MODELLING THE FEASIBILITY OF TRANSITIONING DIESEL-BASED HEAVY-DUTY TRUCKS TO CNG-POWERED ENGINES IN THE GTHA

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Introduction

Heavy-duty trucks are commonly used in freight transportation due to their ability to transfer high volumes of goods. Population growth and globalization increases traffic volume of all types of vehicles, which can lead to congestion. The increase in heavy-duty trucks is of greater environmental concern as most of these vehicles are powered by diesel and on average travel longer distances. The latter is associated with higher quantities of harmful emissions. Exposure to diesel exhaust fumes increases hospital admissions and worsens chronic lung diseases. Additionally, diesel exhaust fumes are likely to be carcinogenic (*11*).

Alternative Fuel Vehicles (AFVs) have the potential to minimize health effects and reduce emissions associated with diesel-powered vehicles. Natural gas, an alternative fuel source is "85 to 99 percent methane…clean-burning, cheap, and abundant in many parts of the world," (*4*) and can be fueled in the form of Compressed Natural Gas (CNG) and Liquefied Natural Gas (LNG). Natural Gas Vehicles (NGV) "have the potential to emit lower levels of particulate matter, non-methane organic gases, nitrogen oxides, carbon monoxide and air toxins" (*14*) than their diesel counterparts. The reduction of these emissions has the potential to improve air quality and in-turn public health.

To facilitate the adoption of NGVs while maintaining the efficiency of goods movement, the overall objective of this research is to address the existing gap by examining the feasibility of alternative fuel infrastructure and the associated supply chain. To this end, the specific objectives of this study are to estimate the potential CNG demand, to advance the current knowledge on CNG refueling and optimal allocation of facilities that can store CNG and CNG-carrying fleets; identify hotspots and potential sites in the Greater Toronto and Hamilton Area (GTHA) where the allocation of the CNG Fueling Facilities will minimize transportation cost.

Background

Freight Trip Generation (FTG) modeling

FTG modeling estimates the number of commercial vehicle trips, which can represent the demand for fuel. Freight trips are more difficult to model than passenger trips as commercial vehicles engage in multiple daily deliveries, and there are various factors such as truck capacity, variable delivery window times, and varying patterns amongst different sectors that affect trip generation (*9*). It is challenging to obtain the necessary information required from businesses and firms to predict models as a lot of the information associated with delivery patterns and route design can aid the competition.

Holguín-Veras et al. (2013) reviewed the existing FTG models to allow for better predictions and the utility outside of the original study area these models originated from. Three major FTG models, the National Cooperative Freight Research Program Project 25 (NCFRP 25) "Freight Trip Generation and Land Use", Quick Response Freight Manual (QRFM) and the Institute of Transportation Engineers' Trip Generation

Manual (ITE), were tested using data obtained from different industries of varying sizes. Comparing the modeled results with the data, NCFRP 25 tends to perform better than the other models and has a smaller range of associated root mean square error. Additionally, it was found that the QRFM tends to overestimate FTG for larger businesses.

Roorda et al. (2010) established a model for Greater Toronto Area (GTA) truck trip-generation. The initial rates were based on the 2007 Region of Peel Commercial Travel Survey and then calibrated to correspond to observed traffic counts of crossing cordons in the GTA and the generated travel assignment. These calibrated rates are based on land use, employment industry and truck type. The three classifications of land use in their model are: Rural and Suburban, Urban and Central Business District. The trip generation model results were compared with observed traffic counts at AM and PM peak hours. The modeled results were in "right order of magnitude [and] [t]he overall sum of screenline totals is very accurate," (*12*). The overall sums of the screenlines were within 2% with the exception for heavy trucks in the PM peak, which was 6.9%. The latter margin of error is acceptable due to the limited freight movement and demand data. Both studies stress the importance of obtaining more data on freight flows and demand patterns to effectively predict FTG and produce accurate models. Additionally, further detailed commercial vehicle counts are also required to verify results.

Locating Refueling Stations and CNG Fueling

Optimization models have been used in past studies to determine the location of fueling stations. These models produce locations that have the potential to minimize travel distance or time or maximize coverage for the study region, therefore increasing the convenience for consumers and businesses for refueling station owners. Hwang et al. (2015) proposed a mathematical model for locating alternative fuel refueling stations on highways. Results showed that more highway truck trips could be serviced with a high number of stations and a higher vehicle driving range. The results lacked convexity, after the optimal number of stations is reached the effective coverage plateaus. Hence, additional stations past the optimal value will not substantially enhance alternative fuel accessibility on highways.

