads and takes into account the unique population and driving intensities of a region. Using data from the National Highway Classification System, this method identified appropriate road intervals to place stations on both rural and urban roads. These studies aim to determine the appropriate range, a component of central place theory, for hydrogen stations. Unlike meso-level analysis, macro-level studies tend to not account for consumer refuelling behaviour that contributes to the efficiency of network form.

The review above demonstrates that many studies on the sufficient number of refuelling stations required to meet demand are based on subsets of the existing gasoline network. Many studies suggest that only a relatively small percentage of existing stations would be appropriate for an early hydrogen refuelling network. Macro-level studies are useful for estimating the number of stations required to meet estimated hydrogen refuelling demand. However, the majority do not take into account the unique transportation network characteristics of regions and driving behaviour. Additionally, few studies have tested the economic feasibility of implementing the suggested number of refuelling stations.

3.3.2 Meso-level Studies

Meso-level analysis refers to the overall form a hydrogen network may take. These studies are often accompanied by macro-level station number estimates for the study areas. Some candidate locations may be better suited than others for satisfying or capturing a large portion of estimated demand. The majority of studies use scenario modelling to test the impacts that different levels of infrastructure deployment have on refuelling availability or meeting demand. The ultimate form a refuelling network takes is influenced by driving and refuelling characteristics as well as demographic and socio-economic characteristics of the population. These influences contribute to hydrogen refuelling demand and are discussed below.

3.3.2.1 Factors Contributing to Hydrogen Demand

Driving and Refuelling Characteristics

Choice behaviour studies reveal where and when consumers are likely to refuel. This influences the form a potential hydrogen refuelling network would take. Most studies on

alternative refuelling assume that people tend to refuel near their home or workplace (Greene et al., 2008; Nicholas and Ogden, 2006; Nicholas et al., 2004; Kitamura and Sperling 1986). Refuelling also frequently occurs during commute trips (Melaina, 2003; Kitamura and Sperling, 1986). Proximity to high traffic volumes is another attractive factor for station siting (Nicholas, 2004; Melaina, 2003). Therefore, both metropolitan and highway locations are important. Place of work and place of residence data can be useful in determining locations for refuelling stations. Origin and destination trip data are also commonly utilized.

A study by Nicholas et al. (2004) used origin-destination data during peak commuting time, when the origins and destinations are primarily work and home, and analyzed driving times for a specified number of hydrogen refuelling stations. The objective was to develop a hydrogen refuelling network, based on a subset of the existing gasoline network, such that driving time to the nearest station was similar to the current gasoline refuelling station. Scenarios were created based on different numbers of refuelling stations as subsets of the existing gasoline network. Demographic data was not included but could be scaled into the model to target HFCV buyers.

Many studies demonstrate the importance of infrastructure accessibility when creating a hydrogen refuelling network (Huétink et al., 2010; Meyer and Winebrake, 2009; Potoglou and Kanaroglou, 2007; Bunch et al., 1993). In one of the earliest refuelling behaviour surveys conducted, Kitamura and Sperling determined accessibility to be a major factor in the decision to refuel (1986). Winebrake and Farrell put forth the idea of "convenience costs" with respect to complimentary goods such as refuelling infrastructure and vehicles (2007). Consumers expect the availability of hydrogen or alternative infrastructure to be similar to that of the existing gasoline network. The low availability of hydrogen infrastructure acts as a barrier and the inconvenience may discourage adoption. Rogers (2003) also purports this idea in his model of

adoption decisions of consumers. These studies suggest that a lack of refuelling availability may affect consumer adoption rates. Thus, the number of hydrogen stations deployed influences the level of HFCV adoption. Several studies use drive time analyses to compare the availability of the existing gasoline network to the proposed hydrogen network (Lin et al., 2008; Nicholas, 2004; Nicholas, Handy and Sperling, 2004).

Demographic and Socio-Economic Characteristics

Population demand characteristics can be used to target hydrogen infrastructure to areas likely to have HFCV users. For example, Potoglou and Kanaroglou (2007) surveyed 426 people in Hamilton, Canada to determine the factors most likely to affect households' decisions to drive cleaner vehicles. Their results showed that age, education and household size and type were important characteristics. They determined that people under age 45, those with a bachelor's degree, as well as those without a long distance commute were more likely to purchase a hybrid electric or alternatively fuelled vehicle. In addition, high income areas are likely to adopt cleaner technology first as purchase price is less of a barrier. Nicholas (2004) also determined high income levels to be indicators of possible early hydrogen fuel cell buyers. Furthermore, Melendez and Milbrandt (2007) identified high demand areas through literature reviews and interviews with experts. They concluded that households with two or more vehicles, education and household income were among key demographic attributes of high demand areas.

Studies on AFV demand can suggest where early refuelling stations should be located in order to maximize demand. However, most studies fail to incorporate socio-economic demand characteristics, usually claiming it is unclear which contribute to hydrogen demand. More recent studies have included demographic and socio-economic characteristics in the estimation of

hydrogen refuelling demand. This produces a refuelling network that targets potential HFCV buyers. For example, Kuby et al. (2009) weighted demand in terms of income, education, number of household vehicles and workers who commute greater than twenty minutes.

3.3.2.2 Meso-Level Models

GIS-based models are commonly used to explore the spatial arrangement of facilities within a network required to meet a given level of demand. Location and central place theories guide this research as they aim to find an optimum spatial distribution of refuelling stations. The models select a set of locations based on maximizing the demand that is allocated to them. By understanding choice behaviour, in terms of where consumers are likely to refuel, demand factors are created that influence the level of hydrogen demand. In terms of refuelling stations, two methods commonly used to generate hydrogen refuelling networks are flow-based and point-based models. After considering these models, issues relating to the scale of network analysis are discussed.

Flow-Based Models

Demand for refuelling centres can be modelled as flow-type or fixed point. This is what differentiates flow models from p-median models. The Flow-Capturing Location Model (FCLM) and Flow-Intercepting Location Model (FILM) were developed in the 1990s to represent demand that is path-based. That is, instead of using points as demand inputs, data represents the routes or paths people travel through the network (Nicholas, 2010; Upchurch and Kuby, 2010; Kuby et al., 2009; Lin et al., 2008). As such, infrastructure is located to intercept as many trips as possible from passing traffic flows. For example, traffic flow indicators such as

vehicular kilometres travelled, or VKT, are typically used in flow-based models to site refuelling stations. Flow-based models can be used to model demand based on the number of potential consumers passing a refuelling station. It is argued by some that flow-based models better represent consumer behaviour because they are well-suited for use when consumers stop to refuel on their way to drive someplace else, as opposed to refuelling near the workplace or home (Upchurch and Kuby, 2010; Lin et al., 2008; Berman et al., 1992). For example, Lin et al. created a fuel-travel-back approach based on vehicle miles travelled to develop a hydrogen refuelling network (2008). However, the majority of studies use point-based demand models. As such, this study also uses a point-based model, in part to enhance the comparability of results.

Point-Based Demand Models

In the 1960's, the p-median model was formulated by Hakimi as the solution to the multi-location problem. This is one of the most popular models for siting alternative fuel stations (Lin et al., 2008; Greene et al., 2008; Nicholas and Ogden, 2006; Nicholas, 2004; Goodchild and Noronha, 1987; Sperling and Kitamura, 1987). Rooted in location theory, this model attempts to optimize retail locations so that distance to the consumer is minimized or demand is maximized. As such, given a specific number of facilities, or *p* number of facilities, the optimum network can be determined. Numerous studies used GIS and the p-median idea to develop potential hydrogen refuelling networks (Stephens-Romero et al., 2010; Bersani et al., 2009; Kuby et al., 2009; Nicholas et al., 2004). As opposed to flow-based modelling, p-median based models reflect demand as nodes or points. This model is frequently utilized under the assumption that consumers are most likely to patronize a refuelling station near their workplace or home. Most studies on hydrogen refuelling networks hold this assumption (Greene et al., 2008; Nicholas and

Ogden, 2006; Nicholas et al., 2004; Kitamura and Sperling 1986). As a result, refuelling stations tend to be clustered as opposed to randomly distributed. As there is a limit on how far consumers will travel to a refuelling station, a maximum covering model or drive time impedance factor can be utilized to account for this. Melaina's use of station densities to represent a certain area of metropolitan land, with the aim that most residents are located within close proximity to a refuelling station is one such example (2003). This type of model is based on the p-median problem idea. It maximizes the number of consumers within a certain distance of a refuelling station. Different population demand factors, developed from choice behaviour studies, can also be used to locate facilities within a refuelling network.

Essentially, point and flow-based models are two methods used to site alternative fuel networks. They are based on different assumptions about refuelling behaviour. The p-median model assumes individuals tend to refuel close to their home or workplace and uses demand points or nodes. On the other hand, flow-based models use traffic data such as VKT and assume people tend to refuel on their way to someplace else. To date, the p-median model has been the most commonly employed method used to explore hydrogen refuelling infrastructure.

