Exploring Alternative Transportation Options in the Greater Toronto Area: Electric and Natural Gas Vehicles

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Executive Summary

In the 1930s, recognizing severe congestion along Highway 2 in many Southern Ontario communities the Government of Ontario began in earnest development of Highway 401. Some 30 years and 508 miles later the last stretch of freeway was completed near Kingston in 1968. Highway 401 has served as Southern Ontario's spine anchoring much of the Province's economy and enviable quality of life. We now stand at a similar, and again crowded, crossroad.

A large-scale transportation initiative is needed for Southern Ontario. Many of the existing 'bones' of road and rail alignments can be used, but this time we need less emphasis on the more and wider roads, and greater emphasis on mobility, connectivity, integration and leadership – here at home and abroad.

Toronto is not unique; cities everywhere are struggling with congestion, infrastructure, finance, and low carbon sustainable transportation and energy strategies. Toronto is however more fortunate than most cities – excellent transportation opportunities exist. For example most major transportation alignments are already in place (rail and road). Ontario's electricity grid is one of North America's lowest in carbon emissions, and natural gas is relatively plentiful and readily available. When assessing transportation options the ideal scale is the greater Toronto area and an integrated long-term approach is necessary.

From the perspective of economic productivity, and as shown in this report, greenhouse gas emissions, and improved local quality of life, transportation improvements are a clear priority. Ontario's and Canada's economy (and arguably many cities around the world where information can be shared) will directly benefit from an improved transportation system in the Toronto region.

This research suggests that by 2050 the Toronto region and linked cities such as Montreal, London, Peterborough, Kingston and Ottawa should be served by an extensive rapid transit system with complementary dedicated heavy duty truck routes and shared local 'commuter vehicles'. As much as practicable, trucks and buses should switch from gasoline and diesel to natural gas, and light duty personal vehicles should be electric. Other fueling systems and transportation grids may emerge, but as a minimum the approach suggested in this review would provide fuel savings costs of some $76 billion and reduced greenhouse gas emissions of more than 100 million tonnes by 2050.

Congestion already costs Toronto some $6 billion per year excluding health impacts and real estate values. To help prioritize movement toward greater sustainability this report introduces a pilot sustainability cost curve for the Toronto region's transportation sector. Key activities can be evaluated relative to each other and if the process proves sound could be replicated in other sectors and other large cities around the world.

This report presents an alternative perspective to a much discussed topic. By disaggregating potential transportation options at the Toronto region-scale, alternatives emerge. A commuter car sharing approach makes sense; separate alignments for heavy duty truck traffic is practical and desirable; possible partnerships on EVs with Montreal and Vancouver emerge (along with other Canadian cities); autonomous vehicles can emerge less encumbered; and new approaches like Uber and GPS monitored vehicles can be developed more quickly and more comprehensively. The report suggests a re-think on individual personal vehicles and suggests moving toward shared vehicles and a more seamless and extensive transportation network.

Not surprisingly transportation in the Toronto region is mostly seen as a major encumbrance. Being stuck in traffic or waiting for a crowded subway raises frustrations. We argue in this report however that improved and integrated transportation in the Toronto region is the best way to reduce greenhouse gas emissions, save money on fuel and operating costs, increase land values and economic activity, and improve overall quality of life.

Acknowledgments

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1. Introduction

The cost of traffic congestion in the Toronto region[1] is nearly $6 billion a year due to increased environmental, health and safety, and vehicle and fuel costs [1]. These costs are expected to rise to $15 billion by 2030, and likely more than double that again by 2050; in addition, premature deaths associated with the related air pollution will also rise. The economy of a metropolitan area is determined by the degree of ease of connectivity and movement of its residents. Road congestion and transit crowding in the Toronto region have reached a tipping point. Unless the transit infrastructure can offer a practical choice to entice hundreds of thousands of commuters out of their cars, we will pay a steep price [2]. Recognizing these growing concerns and constraints, Metrolinx developed the 'Big Move' [3] as a regional transportation plan for Toronto region. The Big Move presents a comprehensive plan to develop transportation infrastructure within an integrated transit system for the Toronto region. The Big Move is a comprehensive plan and is expected to be funded largely through fuel sales and income tax increase [2].

This study complements the Big Move while exploring options for reduced GHG emissions, reduced congestion, greater economic development, and strengthened urban resilience in the Toronto region. Three broad scenarios consistent with the Big Move assessed are

1. Expansion by 35 percent of current market penetration of electric and natural gas vehicles.
2. Introduction of a Highway 401/407 bus rapid transit (BRT) system. This will include stops at designated major interchanges where associated electric vehicle parking lots are located. Passengers use privately owned EVs to drive to work or locally.
3. Expansion of the BRT system to Waterloo, Niagara Falls, Ottawa, Kingston, and Montreal, along with publicly available EVs at parking lots. Passengers can drive EVs (personal or shared) to home or work, and locally. Cars are recharged at parking lots and homes mostly at night.

Option 1 is largely business as usual with a recognition of an emerging price on carbon, and natural gas being a long term cheaper, and cleaner fuel source than gasoline and diesel. Option 2 is the emergence of a collective commuter mind-set. Option 3 is best characterized as a sharing economy where most vehicles are shared rather than owned. Option 3 is particularly

[1] The area used in this report is 'Toronto region', which is consistent with the 'Place to Grow' legislation and the Global Cities Indicator Facility. Greater Toronto area (GTA) is generally considered the City of Toronto plus contiguous regions of Durham, Halton, Peel, and York. The GTHA is the GTA and Hamilton.

relevant as it endeavours to increase the 'effective population' of the Toronto region, thereby increasing productivity and land values.

1.1 Background – Setting the Context

Much has been written on transportation in the Toronto region. Many residents can even recall key facts from memory: average commute time 82 minutes[1]; what would I do with 32 (minutes)?[2]; congestion costs of some $6 billion a year. This report takes a slightly different tack. The transportation issue for the Toronto region is assessed from the rear view mirror of 2050. What type of vehicles are we in as we travel to work in 35 years, do we even drive to work most days, how is our food, commodities, and energy delivered to our homes and businesses in the future? And perhaps even more important, how do we use an integrated transportation system as a key driver for increased productivity and economic development, enhanced quality of life, and a global differentiator?

Currently there is significant latent demand in most transportation systems in the region. For example, if capacity is increased on major highways, or transit facilities, this would likely quickly be filled by people not using the system now due to current congestion. By moving toward a system predicated on convenience and timely transportation services, greater mobility should follow – with commensurate increased economic development.

By taking a retrospective view from 2050 several issues become clearer:

- Toronto's changing place in the world drives much of our transportation discussion (despite the upcoming arrival of 3.5 million new residents the city will move from the world's 50th largest city at the start of the century to barely being in the top 100 by the end of the century – about 80th largest in 2050).
- By partnering with other urban centers – especially Montreal and Vancouver, Toronto region may be better able to optimize solutions.
- A blend of private sector and public sector options may be needed. Ownership models may need to change[3].
- The enormous efforts expended in Toronto's transportation discussions, debates, reports and analysis are valuable in providing a comprehensive background for various options: People are sensitized to the issue and want to move forward.