Nicholas and Ogden (2006) used a p-median problem to minimize travel time between one's home and proposed hydrogen refueling stations. A major assumption made for this model is the general preference of public refueling near the home over at-home refueling. It was further assumed that all regions of study area were the same with respect to the amount of time individuals are willing to drive to refuel. The team found that as the desired travel time decreased the number of stations required substantially grew. For example, for the Metropolitan region of Los Angeles, a desired travel time of seven minutes, five minutes and three minutes warranted 26, 61 and 228 stations, respectively. However, to minimize economies of scale it is ideal to have a lower number of refueling stations. Therefore, there needs to be some tradeoff.

The proposition of this study is to create central stations to house natural gas and store refueling trucks. These refueling trucks will visit truck yards and provide overnight fueling and a virtual-pipeline. A "virtual-pipeline is an alternative method of transporting natural gas to places where there are no pipeline networks available," (*15*). The feasibility of virtual LNG pipelines has been demonstrated in Europe and the United States. In Norway for example, LNG is delivered in large vacuum insulated tanks and trailers.

NGVs utilize on-board CNG in high-pressure cylinders at a pressure of 3,000 to 3,600 psi. CNG vehicles are generally filled at compressor refueling stations that are bound to natural gas pipelines. These stations can deter drivers from their driving route, which brings about additional costs. Implementing a virtual-pipeline to refuel CNG vehicles overnight can reduce travel costs on the fleet operator and can ensure a "fuller" fill. Time-fill is generally used for fleets that can be refueled overnight at a central location as fueling can last several minutes to several hours. The longer fuel time is advantageous as it allows for a fuller fill than fast-fill (similar gasoline and diesel fill times) since the slower fueling rate counteracts the expansion of gas caused by the increase in heat associated with a faster fill.

Proposed Study Area

The Greater Toronto and Hamilton Area (GTHA) is the proposed study area, it can be delineated using both Census Metropolitan Areas and Census Divisions. The GTHA is comprised of the three CMAs: Toronto, Hamilton and Oshawa. The study area was further centralized to incorporate only regions of the GTHA that have census tracts.

The GTHA hosts the largest market in Canada. This market encompasses major cities such as Toronto and Hamilton and the regions of Halton, Durham and York and Peel. In 2011, the GTHA had a population of 6.5 million people, 2.4 million households and a total of 2.9 million jobs. In addition to the population size and the vast number of jobs, commercial vehicle movement is prevalent in this area due to the many warehouse and distributions centers and accessibility and proximity to major Ontario highways such as the Highway 401. Increasing congestion in the GTHA has been observed and has the potential to increase vehicular emissions. Therefore, transitioning to CNG heavy trucks in the GTHA can improve Ontario's air quality and public health.

Methodology

Preliminary Analysis

The data used to estimate heavy-duty truck trips and counts include the employment per industry sector and the number of households per census tract. These datasets were obtained from Statistics Canada and the National Household Survey (2011). Two models are used to predict heavy truck trips: QRFM and the model proposed in Roorda et al. (2010). The Quick Response Freight Manual (QRFM) provides trip generation models for different vehicle classes and is based on origin-destination data from Phoenix, Arizona. The QRFM model inputs include employment per industry and households per zone. Holguín-Veras et al. (2013) found that the QRFM overestimated freight trip generation, however it allows for a quick estimation of commercial trips.

To use the model Roorda et al. (2010) proposed, each census tracts in the study area must be classified based on land use. The Central Business District was selected based on the knowledge of business activities in the downtown Toronto area. The (i) urban and (ii) rural and suburban land uses were then identified based on the census tract area calculated in ArcGIS 10.2. Anything below or equal to 2.1 km^2 is classified as Urban and any census tract with an area above 2.1 km^2 is classified as Rural and Suburban Division.

The Roorda et al. (2010) model provides 12.5-hour trip generation rates. Therefore, these totals must be scaled up to a 24-hour rate to be able to compare these values with the QRFM values. Using the hourly profile for heavy commercial trip generation collected from Edmonton (*6*) the hourly trip fractions can be obtained. Assuming the model predicts trips from 6 am to 6 pm, the modeled trip generation accounts for 92.5% of daily commercial trips. The remaining daily fraction can be used to scale the 13-hour trip estimates to a 24-hour value.