3.3.2.3 Scale of Infrastructure Deployment

There is debate over the effectiveness of infrastructure deployment at national or regional scales versus urban centre scales. Greene et al. (2008) developed infrastructure deployment scenarios based on the 'urban centre concept.' This involved phased introduction to create a refuelling network servicing 20 major urban centres in the United States. However, other studies prefer a national deployment strategy over an urban one as this maximizes geographic coverage (Huétink et al., 2010).

The regional level is becoming increasingly important for providing favourable conditions for the innovation and adoption of new technology (Madsen and Andersen, 2010; Lundvall and Borrás, 1999). Many commitments to achieving hydrogen communities are at the regional level. The Western Isles Hydrogen Community Plans (United Kingdom), North-Rhine-Westphalia (Germany) and Hydrogen Highway (Canada) are some examples of such regional plans. In fact, regional authorities are the most important actor in registering hydrogen communities in the European Roads2Hycom project (Madsen and Andersen, 2010). Thus, regions play a significant role in embracing and encouraging the adoption and diffusion of new technologies.

3.3.3 Micro-Level Considerations

Micro-level analysis of refuelling networks refers to individual station siting. This is affected by safety codes, user acceptance and local/regional constraints. Issues surrounding hydrogen safety and user acceptance may influence and constrain where refuelling stations are sited. The Canadian Hydrogen Installation Code (CHIC) provides installation requirements for equipment relating to hydrogen infrastructure. These guidelines are in place to ensure the safe installation of hydrogen equipment. It proved useful for the approval and installation of hydrogen refuelling stations in British Columbia. However, hydrogen specific zoning codes are also required to guide the placement of individual hydrogen refuelling stations. Very few studies of micro-level considerations exist as few regions have hydrogen zoning constraints or by-laws in place to guide the individual placement of stations. In addition, most studies are based on the existing gasoline network and indirectly include micro-level considerations. Demonstrations on the impacts of potential hydrogen specific zoning codes would be valuable.

4. METHODOLOGY:

In summary, the literature reveals three main approaches to the study of hydrogen refuelling infrastructure: macro-, meso- and micro-level. This research incorporates all levels of analysis to some degree. First, macro-level analysis includes the recommendation of the appropriate number of refuelling stations needed to meet estimated demand. The location-allocation model in this research provides the macro-level analysis. It is used to explore network forms and scenarios based on different numbers of hydrogen refuelling stations. The meso-level analysis assesses the network of refuelling stations at a regional level, focussing on the spatial dimensions and reflected in the local demand and travel time analyses in this work.. Finally, micro-level analysis demonstrates the influence of site specific constraints such as zoning codes or citizen resistance to hydrogen projects. A restricted areas scenario is employed in the location-allocation model to explore these concerns. The approach used at all levels of analysis is to develop hydrogen refuelling infrastructure based on the existing gasoline network. As such, some site specific constraints are indirectly included with the siting of existing gasoline stations. However, the micro-level analysis in this study provides an example of unique insights that are absent from most studies. In this research, the focus is on refuelling and therefore the production, storage and delivery considerations for hydrogen will be ignored.

In addition to the gap in hydrogen specific micro-level assessments, most studies fail to include socio-economic factors in their estimations of hydrogen refuelling demand. However, demand studies suggest that socio-economic characteristics of the population are an obvious influence on demand. Thus, they are important to include in the representation of demand. Targeting people likely to adopt HFCVs can help facilitate adoption. This study addresses this gap by including income and education into the estimation of refuelling demand.

The literature review also shows that many studies use point-based demand within GIS-based models. These models are generally p-median models or variations of it. As such, distance decay is an important factor in many models. Furthermore, the main assumption of these models is that people tend to refuel near their home or workplace. This study uses a GIS-based location-allocation model, with demand represented by census tract centroids, to estimate demand and allocate it to potential hydrogen refuelling stations.

Numerous studies also suggest that infrastructure availability is important to consider when developing a hydrogen refuelling network. This is a key factor in facilitating adoption of HFCVs. Drive time analyses are commonly used to represent infrastructure availability differences between the existing gasoline network and proposed hydrogen networks. This study will use this common type of analysis to make macro-level recommendations.

4.1 Study Area:

The study area is the Kitchener census metropolitan area (CMA). This includes the cities of Kitchener, Waterloo and Cambridge as well as the townships of Woolwich and North Dumfries. However, it excludes the western townships of Wellesley and Wilmot that are part of the Regional Municipality of Waterloo but not the CMA. The Kitchener CMA was chosen for the study due to data availability and the possibility of hydrogen technology being introduced in the region. It is of similar scale to regional studies that are common in recent literature which enhances the comparability of results. The study area is home to internationally renowned universities and colleges and is part of southern Ontario's 'technology triangle'; it is a hotbed of innovation. This makes it an attractive choice for the introduction of hydrogen technology. The

Kitchener CMA (Figure 1) consists of 93 census tracts that provide the foundation for hydrogen demand modelling.

The model selects locations for hydrogen facilities based on the existing gas station locations in the Kitchener CMA. In total there are 94 gasoline stations within the study area. However, only non-independent gas stations are used in this study which reduces the number of facilities to 74. These stations are shown in Figure 1. Non-independent stations are used because during the introductory phase of hydrogen technology, it is more likely that major gasoline retailers would provide hydrogen options for consumers. This is the trend for many current stations; major gasoline companies are partners in hydrogen projects globally.
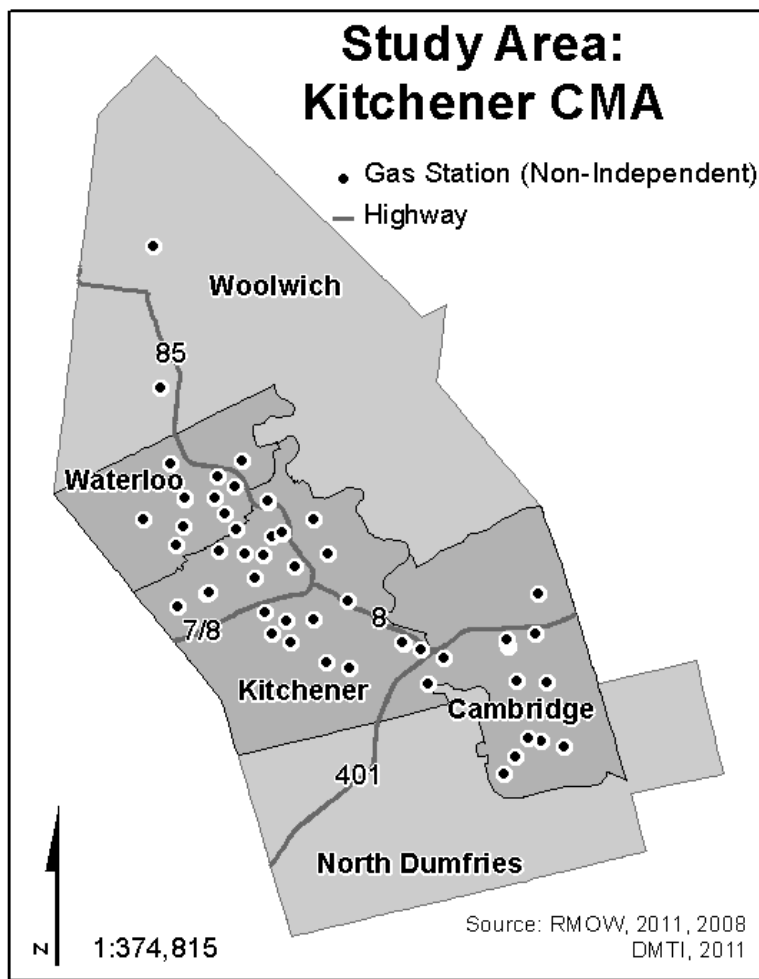

Figure 1. Study Area.

4.2 The Model:

4.2.1 Location Allocation

The study uses a location-allocation model within a GIS to explore what a potential hydrogen network might look like for the Kitchener CMA. Specifically, the maximize attendance problem type within location-allocation analysis is used. A description of this problem type is provided in Appendix A. Demand is represented by demographic and socio-economic variables. These are combined to create a total effective demand for each census tract. This is the main input for the model, in addition to candidate sites based on the existing gasoline network. It is similar to the p-median problem but takes into account both demand and distance in the selection of hydrogen stations. The model selects hydrogen facilities while simultaneously allocating demand to them.