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[1] Projected to increase to 109 minutes by 2040.

[2] 'Move the GTHA advertisements – asking what people would do with projected 32 minutes saved in improved transportation systems by 2040.

[3] The recent Liberty Village to Union Station private transportation initiative is a case-in-point, so too Uber. More *ad hoc* initiatives will likely emerge as transportation barriers (and costs) are addressed through alternative models.

- As well as a retrospective view, a broad view is needed. University of Ontario Institute of Technology, anchored in Durham Region, needs an effective region-wide transportation system. So too do York, Peel, Milton, Halton and a little farther out Barrie, Kitchener-Waterloo, Peterborough, Cobourg, and Niagara Falls. Connecting these communities through effective telecommunication and transportation systems provides enormous economic benefits [4].
- Transportation times (and reliability) from Toronto-center[1] are one of the largest factors in determining real estate prices. The average price for residential and cottage properties declines about 50 percent for every doubling in commute-time.
- The true cost of commuting is usually undervalued. Relatively long commuting times is one of the most significant detractors of the Toronto region's measure of subjective well-being (see Section 5).
- Transportation is better addressed as connectivity and utility (and service availability). Some trips, like getting groceries, could happily be forgone if alternatives were available, while others, like meeting friends, might be increased in frequency if they were easier to undertake.
- Transportation planning in the Toronto region must also consider, in an integrated manner, freight transportation, movement of people and goods through the region, connectivity of the region regionally, nationally and globally (e.g. link to airports), and differences between commercial, business, and personal transportation needs.
- Emissions from the transportation sector are now the region's largest source of greenhouse gas (GHG) emissions, and local air pollution in the Toronto region. Well before 2050 a price on carbon should be anticipated.
- The entire Toronto region (and Ontario and Canada) benefits from an improved regional transportation system; connectivity and resilience (including public safety) are likely the Toronto region's two most salient international attributes (after economic stability and cost of living).
- Much of the region's transportation infrastructure is long-lived – the Toronto subway started in 1954 and 'Highway 401' started in 1947 and was fully navigable between Windsor and the Quebec Border in 1964. Long lead times are common in facility development and construction. A long term perspective is needed, 2050 likely being a minimum time frame.
- Growth of Ontario's economy has been modest for the last decade as the share of GDP from manufacturing has declined. This is likely to continue and new growth in Ontario probably needs to be driven from organic and 'next stage' urban infrastructure systems.
- An energy systems perspective is needed, especially in the Toronto region where transportation emissions make up a larger share than in other parts of Ontario. Also, in all of Ontario the fraction of total energy use through electricity is less than one-third - therefore a 'one size fits all' energy plan for Ontario is limited, especially if it focusses disproportionately on electricity.

Most transportation studies investigate ways to reduce congestion, and maybe emissions – local air pollution and noise, and GHG emissions. This study recognizes the considerable efforts already made in reviewing transportation in the region (e.g., Metrolinx and the 'Big Move'). Considerable costs were incurred in these studies; this particular effort has a modest budget and is not intended to duplicate or 'second-guess' this work. Rather, a 'what-if' approach is taken. What if an integrated view on transportation is taken with a long-term horizon (e.g. to 2050). What if Ontario's economic development, so closely linked to automobile

[1] Toronto-center defined as Union Station (or King-Bay).

manufacturing in the second half of the 20th Century, could be replicated with 21st Century mobility solutions? What if Ontario's considerable effort to reduce GHG emissions through phasing out of coal-fired electricity could be repeated in a subsequent area? What if a strategic approach for Ontario (and Canada) is to increase the relative size of the Toronto region as a way to increase GDP relative to other countries in the 21st Century?

There are about 4,300 gas stations in Ontario [5]. More than $72 billion was invested in Ontario's transportation system from 2002 to 2012 [6]. The standards and regulations associated with vehicles, their fueling, fuel distribution, and links with travel to other jurisdictions are considerable. There is enormous inertia in the existing system. Much of the system appears 'locked-in'. A phased, gradual approach to wide-spread change is likely necessary in order to receive greater support.

Several 'system disruptors' should be anticipated before 2050. These include: (i) autonomous vehicles becoming (relatively) common; (ii) system (data) integration is likely (e.g.; mobile phone connectivity to various transportation modes); (iii) consolidated delivery to businesses and residences (e.g., as Canada Post withdraws household delivery consolidators will emerge); (iv) a price, and possibly a cap on GHG emissions is likely; (v) a 'sharing economy' is likely to emerge (automobiles are probably a key focal point for this); (vi) 'big data' is emerging as an important tool for infrastructure optimization (e.g.; synchronous traffic signalling); (vii) emergence of a distributed electricity system with a greater role for renewables and localized generation (e.g.; through combined heat and power facilities); (viii) much greater attention on resilience and system redundancy (e.g.; system vulnerabilities introduced through heavy reliance on IT and data sharing) – key vulnerabilities include terrorism and criminality, weather-related, susceptibility to price fluctuation, e.g., fuel costs, specialized data management systems and technologies.

The three scenarios investigated in this report provide a spectrum of opportunity. A key aspect of Option 3 is its specific goal to increase the 'effective population' of the Toronto region. National economies are driven by cities; and bigger cities have a disproportionately large impact on the total economy. In other words, one of the ways to help the economy of Thunder Bay, Timmins, Airdrie, AB or Digby, NS may be to increase the effective population size of Toronto. Similarly, connecting Ontario's and Canada's hinterland (to Toronto) is an important source of potential growth for Toronto region as well as rural areas.

1.2 Primary Objectives of this Plan

- Provide an integrated approach; no unique advocacy for a specific technology or fuel type.
- Take a regional approach. Not necessarily the same approach in all areas of the Province of Ontario.
- Enhance productivity and economic development.
- Enhance local quality of life (e.g.; emissions (smog), noise, and public safety).
- Increase overall resilience, particularly in urban service delivery.
- Maximize connectivity – interactions between people (i.e.; reduce congestion and travel times).
- Reduce net travel costs (without unduly increasing other costs).
- Strengthen links across the 416-519-905-613 regions.
- Provide immediate and tangible improvement to the overall transportation system.
- Develop expertise in integrated service provision, in a manner that facilitates international replication (i.e., export local economic development).