Truck counts per census tract were obtained from R. L. Polk and Co for the Windsor-Essex Region. Using Statistics Canada zonal employment data by industry, a linear regression model was developed to determine the relationship between the number of jobs and heavy trucks. This model was then applied to determine the number of heavy trucks in the GTHA. The heavy truck trips and counts were compared to ensure validity of estimates before proceeding to the main analysis. Census tract truck counts were then used to determine the demand for CNG fueling per census tract. The centroid of each census tract will be used to spatially distribute the demand points.

Proposed Locations and Service Areas

Possible sites for CNG refueling and storage stations must be selected in order to determine the optimal locations with respect to CNG demand. The proposed location must meet four requirements: (i) access to an existing natural gas pipeline, (ii) available land, (iii) close proximity to the road network, and (iv) low population. The existing DMTI Natural Gas Pipeline, Ontario Road Network (Highways and Major Roads) and Land Use Data was obtained from the Scholars Geoportal. Open area was assumed to be land that can be purchased, as land-ownership data was not readily available. However, this is likely an overestimation, as the "Open area" land use may be currently owned. The proximity to a major road network enhances accessibility to the market and reduces vehicular emissions. Finally, locating the stations in census tracts with lower population will minimize any risks and concerns associated with the natural gas storage. Population per census tract was obtained from the National Household Survey 2011 (*1*).

"Location is often considered the most important factor leading to the success of a private- or public-sector organization" (*5*). Therefore, this step is essential to ensure the optimal selection in facility locations. With the use of the set of potential locations from the previous step, the ArcGIS 10.2 Network Analyst is used to create service areas to determine the coverage of the proposed facilities. The service areas represent all the streets that can be reached within a specified driving time. The travel time is based on free-flow driving time and is suitable since the refueling fleet will be traveling at night. Further the Location-Allocation solver under the Network Analyst is used to determine the optimal locations of the potential sites. To minimize fixed costs and transportation costs of the fueling facility a P-median problem will be applied to optimize the refueling of the maximum number of trucks with the optimal number and location of facilities. The impedance will be the free-flow travel time.

Results and Discussion

Preliminary Analysis

As previously discussed, three methods were used to determine the number of heavy-truck trips and trucks. The estimated model and associated statistics based on Windsor Heavy-Truck counts per census tract are presented in Table 1. It is evident that the model has strong explanatory power based on the t-statistics and the coefficient of determination.

Table 1: Heavy Truck Count Model

Parameter	*Coefficients*	*Standard Error*	*t-Stat*	*P-value*
Jobs 11 & 23[1]	0.240	0.019	12.345	<0.0000
Jobs 53, 54, 55 & 81[2]	0.032	0.010	3.335	0.00014
R^2	0.853			
Adjusted R^2	0.837			
[1]NAICS Industry Sector 11 (Agriculture, forestry, fishing and hunting) and 23 (Construction) [2]NAICS Industry Sectors 53 (Real estate and rental and leasing), 54 (Professional, scientific and technical services), 55 (Management of companies and enterprises) 81 (Other Services (except public administration))				

The estimated total trucks and trips and the correlations between zonal totals are presented in Table 2. The estimated number of heavy trucks is the lowest of three methods. The number of heavy truck trips and trucks can be compared since they should be similar in magnitude as each truck represents the potential of generating a commercial trip. It is logical that the number of trucks in the GTHA is lower than the number of trips because the number of trucks likely represents the trucks that operate from the GTHA and will return to the zone on a nightly basis.

The QRFM clearly overestimates overall freight trips as previously discussed (*5*). This overestimation may be due to the differences in freight activity between the GTHA and the area the QRFM was derived from. Also, the zones derived in each model may be smaller or larger than census tracts; which causes the MAUP, modifiable aerial unit problem to arise. This occurs when the same analysis is used on different zone sizes or different aggregation schemes are used, causing results to differ when the analysis is applied.

The overall zonal distribution of heavy trucks and trips is quite similar and the three have a strong correlation (all higher than 0.74). The QRFM generated trips and truck counts correlate higher than the Roorda et al. (2010) generated trips. This is likely due to the consistency of the QRFM and truck count model over the study area. The generated truck counts were selected for further analysis, as they are more likely to accurately represent the fleet that exists and operates solely within the GTHA.