The literature suggests that infrastructure availability influences the adoption of alternative-fuelled vehicles. Furthermore, greater distances from a hydrogen refuelling station are argued to deter possible consumers from adopting a hydrogen vehicle. Thus, a drive time impedance cut-off and distance transformation is used to capture their respective influences. A drive time impedance cut-off of five minutes is used. This means that any demand (linked to the centroid of a census tract) beyond a five minute drive time of a selected station is not included. The cut-off can be increased or decreased to reflect the drive time that hydrogen adopters are likely to deem acceptable. The model captures as much total demand as possible while incorporating the fact that demand decreases moderately with distance. The impedance transformation and parameter reflect the rate at which demand decay occurs with increasing distance from a station. This model uses a power transformation with a parameter of 0.25 which results in relatively gentle rates of decay as distance increases. The parameter can be increased

or decreased to reflect a more rapid or gentle rate of decay of demand allocated respectively. The distance decay function is provided in Appendix B. A mock up is provided in Figure 2 to further explain how the location-allocation model and effect of distance decay work.
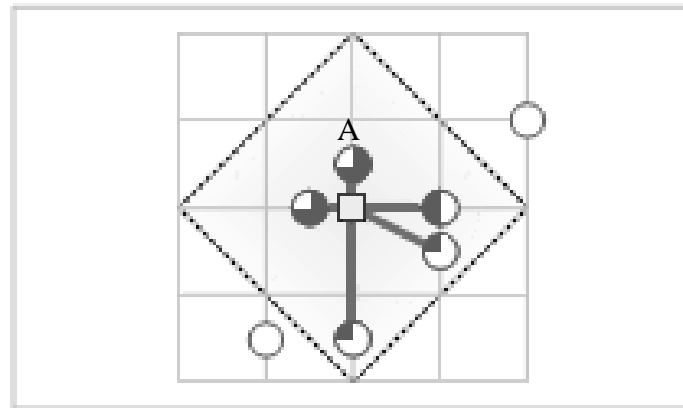
Figure 2. A mock up of the location-allocation model and the influence of the distance decay function. (Source: ArcGIS Resource Center, 2012)

In Figure 2, the central square represents a selected hydrogen station and the circles represent demand points. In this study, the demand points are census tract centroids. As such, distance decay is calculated from a station to the centroid, not to the edge of the census tract itself. The pie charts reflect the percent of demand allocated to the station which depends on the distance decay function. The demand points near the station get a larger portion of their demand allocated. For example, assume that demand point A has a total demand value of 1000 hydrogen vehicles from the estimation of refuelling demand. The distance decay function assigns a portion of these vehicles based on the distance of the demand from the selected station. In this case, the demand is located relatively close and three quarters of the demand is ultimately assigned. Therefore, 750 vehicles are HFCVs as opposed to the total estimation of 1000. The further the demand point is from the station the less demand is allocated. The mock up also shows the five minute impedance cut-off which is reflected by the dotted line. Demand points located beyond this limit are not included in the demand allocation.

4.2.2 Assumptions

There are four main assumptions, supported by the literature, that provide the foundation for the study:

1. People tend to refuel near their home or workplace.

2. The existing gasoline network is related to a future hydrogen network.

3. Consumers will continue to refuel at public, as opposed to private, refuelling stations.

4. There is no fuel supply limit at each station.

The assumptions made influence the type of data used in the model. They are relatively easy to change within the model if the current trends change.

4.2.3 Data Used

The data used in the study are from regional and national sources. The street network is from the Regional Municipality of Waterloo (RMOW, 2011). The gasoline network is from the national 'points of interest' database provided by DMTI Spatial (2011). The representation of demand, encompassing private household numbers, education levels and average household income, is based on Statistics Canada census data from 2006. Employment destinations are another element of demand and are from 2006 Canadian census custom tabulations. They are based on commuting flows at the census tract level and reflect the number of people driving to work by a private automobile. The model is flexible and has the potential to incorporate or remove demand factors as desired. The scenario reflecting possible restricted areas for hydrogen, including station proximity to schools and medical centres, also uses the regional data (RMOW, 2011).

4.3 Representation of Demand:

The first step in creating the model is to represent the demand for hydrogen refuelling. This study uses demographic and socio-economic data to estimate demand. The literature review shows that these factors are being incorporated in more recent studies on alternative infrastructure. The four components of demand used in the model are: number of private households, employment destinations, average household income and education level. This data is used at the census tract level and is mapped in Figure 3. The first two components, number of private households and employment destinations, represent the assumption that people tend to refuel near their home or workplace, as suggested by the literature. Private households are used, as opposed to population data, as the decision to purchase a hydrogen vehicle is made at the household level. Employment destinations are the number of people driving to each census tract for work by private automobile. The average household income and education level represent socio-economic variables that influence demand. The literature shows that consumers with higher incomes and/or higher education levels are more likely to purchase an alternatively fuelled vehicle. Average household income is used to be consistent with the use of private household data. Education level is represented by using the number of persons with a university certificate, diploma or degree.

The four components of hydrogen demand are combined using the following equation to create a total demand map.

$$D_t = (H + E) * [0.5 \left(\frac{I}{\max I}\right) + 0.5 \left(\frac{U}{\max U}\right)]$$

Where:

D_t is the total demand estimated

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H is the number of private households
E is the number of employment destinations
I is average household income
U is the number of people with a university certificate, diploma or degree

This represents the total effective demand, or number of hydrogen vehicles, per census tract. First, the number of private households and employment destinations per census tract were summed together. Secondly, the two socio-economic factors, average household income and education level, were incorporated into a simple multi-criteria evaluation that resulted in suitability scores for each census tract. This process involved converting the income and education data to rasters. A raster calculator was used to add the two socio-economic factors together, equally weighted, and convert to suitability scores from 0 to1. Lastly, the suitability score, or raster value, was multiplied by the sum of private households and employment destinations for each census tract. The end result was a total demand map showing the combined demand that represents the number of hydrogen vehicles by census tract. Table 1 shows several examples of the figures used for the total demand calculation.

Census Tract ID	Sum of Number of Households and Employment Destinations	Average Household Income ($)	Number of Persons with a University Certificate, Diploma or Degree	Raster Value (0 to 1)	Total Demand
541000208	9255	83718	2050	0.47915	4435
541001405	2345	108222	1160	0.43007	1009
541012609	1285	61968	200	0.18727	241
541002500	2580	191428	525	0.56671	1462

Table 1. Components used in the Calculation of Total Demand.

The total demand map is displayed in Figure 4. It shows that there is high demand in northwestern Waterloo which corresponds to a high number of households, high incomes and

high education levels. Northeastern Waterloo also shows a high level of demand due to large numbers of employment destinations, high incomes and high education levels. In terms of Kitchener, the southwestern area shows high numbers of households and employment destinations as well as high education levels, resulting in a high overall demand for hydrogen. Much of Cambridge is classified by the two lower categories of hydrogen demand except for a pocket of high demand in the east of the city. In general, Cambridge consists of census tracts with lower levels of household numbers, lower incomes and lower education levels. Furthermore, no areas fall within the highest education category. However, the northern and eastern census tracts display high numbers of employment destinations.