1.3 Key Facts:

- Congestion costs Toronto residents $6 billion a year, and is growing [1].
- A comprehensive plan, i.e. the Big Move, is already in place to expand public transit in the area; however, additional attention may be warranted regarding specific solutions, e.g., vehicle and fuel type.
- Today, the transportation sector accounts for 50 percent of the Toronto region's greenhouse gas emissions, and per capita emissions are trending upward.
- 78 percent of the daily trips in the Toronto region are made by personal vehicles; public transit's share is only 15 percent.
- Natural gas has a lower carbon emission rate (52 g-CO_2/MJ) on an energy content basis, compared to gasoline (71 g-CO_2/MJ), and thus can be an alternative fossil fuel.
- Ontario's low emission electricity generation sector provides an important advantage as a means to reduce emissions by electrifying parts of the transportation system.
- There were 3.6 million passenger vehicles on roads in 2009 and based on the current population and economic growth trajectories, this is on track to increase to 5.7 million vehicles by 2050. The number of heavy duty trucks will also rise from 52,700 in 2009 to 87,500 in 2050.
- Considering 0.11 l/km passenger car fuel consumption and assuming 15 percent EV and CNG-HDT shares in Toronto's road transport, fuel costs savings and GHG emissions reduction would be $34 billion and 68 Mt$CO_2$e during the period 2016-2050.
- Although Ontario's electricity grid is integrated differences exist: in some areas such as the western part of the Toronto region distribution limitations exist, while in other areas new generation may be more carbon intensive.
- Launching a BRT system across Toronto region, using CNG buses, along with the implementation of an EV car-sharing program will have significant environmental, let alone cost, benefits.
- Covering 17.7 million-km/y, the extended BRT system provides fast, and easily accessible service to nearly 36,000 passengers a day, and 250,000 Toronto region residents participating in the EV car sharing program.

- The car sharing program would serve 1.2 million[1] residents of the Toronto region. EVs, which would be available at public parking lots throughout the BRT system, are estimated to cost \$0.1/km[2] to operate.
- The economic and GHG emissions savings of Option 3 are substantial, which are estimated as 30 Mt-CO_2e for a 30 year period from 2020 to 2050.
- The related GHG reduction cost savings (assuming \$20/tCO_2e) will be \$600 million.
- The optimum approach is to move forward in an integrated manner and implement both Option 1 and 3. GHG emissions reductions would be substantial: 98 MtCO_2e.

1.4 Some Next Steps

The transportation system discussed in this report takes an integrated and longer term approach. Several possible next steps and follow on analysis emerge. These include:

1.4.1 Developing electric vehicles in partnership with Montreal and Vancouver

Transportation system development is usually a provincial or national purview, however in shifting personal vehicles to more of a shared service a municipal (metro area) perspective may be more effective. Also when looking at electric vehicles (EVs) a unique commonality among large Canadian cities emerges. Canada's three largest cities, Montreal and Vancouver (both supplied by very low carbon electricity), and Toronto (mainly nuclear and hydro), are optimum locations to develop EVs (see Kennedy et al. [4]). Developing a common approach – and maybe consolidated purchasing – warrants further review. EVs are seen mainly as an urban vehicle, with most driving anticipated in a city setting. Winnipeg, Halifax and other cities in British Columbia, Ontario (southern), and Quebec are likely good candidates for EVs as well (modifications may be needed for colder climates). Aggressive efforts to modify Toronto's transportation infrastructure could help decrease transportation-related GHG emissions per capita by 75 percent (e.g. transit infrastructure, active transport, parking fees, electric vehicles) [8]. Applying these changes in the Toronto region would reduce GHG emissions by 6.2 Mt CO_2e per year by 2031.

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[1] Every car from a car sharing pool replaces up to three cars from the existing fleet. Ontario's average personal vehicle occupancy was 1.69 passengers per vehicle in 2009 ([7] NRC, 2011, *Canadian Vehicle Survey Summary Report 2009*, Natural Resources Canada, Government of Canada, Ottawa.

[2] Only vehicle and EV charging stations purchase costs, and cost of electricity are considered. Vehicle maintenance and insurance would increase the price of the car sharing program (similar to existing options).

1.4.2 Expanding natural gas distribution to rural and northern Ontario

There is now much emphasis on expanding natural gas distribution in Northern Ontario. This is mainly being driven by the interest in lower heating and industrial process costs (mainly switching form electricity, oil and propane) for natural gas. A key consideration in moving ahead with this plan, may be to factor in the ancillary benefit of developing a lower-cost, lower GHG emissions strategy for the region: i.e. greater use of NG in vehicles. As the vehicle fueling systems, and heavier reliance on heavy duty vehicles and larger personal vehicles (SUVs and pick-up trucks), make switching to NG vehicle fuel (over gasoline and diesel) more practical in Northern and Rural Ontario. A pragmatic two-step approach to reducing GHG emissions and reducing costs emerges: greater reliance on smaller EVs and NG heavy duty vehicles in the larger cities of Ontario (e.g.; Toronto region), and a more aggressive switch to NG vehicles in more remote parts of Ontario, in concert with expansion of the NG distribution system.

1.5 The Next Connections

Bettencourt and West [9] outline an important characteristic about cities: as cities grow their connections and economies grow super-linearly (at about 1.15 times), while infrastructure, like roads, scales sub-linearly (at about 0.85 times). In other words, double the size of your city and the economy grows almost two-and-a-half times, while the money you need to spend on infrastructure is less than double. Big cities count, and the best way to make your cities and your country count even more on the global stage is to make their effective size as large as possible. Make it easy for people to connect, and your local economy benefits. This is especially important for Canada, as Toronto region, the Country's largest city is dropping about 2 places in the 'world's largest cities list' every year – and this despite significant population growth. Montreal, Canada's next largest city is today about the world's 85th largest city – by 2050 it won't even be in the top 200 (Vancouver, the next largest will be about the 230th largest [10]).

Increasing the effective size of Toronto is imperative for a prosperous Ontario and Canada. One way to help this happen is to foster 'connection nodes'. At all the key transit hubs, connection nodes should be established that encourage face-to-face as well as telepresence meetings. Toronto region can shift its transportation challenges, and relative lack of density, to a key strength. Business and government can converge in developing easily accessible 24-

hour meeting spots throughout the region. Combining connectivity, cafes, libraries, vehicle servicing, and meeting facilities in some fifty 'ON-Route' locations would help shift the commuting mind-set while increasing the region's effective population. Making it easier for someone in Kitchener, Durham, or Niagara Falls to participate in the economic growth of 'Toronto' is an enormous economic boon to the region. And increasingly a daily commute is not needed.

1.6 The New Drivers of Urban Mobility

Human error contributes to about 90 percent of all vehicle accidents. The average car is parked 96 percent of the time (depreciating and taking up valuable space). Highways and roads in the Toronto area, reach peak throughput less than 4 to 5 percent of the time. Of the total energy consumed by a typical car only a few percent is actually used to move the driver and occupants. More than a third of Toronto's land area is devoted to the automobile. As drivers age, autonomous vehicles emerge with linked communications systems, and younger consumers shift away from car ownership; big changes are coming in the mobility sector[1].

Ontario owes much of its economic success to the automobile. With North America's rush to the road and the freedom of automobiles, and Ontario's cheap electricity, cities like Oshawa and Windsor, as well as Oakville, Brantford and St. Catharines, had much of their economy driven by the automobile. But building more cars is a less-and-less attractive road to travel. Building better mobility systems is emerging as the industry for the 21st Century. Ontario has a chance to benefit both locally from this shift (less congestion, more economic opportunity) as well as to benefit from exporting this expertise and experience. Almost every city in the world is struggling with urban mobility challenges. Few have expended as much analysis, or have as much need (and ability) for reform as Toronto. An integrated mobility system that invests in the right infrastructure, as well as maximizes the use of the new tools and behaviours of connectivity; that builds in resilience, and partners with key stakeholders like Montreal and Vancouver, IT companies, energy companies, and vehicle manufacturers; that caters to all modes of travel; and that is designed specifically to increase real estate (land) values, is imperative. Ontario could manufacture much of the needed infrastructure and EVs.