Table 2: Total Heavy-Truck Trips and Truck Counts and Correlation Matrix

	Roorda et al. (24 hr)	*QRFM*	*Trucks*	*Totals*
Roorda et al. (24 hr)	1.00			**169,116**
QRFM	0.96	1.00		**211,781**
Truck Counts	0.74	0.85	1.00	**38,972**

In the short run, it was assumed that only 30% of the existing heavy-duty fleet would transfer to CNG due to the associated costs. Based on these predictions, the distribution of truck counts shows that most the census tracts have less than 32 potential CNG trucks. It is evident that the bulk of the estimated CNG trucks fall under 9 trucks per census tract. The cost of converting will depend on the "vehicle model, engine type, engine size, type of conversion and the number of fuel storage cylinders," (*2*). The cost of converting a heavy truck or bus from diesel to CNG powered can be around $20,000 to 30,000 (*10*). Due to the savings associated with fuel costs, the capital costs can be easily recovered.

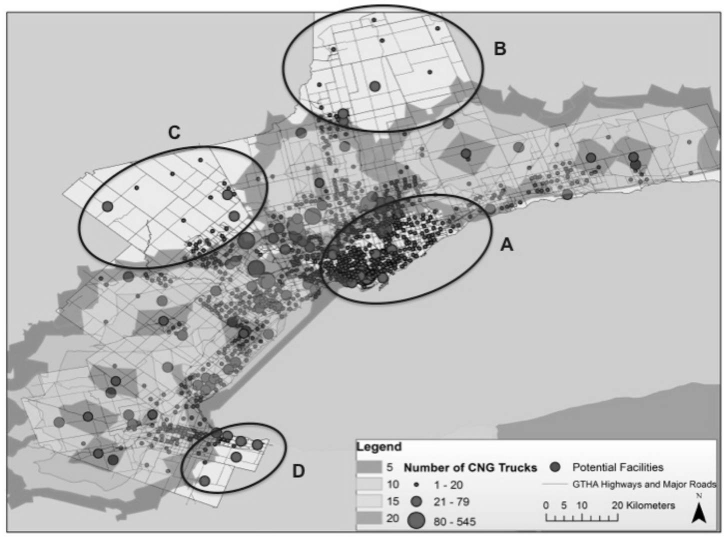

Figure 1: Proposed Facilities' Service Area

Proposed Locations and Service Areas

Loading the existing natural gas pipeline network, the major road network, available land and the population study area in ArcGIS10.2 provided ten potential sites. Only sites with a population lower or equal to 6,750 were considered. Service areas were obtained for the ten potential sites serving the GTHA. From Figure 1 it is evident that four major areas are not served. Area A is the City of Toronto, and is not serviced due to the high population density and the lack of natural gas pipelines and available land in the area. Regions B and C have sparse CNG demand and in general are not reached within a twenty-minute driving range due to their distance from proposed sites. With the existing proposed facilities, it may not be economical to convert fleets in regions A to C to NGV. Region D is a small section of un-serviced area that may be better suited to be serviced from outside of the GTHA if adjacent areas have lower populations and land prices may be cheaper.

Selecting Proposed Facilities

From the previous results, two methods for selecting proposed facilities are proposed. The first is locating CNG facilities based on total demand and the second is locating CNG facilities based on demand within a 20-minute service area. The latter method stresses which areas truck firms should consider switching their fleets to CNG. The CNG demand per heavy-duty truck was assumed to be an average of 90 Diesel Gallon Equivalent (DGE) (*11*). The capacity of a CNG refueling trailer was not readily available, therefore a ratio of 60 between the capacity of a LNG refueling trailer (12,000 gallons) and a LNG truck tank (200 gallons) was determined and this ratio was then scaled to the capacity of a CNG truck tank to determine an approximate value for CNG capacity: 5,400 DGE. The number of refueling trucks assigned per station varied based on scenario, therefore changing the plant's capacity.

Total GTHA Demand

To service the total study area demand, the capacity of each proposed site was assumed to be 135,000 DGE with 25 refueling trucks. Each proposed facility was assumed to have an equal weight and all the census tracts that had more than five CNG trucks were considered as demand points. It is assumed that it will not be cost-effective to send a refueling truck to a site with less than five CNG trucks, as it may be easier to refuel at a public station. Therefore, the total number of demand points used ended up being 396.

Locating the proposed facilities using a p-median problem and allocating demand proposes all ten facilities to be established. However, this scenario does not exploit the potential capacity of each facility as several of these proposed facilities would have low capacities. Also, from an economic perspective it does not make sense to establish ten facilities for CNG when it is still not in high demand. Investing in a few facilities at first and establishing more facilities in the future based on consumer demand is more strategic as these facilities require a large capital investment. Additionally, a lower number of CNG facilities will improve the economies of scale. However, minimizing the number of facilities will increase the travel time of the refueling fleet and therefore incur additional costs associated with travel and the CNG-filled tractor-trailers will be exposed to traffic for a longer time interval, which increases risk.