At the metropolitan level, the total demand map shows that high demand areas are in suburban locations. Consequently, the urban cores show low levels of hydrogen demand. This is explained by relatively low income and low education levels of those living within core census tracts. Additionally, many employment areas are decentralized away from the core areas. The total demand map reveals the spatial patterns of hydrogen demand that influence the selection of refuelling stations by the model.
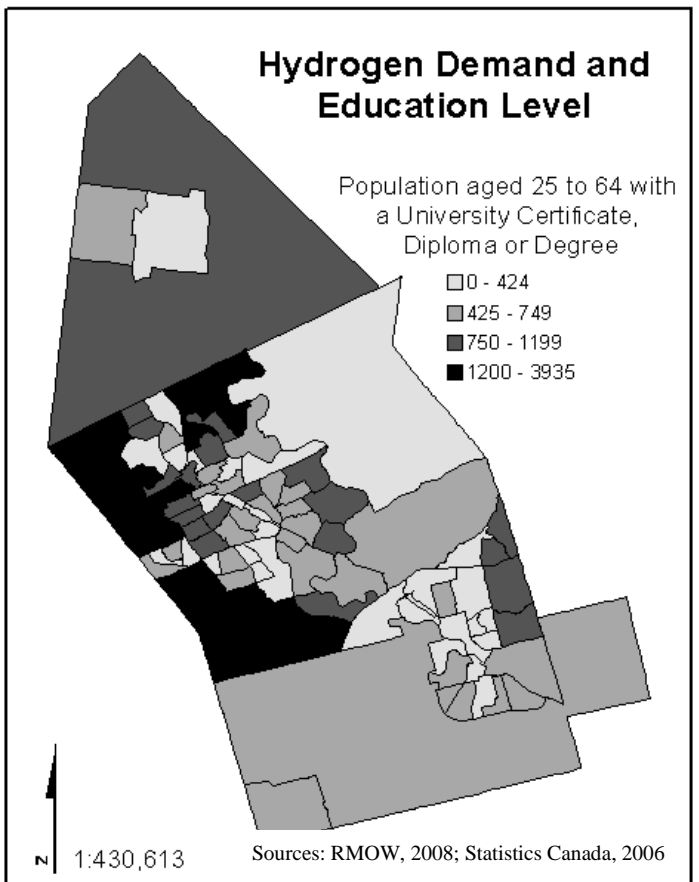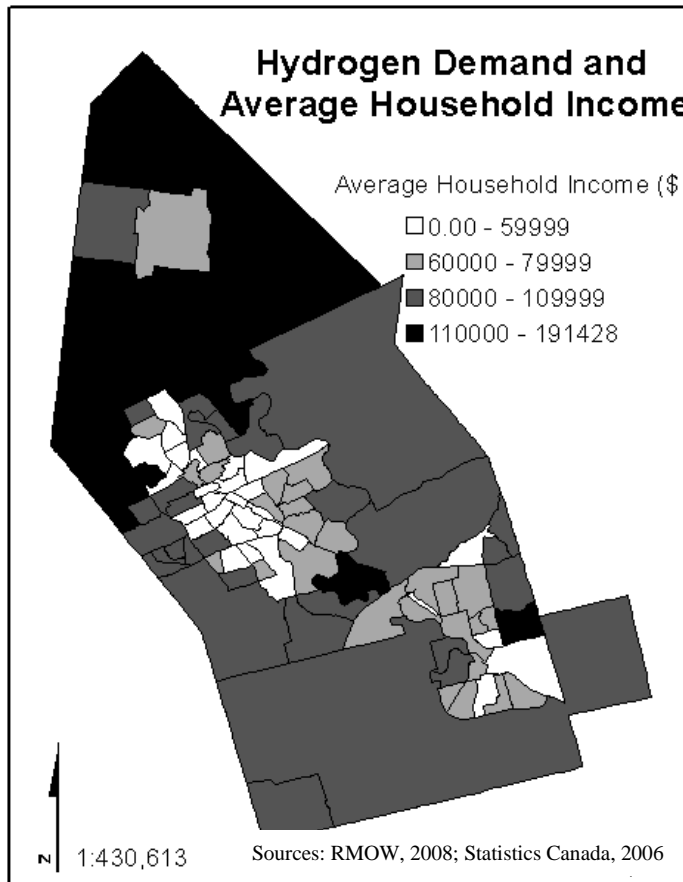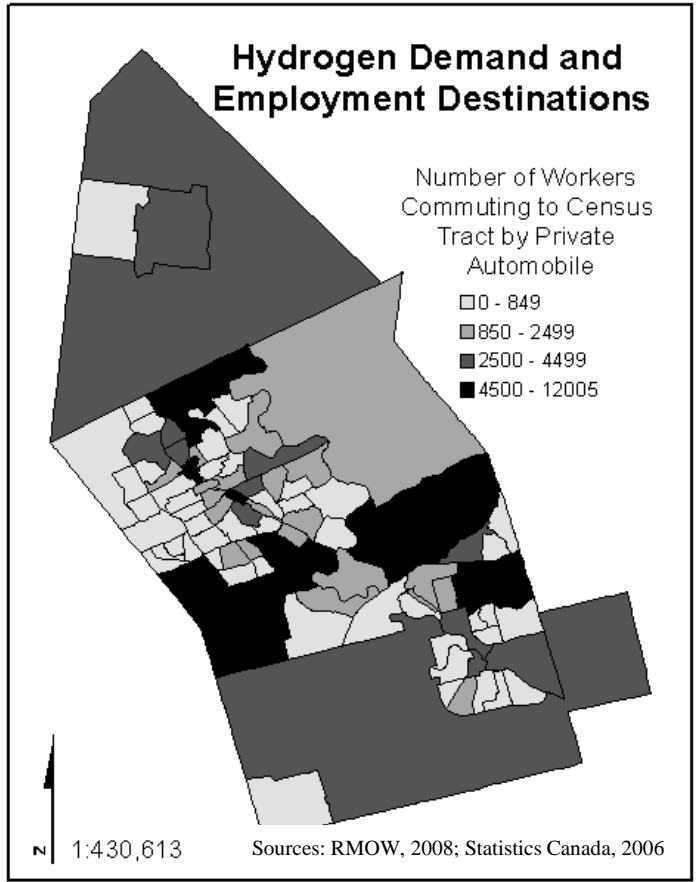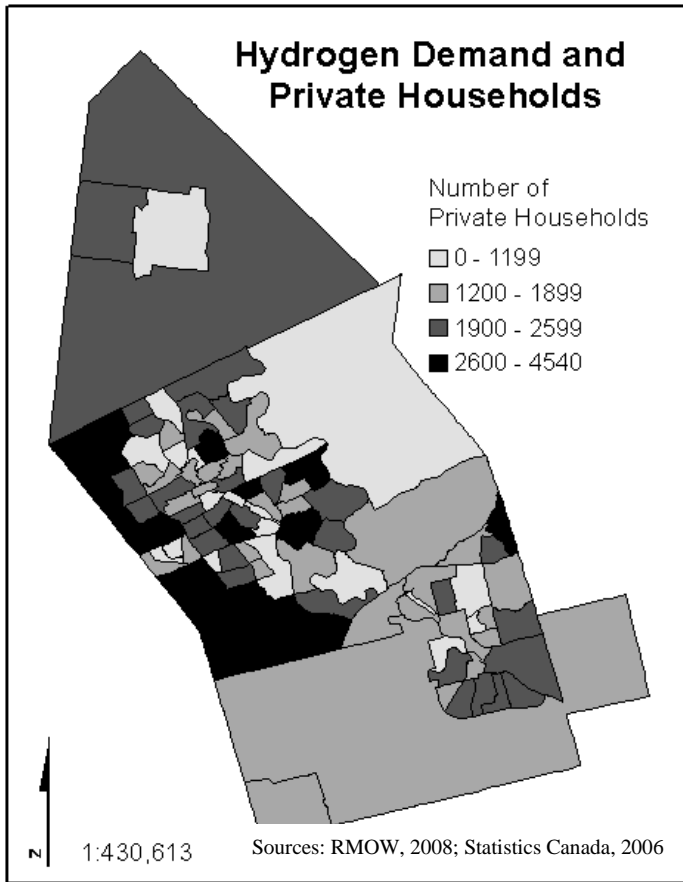
Figure 3. The Components of Demand.

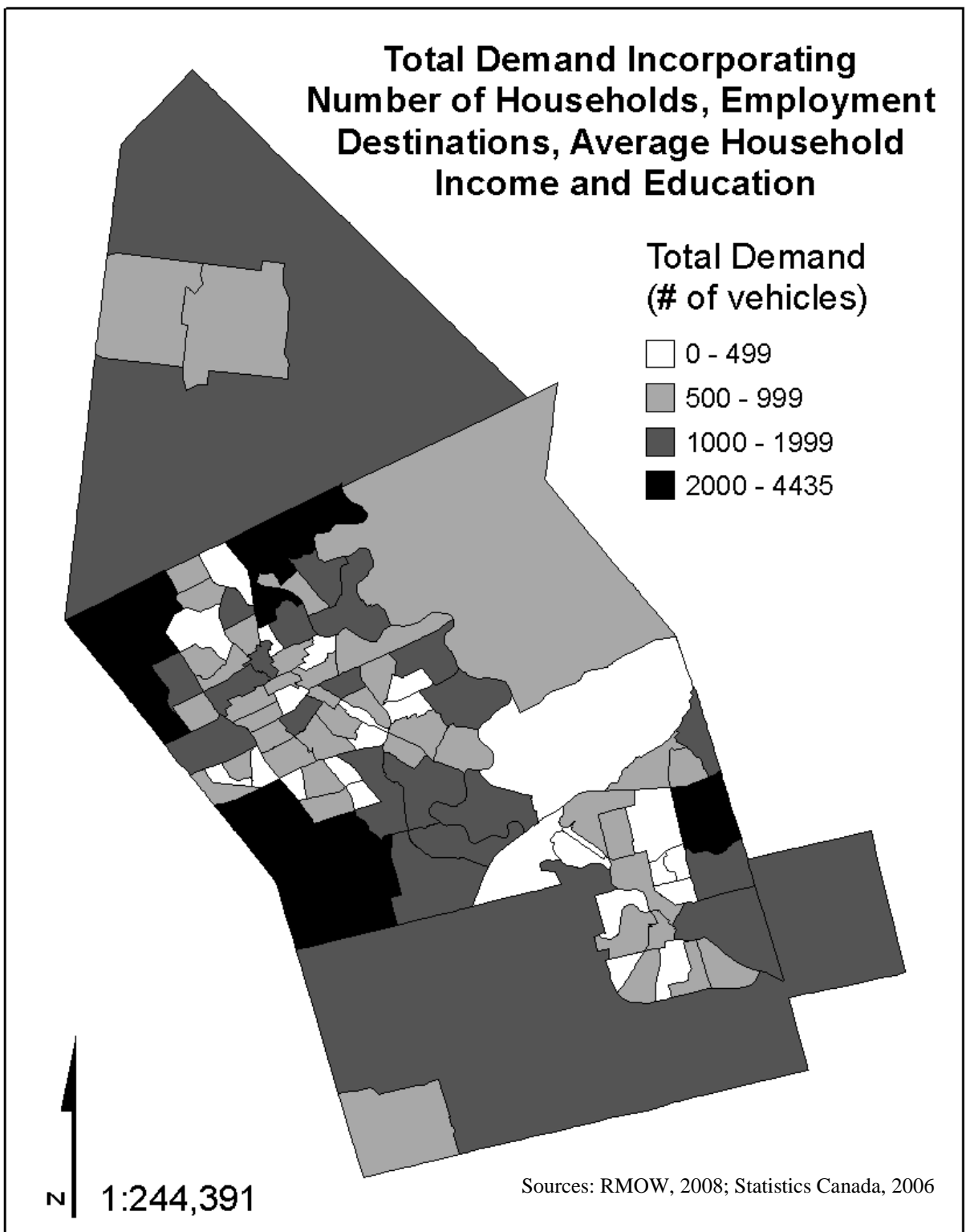**Figure 4. Total Demand Map with Estimated Demand per Census Tract.**