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[1] Values from, McKinsey, 'Resource Revolution: How to capture the biggest business opportunity in a century'.

1.6.1 Introducing sustainability cost curves

Figure 9 provides a draft notional sustainability cost curve for the Toronto Region transportation infrastructure. The curve, once further refined, can assess long-lived urban infrastructure from a sustainability and cost (and benefit) perspective. Potential investments can be compared by cost effectiveness in delivering sustainable development objectives to 2050. Sustainability cost curves will facilitate fact-based comparison and credible public policy development. They should become wide-spread for all large scale public infrastructure (at a city level). The curve, and a mechanism to consolidate a comprehensive aggregation of impact estimates, will be first introduced for Toronto's transportation and connectivity sector, however the goal is to develop the curves for energy and basic services (water, waste, and drainage). Toronto is the first city where this UOIT research approach is being applied; however the goal is to develop these for all the world's large cities, e.g. those expected to have over 5 million residents by 2050 (about 122 cities).

2. Greenhouse Gas Emissions

Total greenhouse gas emissions related to a specific energy option are a function of the cumulative lifecycle impacts associated with the activity. For example solar photovoltaic (PV) generation is emission free; however, during manufacture, transportation and disposal of photovoltaic cells greenhouse gas emissions are generated. Nuclear energy is relatively low in overall GHG emissions, yet emissions associated with plant construction can be large. Coal-fired power plants generally have the highest level of greenhouse gas emissions among all energy options. Therefore, avoiding electricity generated from coal (as an energy source) decreases carbon emissions. Annex 1 provides the average lifecycle greenhouse gas emissions from several power generation options including coal, natural gas, solar PV and nuclear.

In Ontario, electricity is mainly (>50%) generated by nuclear power plants, and hydropower (~30%), both of which generate relatively low GHG emissions. With Ontario's phase out of coal fired electricity the main source of carbon emissions today is from the transportation sector – mostly gasoline and diesel combustion. A breakdown of carbon emissions in the Greater Toronto Area in 2009 is given in Table 1. Diesel and gasoline combustion contribute a significant share of the annual total 54 $MtCO_2e$ GHG emissions. The values in Table 1 include a 10 percent reduction in carbon emissions from the 2005 level.

Table 1: Carbon emissions in the Toronto region

	Million tonnes of CO_2e (2009)	Share, %
Electricity	6.5	12.1
Natural gas	16.9	31.0
Gasoline	15.8	29.4
Diesel	5.1	9.5
Others	9.6	17.8
Total	53.9	100

Adapted from Ref. [11]

It is worth comparing the levels of carbon emissions from each energy sector in Ontario broadly, and the Toronto region specifically (nearly 45 percent of Ontario's residents live in the Greater Toronto Area). Transportation accounts for 34 percent of Ontario's overall GHG emissions, while in the Toronto region transportation accounts for almost 50 percent of total emissions (Table 2). The significant impact of transportation in the Toronto region – from the perspective of GHG emissions, economic development, and quality of life – drives the need for rapid development of less polluting more efficient transportation alternatives.

Table 2: Greenhouse gas emissions by sector in Ontario and Toronto region

Sector	Ontario[1] ($MtCO_2e$)	Toronto region[2] ($MtCO_2e$)
Transportation	58	26*
Electricity	15	6
Residential, industrial, agriculture, waste	98	22
Total	171	54

[1]Adapted from Ref. [12], data reported for 2011

[2]Adapted from Ref. [11], data reported for 2009

* Includes jet fuel consumption. Emissions from road transport were 21 $MtCO_2e$ in 2009

Both the Province of Ontario and City of Toronto have set regulations and targets to reduce emissions from fossil fuel energy use (Table 3 provides a summary of the targets to 2050). The targets are set according to the 1990's GHG emissions level (177 Mt CO_2e): By 2050 carbon emissions in the Toronto region are expected to be reduced to 35 Mt CO2e. This ambitious target can only be met through higher transportation fuel economy, low-carbon power generation, and an overall decrease in per-capita energy consumption. Ontario is likely better positioned to meet GHG reduction targets; however, meeting the 2050 86 percent reduction target is unlikely [13].[1]

Table 3: Greenhouse gas emission targets in Ontario and Greater Toronto Area (percentile decrease from the 177 Mt CO_2e emission levels of 1990)

Target year	2014	2020	2050
Ontario[1]	6%	15%	86%
Toronto region[2]	18%[3]	30%	80%
[1]Adapted from Ref. [14] [2]Adapted from Ref. [11] [3]2016 target			

3. Role of Natural Gas

Increased supply of 'unconventional' natural gas, particularly from the US, is raising expectations for higher natural gas penetration in Canada. According to the United States Energy Information Administration the estimate of technically recoverable Canadian Shale gas is 537 trillion cubic feet, [15]. Assuming current consumption rates, Canada's natural gas resources will likely be available for the next 100 years. Natural gas has the lowest carbon content of all hydrocarbon fuels. Therefore substituting oil and coal with natural gas will lead to a substantial decrease in greenhouse gas emissions in Canada (aside from a gradual increased demand for energy). In 2013, fossil fuel combustion generated 71 percent of Canada's greenhouse gas emissions. If substituted with natural gas, emission levels would decrease 20 percent.

[1] For example much discussion centers around the Alberta oil sands, however more than 80% of the GHG emissions associated with any transportation fuel are generated through combustion (use). Reducing use is far more impactful than recovery, refining and distribution practices.

3.1 Natural Gas for Transportation

Natural gas vehicles are common in Iran, Pakistan, Argentina, Brazil, China and other parts of the world; mostly as taxicabs, and light duty trucks. There are more than 15 million natural gas vehicles around the world that run on compressed natural gas, confirming that NG can be used in the transportation sector safely and economically [16]. Federal and provincial policies and regulations promoted the use of NGVs in Canada from the late 1980s to the early 2000s, making Canada a leader in NGV use at the time. However the number of natural gas powered vehicles in Canada declined in the early 2000s and dropped to 12,500 by 2012. Today, the number of registered NGVs in Canada is relatively low compared to countries with widespread NGV use (Canada ranks 29th globally in its adoption of NGVs)[1].

3.2 Natural Gas for Electricity Generation

According to the World Bank, 21 percent of the world's electricity is generated through combustion of natural gas. High efficiency in both base-load and off-peak generation, lower carbon emissions (compared to coal), and fast response to load variations, suggests that natural gas power plants will play an increasingly prominent role in the electrical energy market by 2050 (despite a likely price on carbon).

4. Electric power Generation in the Greater Toronto Area

Ontario's coal phase-out was completed by April 2014 (current electricity market make-up is shown in Figure 1). Nuclear and natural gas power plants dominate the electricity generation market in Ontario, with 12,947 and 9,920 MW of installed capacity, respectively. Generating 17.1 TWh of electricity, NG power generation contributed 11 percent of the provincial demand in 2013, which is ranked third after nuclear (59%) and hydro (23%) [17].