Restricting the analysis to select only a specified number of facilities will allow for the comparison of travel times associated with the varying number of facilities. Figure 2 is a graph of the minimum, maximum and average travel time from established facilities to the demand point for a varying number of facilities. The travel time values tend to be consistent from the starting point of ten to six established facilities, once the number of established facilities is five or lower then both the mean and average travel time slowly increase, while the maximum travel time jumps from 44 minutes to 66 minutes (three to two required facilities). The total travel time of the entire demand skewed from the steady but minimal increase from six facilities to five facilities, however substantially increases after reducing past three facilities.

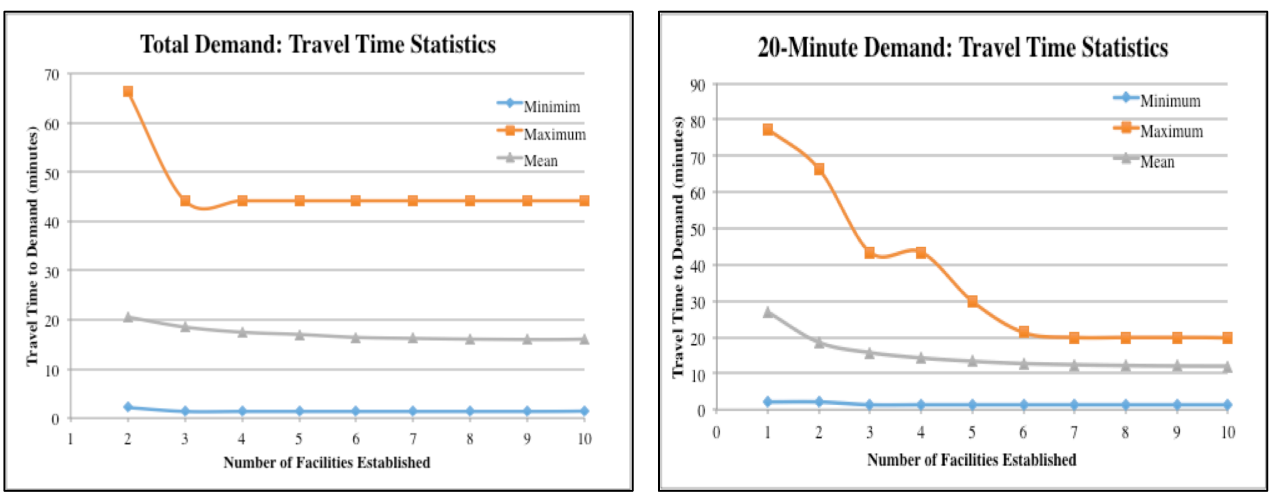

Figure 2: Travel Time Statistics

20-Minute Demand

To service the demand within a 20-minute coverage of proposed sites, the capacity of each proposed site was assumed to be 108,000 DGE with 20 refueling trucks. The only major difference found between the total demand and those within the coverage of all potential sites is the maximum travel time starts increasing when there are less than six facilities and the average travel time is slightly lower than the total demand.

Discussion and Validation of Location Results

Based on the results of the two above scenarios, there is not much variation in the average, minimum and maximum service time when the number of proposed facilities drops from ten to six; therefore, it is not economical to establish more than six facilities to service the GTHA area. Six facilities may be too costly to establish for a new NGV market, as the demand may not be strong. Establishing three facilities will allow for similar average service times as six facilities. On the other hand, establishing four facilities will allow for similar average and total service times as six facilities. Additionally, establishing four facilities provides the opportunity for servicing areas outside of the GTHA, which may be advantageous since one of the proposed stations is on the edge of the study area. Figures 3 and 4 provide the locations of the proposed sites for three and four established facilities respectively, serving the entire estimated GTHA demand. Three facilities are recommended if the objective is to reduce fixed costs associated with the CNG stations and four facilities are recommended if lower variable costs are required and service outside of the GTHA is desired in the future.