4.4 Scenarios:

Nine scenarios were created by altering the number of hydrogen stations selected by the model. These scenarios are: 2, 5, 10, 15, 20, 25, 30, 40 and 48 hydrogen stations. Scenario modelling is an accepted approach for exploring hydrogen infrastructure. As mentioned earlier, the current number of non-independent gasoline stations in the Kitchener CMA is 74. Forty eight hydrogen stations is the upper bound for the scenarios because at this level any additional stations are redundant in terms of satisfying estimated demand as determined by the location-allocation model in the GIS. The selection of hydrogen stations is influenced by demand levels and drive time.

4.5 Restricted Areas Scenario:

There are many micro-level, or site specific, concerns that may affect a hydrogen refuelling network. The Canadian Hydrogen Installation Code outlines voluntary safety standards for hydrogen generating, utilization, dispensing, storage and piping equipment. This information is very difficult to include in a model as it requires site specific details on each individual candidate gasoline station. However, one micro-level aspect that can be incorporated into the model used in this study is the effect that negative public perceptions may have on the distribution of hydrogen refuelling facilities. As discussed in the literature review, community attitudes may be unfavourable towards the introduction of hydrogen facilities due to their flammability and use of unproven technology. Much of the public is unfamiliar with this technology and may be wary or mistrusting of it during the initial introductory phase. Very few studies have included micro-level concerns into models as safety and zoning standards specific to hydrogen as they are still emerging. However, this study presents a demonstration of the influence of possible restricted areas for hydrogen refuelling based on likely negative community

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attitudes. A 20 station scenario is used with restricted areas incorporated to demonstrate the

effect that community attitudes or potential zoning codes may have on the distribution of

hydrogen facilities selected by the model. The restricted areas used in the model exclude any

stations within 200 metres of a school or medical centre. The choice of 200 metres is based on

Waterloo zoning by-laws. They state that gasoline stations cannot be located within 100 metres

of residential zones. This was extended to 200 metres for hydrogen because it is not yet as

widely accepted as gasoline is. This scenario is for demonstration purposes only and the

exclusion zone and restricted features may be easily altered to reflect the local environment.

5. RESULTS:

5.1 Number of Hydrogen Stations:

The selection of stations based on the nine scenarios is presented in Figure 5. This shows the spatial distribution of the hydrogen facilities chosen by the location-allocation model. There are important spatial patterns to discuss in terms of the distribution of hydrogen facilities. With respect to Cambridge and the two station and five station scenarios, zero and one stations are allocated respectively. This reflects the overall pattern of demand. Cambridge has relatively small demand compared to Waterloo and Kitchener, as is displayed on the total demand map. This is due to the fact that Cambridge has many census tracts with low household numbers, lower incomes and lower education levels as was demonstrated in Figure 3. As such, fewer stations are allocated within Cambridge as one would expect. The facilities in the two station scenario are not located within census tracts that have the highest demand level. However, they are located near high demand census tracts. They are located such that as much demand as possible is allocated to them within the five minute drive time limit. In all the scenarios, hydrogen facilities tend to be spread across the study area as opposed to being clustered. This is expected because when a station is selected, the census tracts nearest to it have high proportions of their demands met. Thus, the model would be unlikely to select another station in close proximity because there is little demand left to capture in that area.

Figure 5. Scenarios and Locations of Hydrogen Stations Selected by the Model.

5.2 Percent of Census Tract Demand Allocated:

For every scenario, demand from certain census tracts was allocated to the stations. The percent of census tract demand allocated is shown in Figure 6. This does not represent the percent of total demand within the Kitchener CMA. Rather, it is the percentage of actual allocated demand from the total potential demand in each individual census tract. For example, in every scenario there are some census tracts that end up with zero demand allocated to a hydrogen station. They are shown in white in Figure 6. The darker the shading in the census tract the greater percent of its demand was allocated. These values vary from 67% to 100% of demand allocated.

Figure 6 reveals that as the number of hydrogen stations increases, the percent of census tract demand allocated also increases. For example, in the two station scenario in Figure 6a, the majority of census tracts have no shading. Thus, there is an enormous amount of the total regional demand left unmet with only two hydrogen stations. When the station number is increased to five as in Figure 6b, the number of shaded census tracts dramatically increases. Thus, there is less total demand that is unmet. The same pattern is shown with the ten and fifteen station scenarios in Figure 6cd. However, when one compares the twenty and thirty station scenarios in Figure 6ef, there is only a marginal change in the total regional demand that is unmet as well as the percent of census tract demand allocated. Therefore, in scenarios with greater than twenty stations, the rate of change of demand actually allocated compared to potential demand declines sharply.
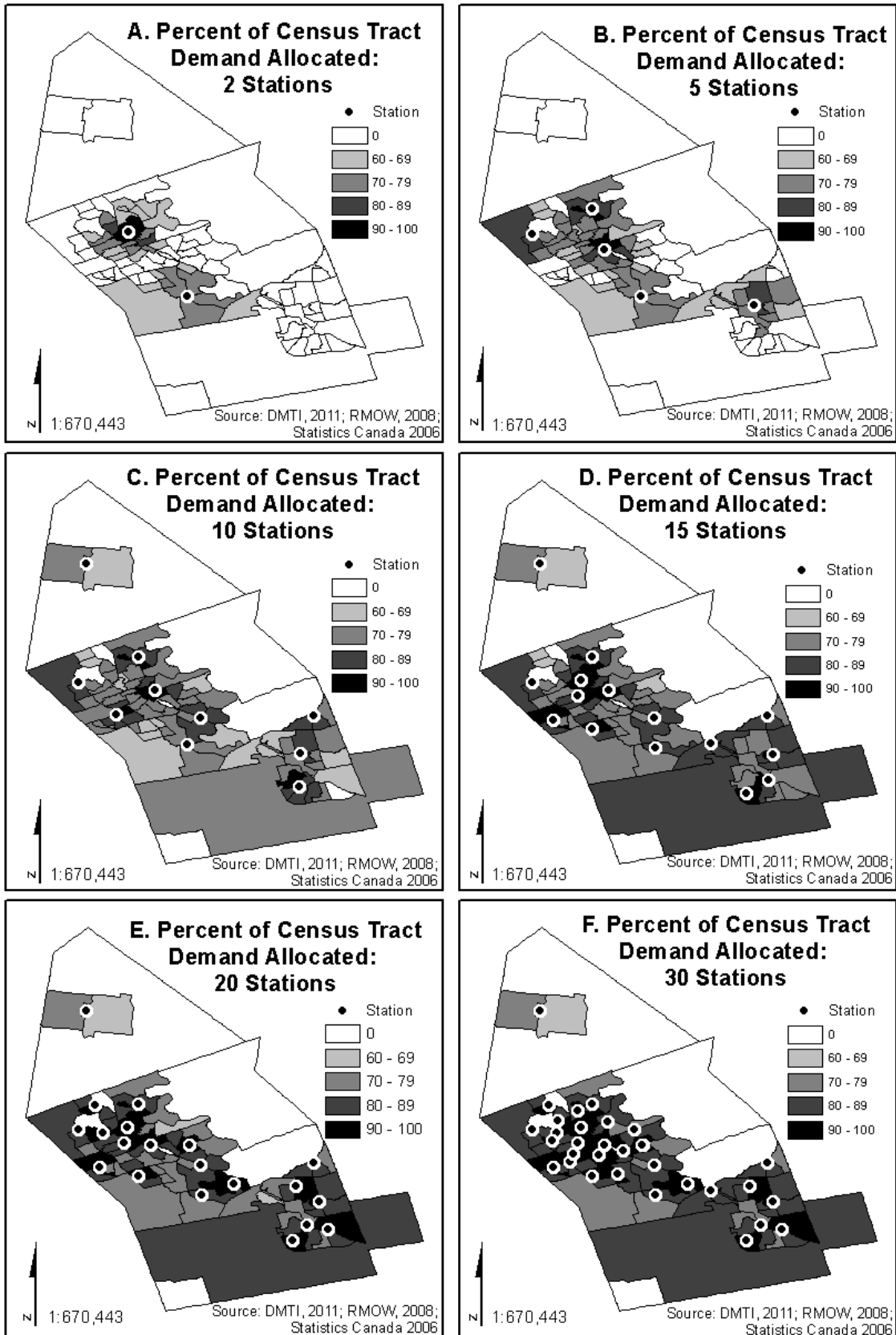
Figure 6. Percent of Census Tract Demand Allocated under Different Scenarios.