By considering average lifecycle greenhouse gas emissions from power plants, the annual carbon contribution of Ontario's power generation in 2013 is estimated at 15.2 million tonnes of CO_2e. This results in an average emission intensity of 98.7 g-CO_2e/kWh. However, by

[1] NGV Global (formerly known as The International Association for Natural Gas Vehicles – IANGV) publishes NGV statistics in which Canada is ranked 29th for its number of existing NGVs.

closing coal-fired power plants (or converting them to natural gas) in 2014, the carbon intensity of electricity generation in Ontario dropped to 80 g-CO_2e/kWh. This is considerably less than the GHG emissions from direct combustion of gasoline (270 g-CO_2e/kWh)

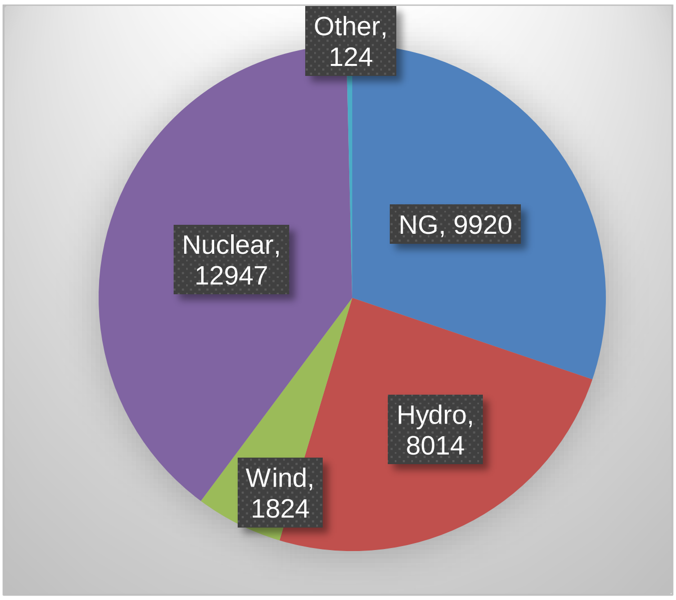

Figure 1: Ontario's electricity generation capacity, MW [17]

5. Transportation Modes in the Greater Toronto Area

Nearly 78 percent of the personal trips in the Toronto region are taken by passenger vehicles using fossil fuel. The remaining trips are taken by either public transit (15%), or walking and cycling (7%). Figure 2 highlights the results of a survey conducted by the Data Management Group at the University of Toronto [18]. The study, Transportation Tomorrow Surveys (TTS), is part of an ongoing survey that started in 1986, and is conducted in 5 year intervals.

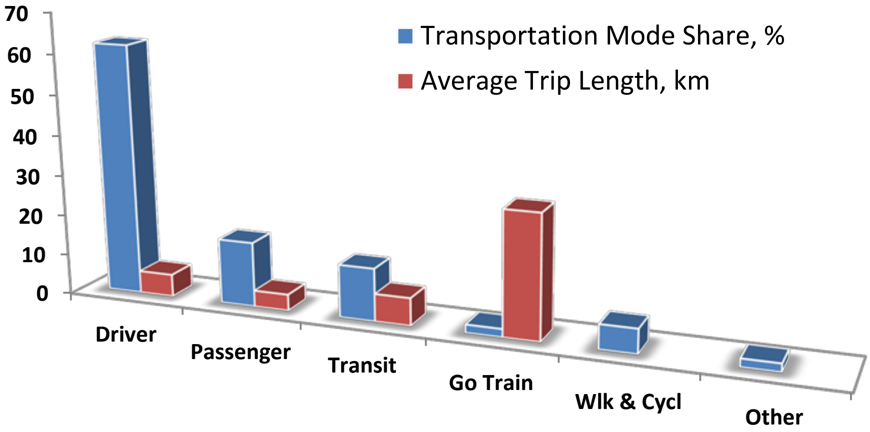

Figure 2: Transportation mode share and average trip length in the Toronto region in 2011 [19]

Table 4: Personal and public transit characteristics of Toronto region

Ave. time of car trip, min	Ave. time of public transit trip, min	Travel cost by cars, $/km	Travel cost by public transit, $/km	Energy use of cars, MJ/passenger-km	Energy use of transit vehicles, MJ/passenger-km
14[1] (5.5 [18])	28[1]	0.106[2]	NA	2.2[3]	1.14[4]

[1]Adapted from Ref. [20]

[2]Gas is priced at $1.24 per liter, and 18,000 km is considered [21], this only represents the cost of fuel per km. maintenance costs are not considered.

[3]Based on an average gasoline consumption of 10.6 l/100-km and average car occupancy of 1.60 in Ontario.

[4]Adapted from Ref. [22]

The majority of Toronto region residents use passenger vehicles for their personal trips, and these average 5.5 km per trip. While only 15% of personal passenger trips were by public transit, the average trip length is as high as 31 km. Average values for trip time, cost, and energy consumption are given in Table 4.

Carbon emission intensity compares transportation modes in terms of their greenhouse gas emissions. Numerous reports are published on differing scenarios and regions. Engine efficiency, fuel purity, climate, road conditions, and traffic can affect net vehicle tailpipe emissions. The carbon emission intensity of passenger vehicles varies between 0.2-0.4 kg-CO_2e/km; corresponding values for heavy-duty trucks are higher. Figure 3 shows the values reported by Natural Resources Canada. The given values account for fuel lifecycle, and does not include carbon contribution from vehicle production.

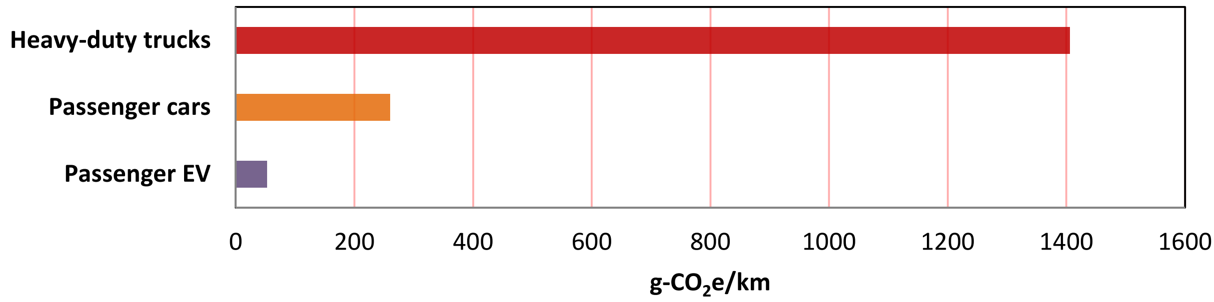

Figure 3: Emission intensity of some transportation modes [23]

An important factor affecting carbon emission intensity is the vehicle's fuel type. The dominant vehicle fuels, diesel and gasoline, have lower heating values (LHV) as high as 43 MJ/kg. However, carbon emission from the combustion of diesel on a gravimetric basis (in standard conditions) is higher than the emissions from burning gasoline. Table 5 provides information on the LHV of several transportation fuels and their lifecycle carbon dioxide emission intensities. On a per kg basis, natural gas contains more energy than diesel and gasoline, and CNG has the lowest level of carbon emission followed by LNG.