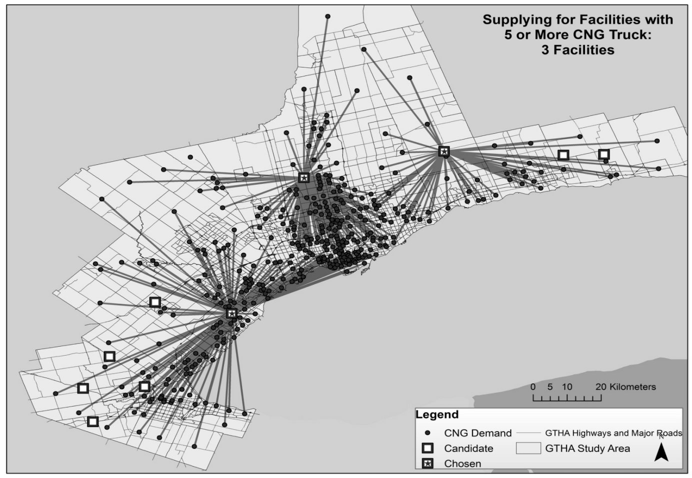

Figure 3: Allocation of 3 Facilities

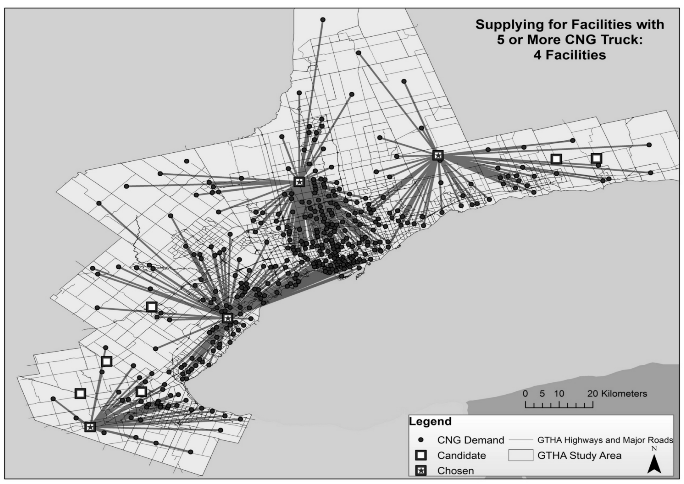

Figure 4: Allocation of 4 Facilities

To determine the coverage difference between three or four facilities, existing trucking firms in the GTHA were obtained from the Yellow Pages. It was found that there are 1,588 trucking firms in the GTHA. The 5, 10, 15 and 20-minute service areas were obtained for establishing two, three and four facilities. Minor overall coverage differences were found for two, three and four facilities. Two facilities could service 64% of these trucking firms in under 20 minutes, while three and four facilities were able to service 68% and 70%, respectively. Due to the minor differences associated with coverage, two facilities are proposed if expansion outside of the GTHA is not desired, while three facilities are recommended if it is.

Conclusion and Recommendations

Natural Gas Vehicles (NGVs) have the potential to reduce the environmental and societal impacts associated with diesel powered heavy-duty trucks used for urban freight movement. To enable the adoption of CNG, mobile on-site refueling at truck yards is proposed. CNG can be housed at central stations with locations optimized based on demand. In the GTHA context, two CNG storage stations are recommended.

While existing goods movement strategies have been focusing on improving operational practices (e.g. optimize truck routes, shift freight delivery times) in freight movement, the idea of considering alternative fuels such as CNG to power heavy trucks is not considered in future policies (*6*). Analysis conducted in this study however should be considered as an essential part for any future goods movement strategy in the GTHA. Transport policies must consider alternative fuels as one of the key elements for future planning and this should not be only constrained to private vehicles. The review of existing studies suggests that CNG has the potential to replace diesel when powering heavy duty trucks, and the feasibility of identifying appropriate locations for fueling stations in a place like the GTHA has been demonstrated in the conducted analysis. As such, the results from the analysis can have a direct impact on formulating the future of transportation policies in major Canadian cities.

To determine the feasibility of this project it is essential to obtain more detailed costs associated with: the conversion of vehicles to natural gas, refueling vehicles and the capital cost of establishing a natural gas station in any of the proposed census tracts. Additionally, detailed data about land ownership in the GTHA will provide more realistic sites for potential facilities. It remains however that targeting specific areas in the GTHA for CNG conversion could enhance coverage and reduce travel time. Information regarding local regulations and the actual capacity of CNG-carrying tractor-trailers will provide more accurate demand-allocation results. Determining the refueling time per heavy-duty truck will aid in determining the feasibility of mobile refueling per fleet basis and in the planning and operation of the supply chain.

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