The finding that the level of census tract demand met levels off at twenty stations is also supported graphically in Figure 7. This graph shows the average percent of demand allocated by all census tracts that have some of their demand allocated to stations, over all nine scenarios. The greatest rate of change occurs from ten to fifteen and fifteen to twenty hydrogen facilities. Beyond this the slope evens out. In addition, it shows the number of census tracts that have a portion of their demand allocated in each scenario.

These findings reveal information about the appropriate number of stations required to appropriately meet estimated hydrogen demand in the Kitchener CMA. This study suggests that at 20 stations, most of the demand to refuel within five minutes of work or home is met at the census tract level. This is important from an implementation standpoint as it has implications for adoption. If only a few hydrogen stations are introduced, infrastructure costs would be low but adoption rates would be lower than if a greater number of stations were installed. On the other hand, with the introduction of 40 or 48 stations, adoption rates would be high but costs would also be significantly higher. Thus, 20 stations strikes a balance between achieving relatively low infrastructure costs and high adoption rates.
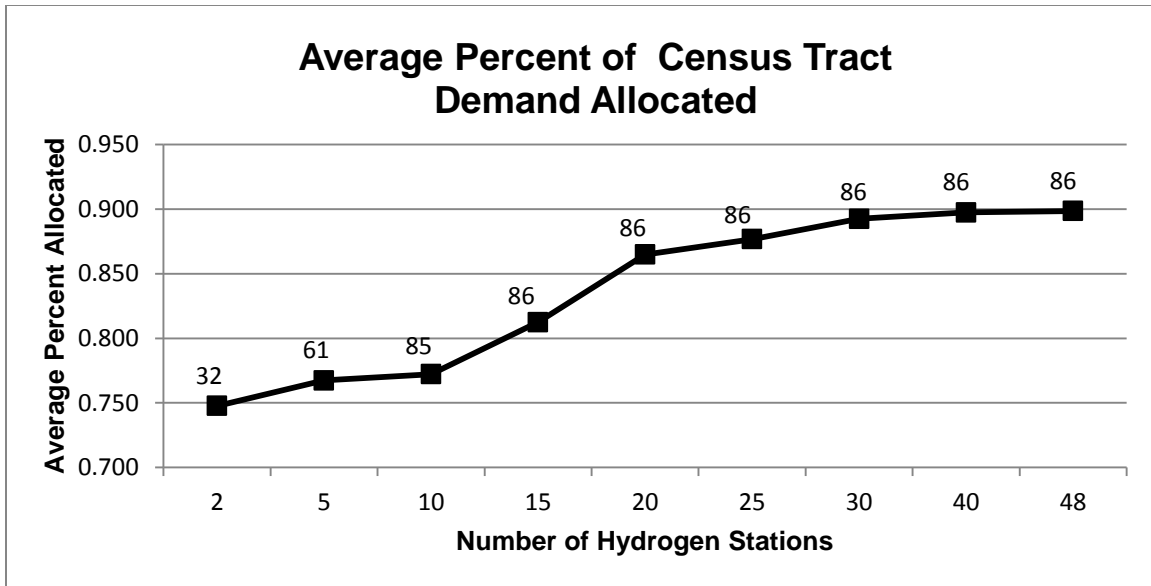
Figure 7. Local Demand Allocated under Nine Scenarios.

5.3 Total CMA Demand:

The previous section discussed the amount of demand met at the census tract level. This section discusses the demand allocated as a percentage of the total estimated hydrogen refuelling demand in the Kitchener CMA. The percent of total demand allocated is shown graphically in Figure 8. As the graph indicates, 100% of the total regional demand is never achieved. This is due to the distance decay function incorporated within the location-allocation model. The general trend shows that as the number of stations increases so too does the percent of total demand met. For example, 29.0% of total demand is met with the two station scenario. If the number of stations is increased to five, demand met dramatically increases to 54.4%. By increasing the number to ten stations, 72.5% of total CMA demand is met. However, the percent of total demand met begins to level off after only ten stations are present. The difference in total demand met between the twenty station scenario and forty eight station scenarios is only 3.0%.

Referring back to demand met at the census tract level, it suggests twenty stations were appropriate for satisfying local demand. However, when analyzing total demand met at the

CMA level, it suggests that as little as 10 stations are required to satisfy a significant portion of estimated demand. If 10 stations are implemented, 73% of total demand is met. Fifteen stations is also an attractive option with 78% of total demand met. Ten stations represent only 11% of the existing non-independent gasoline network as opposed to the 22% (15 stations) recommended in the analysis of demand at the census tract level.
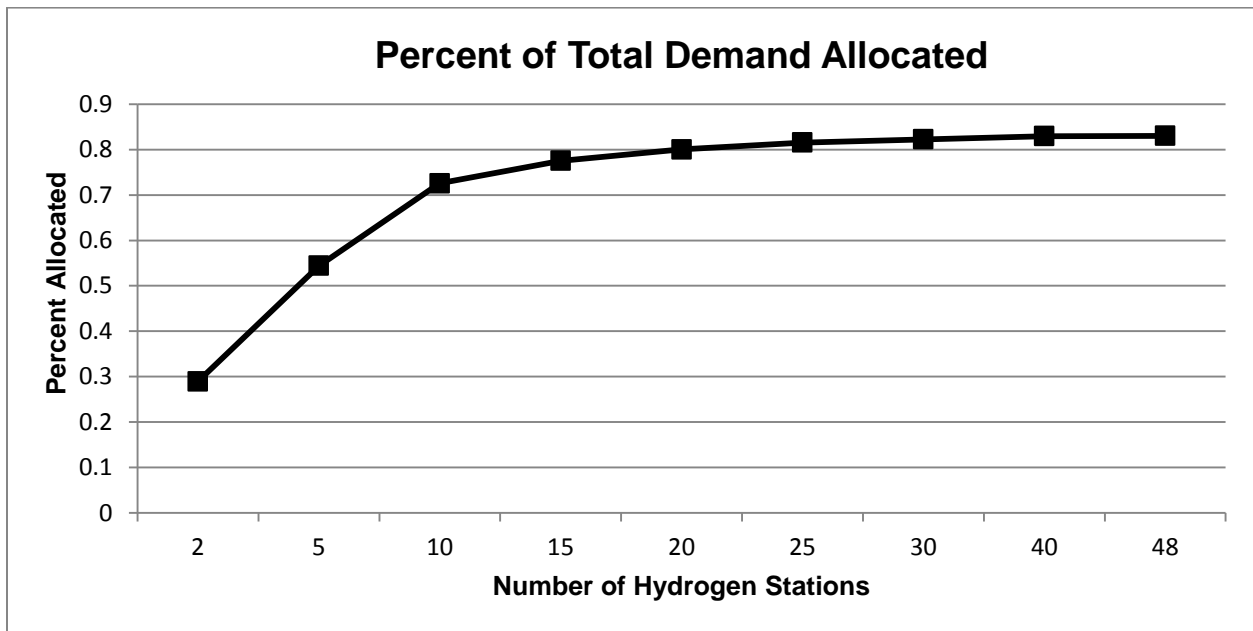
Figure 8. Percent of Total Metropolitan Demand Allocated under Nine Scenarios.

5.4 Drive Time:

Average drive time to the nearest gasoline station and the nearest alternative fuel station are frequently used comparisons in alternative refuelling studies. This information provides insights on the availability of refuelling infrastructure that the literature suggests is important for adoption. It also helps suggest an appropriate number of stations to satisfy potential consumers. This study calculated driving times from the street length and speed limit. Thus, urban driving times may be underestimated as congestion and wait times at stoplights are not taken into

account. With the existing network of 74 non-independent gasoline stations, the average driving

time to a station from census tract centroids is 1.6 minutes. Figure 9 shows the average driving

time for the nine scenarios; as the number of hydrogen stations increases the average driving

time decreases. However, decreases in driving time become redundant at twenty five or thirty

stations. With only ten hydrogen stations, the drive time is a reasonable 3.1 minutes, or roughly

double the average drive times for the existing gasoline network. However, for consumers who

want similar convenience as the existing gasoline network, a doubling in driving time to a

refuelling station may be unacceptable.   In addition, the percent of census tract demand

allocated with 10 stations is relatively low. Therefore, 20 hydrogen stations may be more

appropriate as the average driving time is more reasonable at 2.1 minutes. Furthermore, 20