Table 5: Lower heating value and lifecycle carbon emission of common transportation fuels

	Lower heating value (MJ/kg) [24]	Carbon emission (kg-CO_2/kg-fuel)	Carbon emission (g/MJ) [23]
Diesel	42.8 (35.5 MJ/l)	4.25	99.4
Gasoline	43.7 (32.5 MJ/l)	3.97	90.7
CNG (Mobile)	47.2 (33.6 MJ/m^3)	3.49	73.9
Density of diesel 830 kg/m^3, gasoline 744 kg/m^3, and CNG 0.712 kg/m^3			

Several peer-reviewed studies assess vehicle emissions through experimental or analytical approaches [25, 26]. For example Sandhu et al [27] measured fuel consumption and emissions rates of six refuse trucks (model years 2004 to 2010) using portable emissions measurement systems. The experiment was conducted on operations over 47 hours and 901 km. The refuse trucks operated in an idle mode for 44 percent of the time, and daily average fuel economy was 0.98-1.4 km/l. The PM emission rates for trucks with diesel particulate filters are 98 percent lower than those without. Emission rates from the trucks are strongly related to their daily operating regime. The differences between highest and lowest emission rates are 46 percent for fuel use and CO_2 emissions, 121 percent for CO, 57 percent for HC, 59 percent for NO, and 72 percent for PM. Newer trucks have comparatively lower emission rates. Table 6 provides the results of the emission rates from the tested diesel refuse truck.

Table 6: Fuel use and emission rates for an average daily activity cycle of a refuse truck [27]

Fuel (Diesel)		CO_2	CO	HC	NO_x	PM
L	km/l	kg/km	g/km	g/km	g/km	g/km
140	1.1	2.4	1.2	7.5	14	0.01

Rose et al [28] show significantly lower emissions rates from NGV refuse trucks (mostly for CO and NO_x) than similar diesel vehicles. Karman et al. review transportation emissions in the United States and Canada [26], where emission regulations for heavy duty trucks are based on the EPA's 2010 standards. In the case of trucks, relatively small amounts of distance is traveled over total operating hours (e.g. refuse trucks and construction equipment for example), the emissions cannot be expressed in terms of g/km but are rather expressed in terms of the mass of emission per energy delivered to the dynamometer, g/bhp-hr. These emissions regulations are provided in Table 10.5 in Ref. [26].

6. Alternative Transportation Options

This section presents the three proposed scenarios. Implementation of these scenarios will reduce congestion and greenhouse gas emissions, while strengthening economic activity and resilience of the Toronto region. The scenarios are as follows:

Option 1: Expansion of market penetration of electric and natural gas vehicles by 35 percent.

Option 2: Introduction of a Highway 401/407 Rapid Transit (RT) system with stops at major interchanges where parking lots with electric vehicle charging capabilities are allocated. Passengers would mostly use their privately owned EVs.

Option 3: Expansion of the RT system to Waterloo, Niagara Falls, Peterborough, and Cobourg: Public (shared) EVs would be available at nodes along the bus rapid transit (BRT) system. Passengers can drive the electric vehicles home (recharging batteries at homes, businesses and parking lots overnight). This option promotes economic development through greater connectivity and a larger functional population size for the Toronto region.

The three proposed options will shift electricity requirements to transportation with charging occurring mostly during off peak times.

6.1 Option 1: Expansion of the market penetration of electric and natural gas vehicles

Increasing the share of EVs and NGVs in the Toronto region requires an understanding of overall vehicle capabilities. In particular, these vehicles are considered for their potential to mitigate both fuel costs and emissions. The cost of vehicle manufacturing, insurance and maintenance is considered comparable for the purpose of this study. As this study uses a 35 year retrospective assessment, vehicle technologies, personal behaviours, and transportations patterns are likely to change substantially. Moving toward wider use of EVs and NGVs is likely to occur in most large urban areas – the Toronto region is well positioned to encourage (and ideally lead) this as natural gas is relatively available, Ontario's electricity carbon intensity is one of the world's lowest, regional automotive manufacturing expertise and app development and software (information technology) capacity is considerable. Significant needs and capabilities are aligning.

Wide-spread adoption of alternative vehicles requires consideration of the following issues:

- Most passenger vehicles are parked at owner's homes, particularly at night. Hence, in-home vehicle charging stations are needed.
- Local distribution companies (LDCs) may require modification and new infrastructure to service home fueling (electric and natural gas). Greater draw on electricity grids and NG pipelines needs to be accommodated.
- Retail refueling stations are required in high-density residential areas to attract and accommodate a wider range of users. So too stations (especially for EVs) in apartments and condos.
- Existing design operation and safety regulations and standards may need to be updated to account for the additional stress on natural gas and electricity distribution systems.
- Consumer education and training is also required to increase receptivity to natural gas and electric vehicles.
- An actual, or 'shadow price' should be applied to carbon to improve system design and provide proper pricing signals to governments and drivers.
- Harmonization (and possible disaggregation) of some Canadian and Ontario regulations and standards with those of USA, Quebec and other jurisdictions.
- As both natural gas and electricity prices are regulated in Ontario, signaling of likely long term pricing regimes is needed. As transportation fuels electricity and natural gas would displace gasoline and diesel (reducing price volatility, but requiring clear provincial and Government of Canada signaling on likely taxation regimes).

Ontario’s economy is anchored to the automobile. With relatively cheap electricity and access to the large US market (supported by the 1965 Autopact) Southern Ontario emerged as one of the world’s major automobile manufacturers[1]. Ontario is now faced with the challenge of a declining auto industry (manufacturing). As outlined in this report there is possibility to bring in an integrated transportation system for the Toronto region. This will require advances in IT systems, EVs, NGVs, smart grid development (electricity and pipelines), standards and regulations, low carbon electricity, and many related components. However emergence of one dominant manufacturer such as previously experienced with the automotive industry is less likely. With advanced manufacturing techniques, vehicles are likely to be more customized by city (major urban area).

A more comprehensive economic analysis is required than presented in this report. What are potential benefits of health impacts from a revised Toronto region transportation system? How will land values be impacted by a more comprehensive transportation system? How can the governments of Ontario and Canada disaggregate standards and regulations by city (metro area)? What are likely trends for long term material flows (trucking) – can heavy duty transport trucks be steered toward a dedicated route through the Toronto region? How can Ontario maximize economic development and productivity gains through the revised transportation system presented here?

6.1.1 Assumptions and data use

Costs and GHG emissions are estimated for the three proposed Options. The assumptions for Option 1 are provide (data used in the calculations are given in Tables 7-9) below:

- EV, passenger NGV, and NG HDT penetration by 2050 are 15, 5, and 15 percent, respectively.
- On average a light duty vehicle in Ontario consumes 10.6 litres gasoline per 100-km. North America’s target is 7.8 l/100-km [29].
- Fuel prices are listed according to the average 2014 real-market prices in Ontario, according to the Ministry of Energy [30]. A 1 percent annual increase in fuel prices is applied.
- Household electricity prices are used in EV charging cost estimations; although prices for public EV charging, which include taxes, retail markup, and retail capital cost recovery should be considered for options 2 and 3.