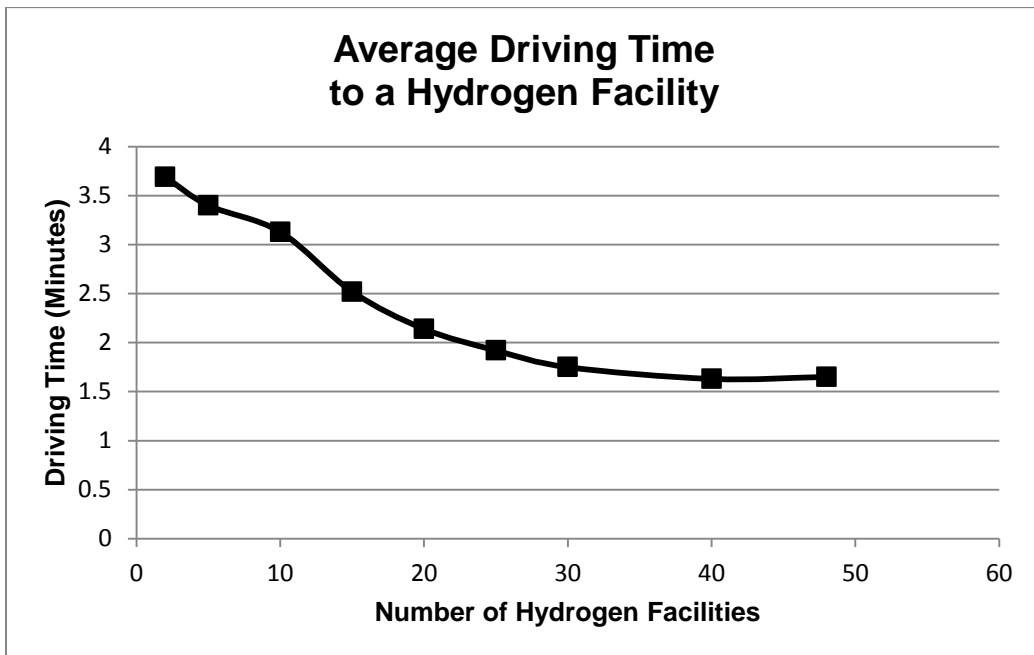stations meet a larger portion of local demand, as previously discussed.

Figure 9. Average Driving Time to a Station under Nine Scenarios.

5.5 Demonstration of Restricted Areas:

The literature suggests there may be community resistance or NIMBYism towards the development of a hydrogen network during the initial introductory phase. These site specific concerns, along with zoning codes, can be incorporated into the model employed here. The twenty station scenario was selected to perform the demonstration of restricted areas. The base twenty station scenario is shown in Figure 10a beside the restricted area scenario in Figure 10b. In this scenario, gasoline stations located within 200 metres of school or medical centres were removed from the possible candidate sites. This reduced the number of potential sites to 70 from 74. The location-allocation model then selected the twenty stations under the new scenario. Figure 10 shows a small change in the resulting hydrogen network, particularly in the central area of the CMA. This demonstrates that even a small change to the number of candidate sites results in changes to the overall hydrogen network.

The types of potential restricted areas depend on the specific case of the community considering hydrogen adoption. This scenario is simply a demonstration; the restricted areas can be changed in the model to reflect different community concerns and safety standards. It is important to note that many site-specific considerations are already incorporated into existing planning and zoning regulations related to gas stations and are reflected in that only four candidate stations are removed. For example, the locations of gasoline stations must meet criteria under city by-laws so as to not be a detriment to environmentally sensitive areas or being situated too close to residential areas. This demonstration is particularly useful for planners developing hydrogen specific zoning codes as the model can be used to test the impacts of their proposals.
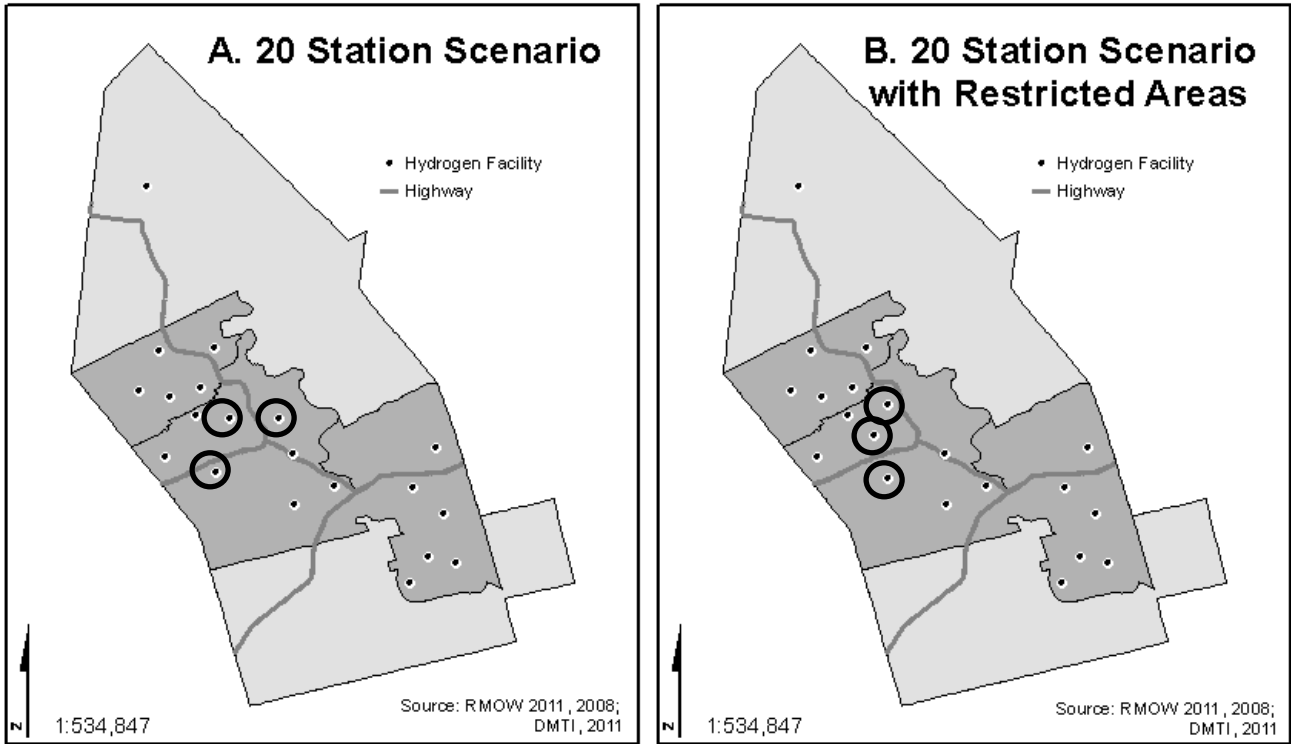
Figure 10. Comparison of 20 Station Scenario and Restricted Areas Scenario.

6. DISCUSSION AND RECOMMENDATIONS:

The first step in creating the model used in this study was to estimate demand for hydrogen refuelling. It includes the prominent assumption in the literature that most people tend to refuel near their home or workplace. However, it also incorporates socio-economic characteristics to target potential HFCV buyers similar to the recent Kuby et al. study (2009). The representation of demand for the Kitchener CMA seems reasonable and the components are based on developments in the literature. The types of socio-economic data included in the estimation of demand can be easily altered to reflect the findings of future choice behaviour studies.

It is important to balance the number of stations deployed, minimizing costs while at the same time ensuring there are enough stations to satisfy demand and facilitate the adoption of vehicles. This relates to the importance of refuelling availability, purported by many studies to affect adoption rates (Huétink et al., 2010; Meyer and Winebrake, 2009; Rogers, 2003; Kitamura and Sperling, 1986.) The use of a drive time impedance transformation (distance decay affect) and limit within the model reflect this; a person is less likely to adopt a HFCV if they live or work a significant distance from a hydrogen refuelling station. The inclusion of the influence of refuelling availability allows for the average percent of census tract demand allocated to be used as a proxy for adoption rates. This is a development unique to this study. The results support the literature in that fewer station numbers result in lower adoption rates (demand met) due to lower availability (fewer stations). For example, Figure 7 shows that the average census tract demand allocated in the 2 station scenario is only 75%. This means that of the census tracts that have demand assigned to the selected hydrogen stations, the average adoption rate is 75%. The 20 station scenario shows that adoption rates increase with greater station numbers that increase refuelling availability. The average adoption rate for the 20 station scenario is 86%. Therefore, this study has produced a valuable proxy for HFCV adoption rates.

The census tract demand, total demand and drive time analyses have implications for the implementation of a hydrogen refuelling network. The previous section provided individual analyses on demand and driving time, resulting in macro-level analysis on appropriate station numbers. The macro-level analysis provides a recommended range of 10 and 20 hydrogen stations. The census tract demand analysis suggests that 20 stations are appropriate for satisfying estimated hydrogen refuelling demand at the local level. There are no significant increases in percent of demand met beyond this level. In terms of total demand, the 10 or 15 station scenarios are appropriate and satisfy a significant portion of regional demand. Similar to local demand, significant increases in the portion of demand met are witnessed with fewer station numbers. In the total demand case, increases in demand met are redundant beyond 15 stations. Lastly, 20 stations are suggested from the average drive time analysis. Again, the influence becomes redundant beyond this level. The 10 and 20 station recommendations represent 11% and 22% of the existing non-independent gasoline network respectively. These results are directly in line with the range of 5 to 25% of existing stations recommended in the literature.