[1] More than 80 percent of Canada’s automotive industry is based in Ontario; 80 percent of production is exported. Employment peaked at 153,000 workers in 2000 and is now below 100,000 workers (and declining). Canada’s automotive industry is recognized to have largely been launched by Colonel R.S. McLaughlin, in Oshawa, who eventually sold production to General Motors. From 1918-1923 Canada was the world’s second largest exporter of motor vehicles. In the 1920s mass manufacturing of automobiles, e.g. Ford’s Model T, consolidated more than 2000 pre-existing auto manufacturers.

- The Ontario electricity generation mix [31] is used to calculate the specific carbon emissions from electricity generation. This is used to calculate the level of GHG emissions from electric vehicles.
- Average passenger, GO Bus, and heavy duty truck kilometer-traveled per day are obtained from the 2009 Canadian Vehicle Survey report by the Natural Resources Canada [7].

To adjust fuel prices, an annual 1 percent increase is applied; however, a more refined fuel price scenario should be developed for a more accurate long term cost evaluation. Floor prices for gasoline and diesel could be reviewed. Table 9 provides estimates for the number of vehicles in the Toronto region today, and in 2020 and 2050, based on a historical growth patterns reported by Natural Resources Canada [7].

Table 7: Assumptions and data used in the three proposed Options

	2014	2020	2050
EV penetration, %	NA	5	15
Passenger NGV penetration, %	NA	2.5	5
NG HDT penetration, %	NA	5	15
Gasoline price, $/l	1.33		
Diesel price, $/l	1.34		
Electricity price, ¢/kWh	15.5[1]		
CNG price, $/kg[2]	1.28		
Fuel Economy			
Ave. passenger vehicle fuel consumption, l/100-km	10.6[3]	10	7.8
Ave. EV energy consumption, kWh/100-km	20[4]	20	18
Ave. NGV fuel consumption, kg-NG/100-km	7	7	5.5
Ave. HDT fuel consumption, l/100-km	33.2 [7]	33.2	33.2
Ave. NGV HDT fuel consumption kg-NG/100-km			
Ave. passenger vehicle-km traveled per day, VKT[5]	44 [7]	44	44
Ave. HDT km traveled per day	207 [7]	207	207
Electricity generation data are given for 2032 based on Ontario LTEP 2013			

[1] Average electricity price 10.7 ¢/kWh, plus 4.75 ¢/kWh delivery and distribution charges to a household in the GTA

[2] The cost of NG delivered to the home or a business is about $0.35/kg. The price of home CNG refuelling including capital recovery and electricity cost is closer to $1.00/kg. The all-in cost of NGV is also considerably cheaper than retail for a private on-site facility that does not pay retail margin and O&M markup ($0.9/kg).

[3] Average gasoline consumption of light vehicles (cars, station wagons, vans, SUVs, and pick-up trucks) in 2009 in Ontario. [7] NRC, 2011, *Canadian Vehicle Survey Summary Report 2009*, Natural Resources Canada, Government of Canada, Ottawa.

[4] [32] NRC, 2014, *Fuel Consumption Guide*, Natural Resources Canada, Government of Canada, Ottawa.

[5] Average distance traveled by light vehicles in 2009 in Ontario was 16,200 km/y.

Table 8: Ontario electricity generation mix (percentage) and related lifecycle GHG emissions

	2014	2020	2032 (2050)
Nuclear[1]	56.6	47.3	43.6
Hydro	24.4	26.0	24.6
Natural Gas	10.6	11.9	17.0
Renewables	8.4	14.7	14.8
Emissions			
Electricity (lifecycle), g-CO_2/kWh	79.6	86.1	109.7

Table 9: Number of vehicles on Road in the Greater Toronto and Hamilton Area

	Present	2020	2050
# of personal vehicles, million	3.55 (2011)[2]	3.95	5.67
# of EVs, million	NA	0.20	0.85
# of personal NGVs, million	NA	0.10	0.28
# of Heavy duty trucks	52,751 (2009) [7]	65,000	87,500
# of NG heavy duty trucks	NA	3250	13,125

6.1.2 Results and discussion

In 2011 there were 3.55 million personal vehicles on the road in the Toronto region; an average of 1.5 vehicles per household. The residents of the Toronto region made their daily trips using personal vehicles (78%), public transit (13%), Go Train (2%), and walking and cycling (7%). In total, over 13.6 million trips were made averaging 5.2 km/trip for personal vehicles, 6.8 km/trip for public transit, and 30.5 km/trip for GO train trips. Personal trips are categorized as "Driver" and "Passenger"; historical data are shown in Figure 4. A linear increase is indicated and a corresponding projection yields an estimated total of 12.1 million trips per day in 2020.

[1] Adopted from Ontario Long Term Energy Plan 2013, the data for 2032 are used here for 2050

[2] [18] Data Management Group, 2011, *Travel Survey Summaries for the Greater Toronto and Hamilton Area*, Department of Civil Engineering, University of Toronto, Toronto.

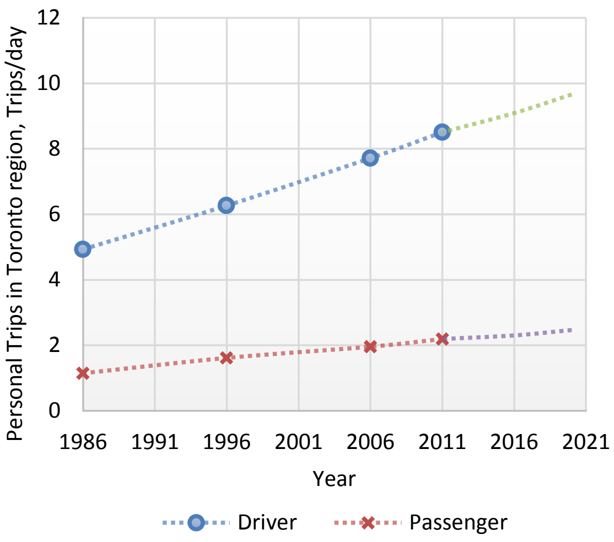

Figure 4: Personal trips made by the residents of the Greater Toronto and Hamilton Area

According to Figure 5, similar trends in growth for population (62% increase) and personal vehicle ownership (73%) were experienced from 1986 to 2011. These growth rates increased somewhat during the period of 2006 to 2011. According to the Government of Ontario [33] the Toronto region's population is estimated to reach 8.9 million in 2036, which follows the same growth rate as in the last 25 years.

A linear estimate to the year 2036 for population and vehicle ownership in the Toronto region results in 4.9 million personal vehicles, which corresponds to 0.54 vehicle per capita (7.4 million residents and 3.95 million personal vehicles in 2020).