This study also provides meso-level analysis on the overall form a hydrogen refuelling network may take. Most of the results are consistent with expectations. First, the selected hydrogen stations are not clustered, reflecting the model's attempt to capture as much demand as possible. When a station is selected, the census tracts around it have much of their demand allocated to it. Thus, a second station is unlikely to be cited in close proximity because a large portion of the demand is already met. Secondly, the selected stations tend to be situated on streets with high vehicular traffic. These are desired locations for hydrogen stations, as suggested by the literature (Melaina, 2003). Most of the existing gasoline stations within the Kitchener CMA are located in high traffic areas. Thirdly, few hydrogen stations are located in core areas. This is due to the low levels of estimated demand for hydrogen refuelling in the

cores as well as the few numbers of existing stations within them. Households and employment destinations are decentralized across the three cities within the Kitchener CMA. In addition, the downtown areas experience low average household incomes and low education levels. These contribute to low overall demand in the core areas, resulting in few hydrogen stations being sited within them. However, some studies resulted in stations sited in downtown areas (Kuby et al., 2009; Nicholas, 2004). This is likely due to the unique transportation characteristics of each study area. For example, Kuby et al. aimed to locate stations as to capture the greatest volume of vehicle flows (2009). They studied the Orlando metropolitan area that has highways crisscrossing through downtown. As such, the downtown of their study area exhibits much greater hydrogen demand than the Kitchener CMA. Therefore, the unique transportation networks influence station siting.

Some studies point out the importance of providing hydrogen refuelling stations along highways (Kuby et al., 2009; Nicholas, 2004; Melaina, 2003; Kitamura and Sperling, 1986). Many studies purport that it is important to provide refuelling options for those who commute relatively long distances to work or are travelling on longer trips. The Kitchener CMA has very few existing options for refuelling directly along highways. In addition, the area has only two major highways. The studies that target the siting of highway refuelling locations tend to be larger study areas, such as counties or states, or include long range commuters in demand estimations. In the case of Kuby et al.'s study based on the Orlando metropolitan area, many highway locations were sited (2009). This is due to the inclusion of workers who commute greater than twenty minutes into the model that estimates demand for hydrogen refuelling. Furthermore, Orlando is criss-crossed with highways that cover a large portion of the study area and penetrate the downtown area. Thus, highway stations have indirect preference due to long range commuters being included in the demand estimation. There is also a much greater number

of highway locations compared to the Kitchener CMA. If hydrogen infrastructure was being

initiated at a greater scale, such as southwestern Ontario, or targeted towards long range

commuters, highway locations would become more valuable. It would be relatively simple to

include the necessity of providing highway stations in the model. The demand could also be

altered to include long range commuters in the estimation of hydrogen refuelling demand.

In terms of micro-level, or site specific, analysis, the stations selected by the model are

suggestions, as opposed to being absolute, and would need to be individually evaluated to ensure

the provision of hydrogen is possible. A review of the literature reveals that most studies are

based on the existing gasoline network. This network is already influenced by zoning by-laws

that address potential safety and citizen concerns. However, very few communities have

hydrogen specific zoning codes in place. This study provides a valuable tool that can be used by

planners to develop hydrogen specific zoning codes for municipalities considering the

implementation of hydrogen infrastructure. The effects that different codes and restrictions have

on the resulting refuelling network can be tested within the model relatively easily. If significant

site specific concerns are known, they may be incorporated into the model as demonstrated by

the restricted areas scenario.

7. CONCLUSION:

There is an ever-pressing need to diversify our energy resources to reduce harmful emissions, mitigate climate change and achieve energy security. The automotive sector has great potential to address these concerns by transitioning to alternative fuels. In terms of hydrogen, there is currently little infrastructure in place; this discourages consumers from adopting and automobile companies from developing vehicles. Exploring options for introducing alternative refuelling station networks is vital to overcoming this 'chicken-and-egg' problem.

This study explored what a potential hydrogen refuelling network might look like for the Kitchener census metropolitan area. It is unique in that it incorporates socio-economic factors into the estimation of refuelling demand. It is also one of the first Canadian studies on hydrogen refuelling infrastructure. Furthermore, it provides a demonstration of how site specific constraints may alter a refuelling network. The model can easily be applied to other regions with the appropriate GIS and statistical data.

The study estimated hydrogen refuelling demand and demonstrated the spatial pattern of suggested stations over a variety of station number scenarios. The level of local demand and total demand met under different scenarios give insights into adoption. They suggest that 10 to 20 stations are appropriate for meeting hydrogen refuelling demand while encouraging adoption and minimizing infrastructure costs. Average driving time to a hydrogen station is also used to explore implementation. It suggests that 20 stations would be more acceptable than 10 at maintaining convenience in terms of existing infrastructure availability.

There are several limitations with this study including station capacity limitations, flow-based demand and home-based refuelling. First, the study does not utilize capacity limitations on the refuelling stations. This data could be incorporated into the model if it was known. Capacity limitations are important because they may affect the overall spatial distribution of

stations. The demand could be capped and shifted elsewhere within the network, affecting the form of the network. Secondly, the model does not include flow-based demand such as vehicular traffic. Instead, it incorporates point-based demand data at the census tract level. Flow-based models can be used to represent refuelling that occurs in the middle of a trip, not necessarily near the home or workplace. Thirdly, the model does not incorporate home-based refuelling. Hydrogen has the potential to be dispensed not only at retail stations, similar to the existing gasoline network, but also directly at one's home. However, there is a lack of information and knowledge on whether this will be a viable option in the long term. Home-based refuelling is also unlikely to occur during the initial infrastructure deployment phase. Thus, home refuelling was not included in this study.

Future directions for research include more studies on understanding the demographic and socio-economic factors of those likely to adopt hydrogen vehicles. There are very few studies focussed directly on the characteristics of probable hydrogen adopters. These factors are important because they contribute to estimated demand. By understanding these characteristics, demand is more accurately represented along with the resulting refuelling infrastructure. A second area that requires further research is hydrogen zoning codes. Very few communities currently have them in place. While the existing gasoline station locations are governed by zoning, codes specific to hydrogen concerns must be developed. Zoning codes have the potential to either discourage or encourage hydrogen adoption. A third area for research is creating hybrid models to incorporate both point- and flow-based demand. A hybrid model would be valuable as it includes refuelling that occurs during a trip to someplace else, in addition to home and work based refuelling.

Ultimately, this study produced a planning tool for use by communities considering the implementation of a hydrogen refuelling network. It also developed a proxy for adoption rates

with respect to the average percent of census tract demand allocated. The model requires data that is easily obtainable for many communities. Different scenarios can be tested and analysed to determine the appropriate number of stations to implement to meet demand. It can be used by planners to develop hydrogen specific zoning codes and to test the impacts that proposed codes may have on proposed hydrogen refuelling networks.

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APPENDIX A

Description of the Maximize Attendance Problem Type for Location-Allocation

The following was taken from ArcGIS10 Desktop Help (2012)
http://help.arcgis.com/en/arcgisdesktop/10.0/help/index.html#/Location_allocation_analysis/004
700000050000000/:

Maximize Attendance
Facilities are chosen such that as much demand weight as possible is allocated to facilities while
assuming the demand weight decreases in relation to the distance between the facility and the
demand point.

Maximize Attendance chooses facilities such that as much demand weight as possible is
allocated to facilities while assuming the demand weight decreases with distance

Specialty stores that have little or no competition benefit significantly from this problem type,
but it may also be beneficial to general retailers and restaurants that don't have the data on
competitors that is necessary to perform market share problem types. Some businesses that
might benefit from this problem type include coffee shops, fitness centers, dental and medical
offices, bowling alleys, and electronics stores. Public transit bus stops are often chosen with the
help of Maximize Attendance. Maximize Attendance assumes that the farther people have to
travel to reach your facility, the less likely they are to use it. This is reflected in how the amount
of demand allocated to facilities diminishes with distance. You specify the distance decay with
the impedance transformation.

The following list describes how the Maximize Attendance problem handles demand:

- Demand outside the impedance cutoff of all facilities is not allocated to any facility.
- When a demand point is inside the impedance cutoff of one facility, its demand weight is
  partially allocated according to the cutoff and impedance transformation. The demand
  points in the graphic above have pie charts to represent the ratio of their total demand
  weight that was captured by the chosen facility.
- The weight of a demand point covered by more than one facility's impedance cutoff is
  allocated only to the nearest facility.

APPENDIX B

Equations

1. Distance Decay Function

$$D_a = D_t \ \frac{1}{(d)^b}$$

Where:

D_a is the amount of demand allocated
D_t is the total demand estimated
d is the distance from selected station to demand point
b is the impedance parameter

APPENDIX C

Percent of Census Tract Demand Allocated for 25, 40 and 48 Station Scenarios