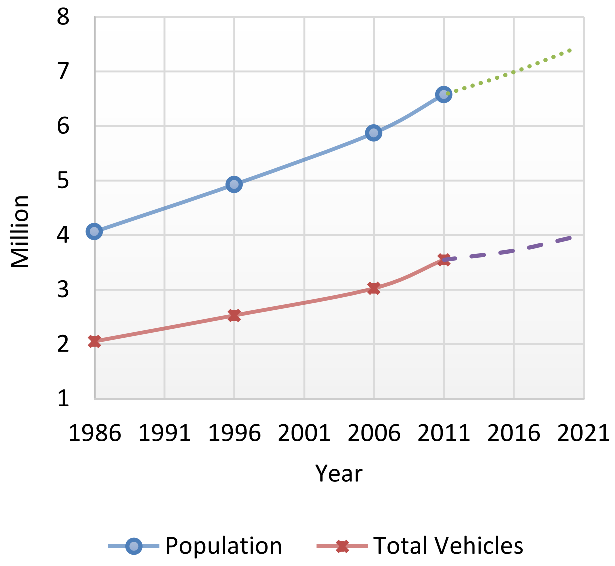

Figure 5: Population and vehicle ownership in the Greater Toronto and Hamilton Area

According to Natural Resources Canada [7], the average distance traveled by light vehicles in Ontario is 16,200 km/y. By considering an average gasoline consumption of 10.6 l/100-km for passenger cars and 2.95 kg-CO_2e/l-gasoline (see Annex 4), the equivalent carbon emissions from passenger transportation in the Toronto region is estimated as 19 Mt-CO_2e/y. Any change (improvement) in the transportation modes in the Toronto region that results in increased use of electric and natural gas vehicles for personal trips will reduce GHG emissions.

Average fuel consumption of light and heavy duty vehicles in Ontario is 10.6 and 33.2 l/100-km respectively, according to a report by Natural Resources Canada in 2011 [7] . The average distance traveled by HDTs is reported as 76,000 km/y. At the time of this report, we were not able to estimate the number of heavy duty trucks on Toronto region roads; however, an estimate is made based on the number of HDTs in Ontario in 2009. According to the 2009 Canadian Vehicle Survey, there were 7,362,689 vehicles on Ontario's roads with the following breakdown based on vehicle type:

- 7,166,834 light vehicle, e.g. cars, SUVs, and pick-up trucks (0.5 vehicle per person, which is quite similar to the value for the Toronto region reported in the 2011 Toronto Transportation Survey)
- 90,353 medium duty vehicles
- 105,503 Heavy duty trucks

Comparing the number of personal vehicles in Ontario (7.17 million cars) and the Toronto region (3.55 million cars), the Toronto region home to 50 percent of the province's light duty vehicles. If the same ratio is assumed for heavy duty trucks, it is estimated that there were 52,751 HDTs on Toronto region roads in 2009.

The results of the emissions and cost analyses for Option 1 are given in Tables 10 and 11, and the relevant equations are provided in Annex 2 and 3. Costs related to vehicle purchase and operation and maintenance are not considered in the calculations. With the business as usual (BAU) scenario, 295 billion litres of gasoline and diesel are consumed by passenger vehicles and heavy duty trucks from 2015 to 2050, which contribute to the emission of 907 Mt of greenhouse gases. Assuming the current trend in vehicle population growth in the Toronto region, a 15 percent EV and NG-HDT, and 5 percent passenger NGV market penetration will help decrease the level of GHG emissions by 68 $MtCO_2e$, within the same time frame. Applying a carbon price of $20/$tCO_2e$, shows $1.4 billion in carbon cost savings. The cost saving relative to the fuel consumption savings is approximately $34 billion, as given in Table 11.

Table 10: Fuel consumption and costs, and GHG emissions of light and heavy duty vehicles, and relative savings by implementing Option 1

	2016-2020				2021-2050						
	BAU[1], billion litres gasoline	Gasoline, billion liters	EV, TWh	NGV, billion kg	BAU, billion litres gasoline	Gasoline, billion liter	EV, TWh	NGV, billion kg		**2016-2020**	**2021-2050**
Total Fuel Consumption	40.5	38.8	1.9	0.5	254.4	220.9	44.6	9.4	Savings, Billion litres gasoline	1.7	33.6
	Total	Gasoline	EV	NGV	BAU	Gasoline	EV	NGV		2016-2020	2021-2050
Total Fuel Cost, billion $	56.3	53.9	0.3	0.6	423.9	366.7	8.8	12.7	Savings, billion $	1.5	35.7
	BAU	Gasoline	EV	NGV	BAU	Gasoline	EV	NGV		2016-2020	2021-2050
Total Emissions, Mt-CO_2e	123.9	118.8	0.2	1.8	783.7	681.3	4.7	32.9	Savings, Mt-CO2e	3.2	64.8

[1]Busines as usual (BAU) represents data for a case that all the passenger vehicles on the road run on gasoline

Table 11: Economic results for Option 1- cumulative for the period 2015-2050

	Total cost of infrastructure (charging and refueling stations)[a]	Fuel Savings[b]	Net Cost Savings
Total cost, Option 1, billion $	3.40	37.2	33.8

[a]Cost of home charging stations: $2,000

[b]Savings related to less gasoline/diesel consumption (increased use of EVs and NGVs)

6.2 Option 2: BRT line across HWY 407, with stops at the major interchanges and public EV charging stations

Several of the major intersections along the 407 highway are shown in Figure 6. At each stop, parking lots would accommodate electric vehicles (passengers can park their own EVs while commuting or during other personal trips).

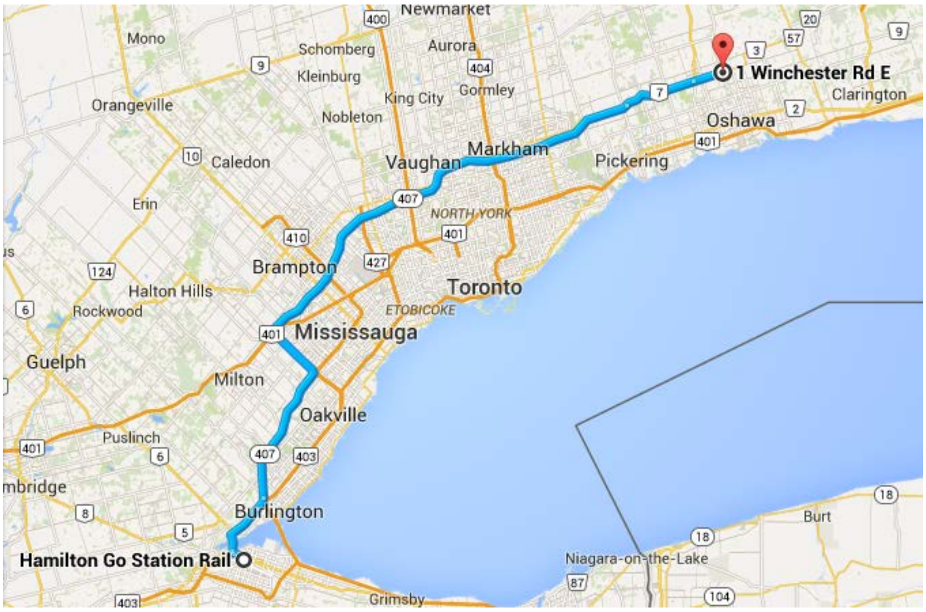

Figure 6: Proposed BRT line across HWY 407, Option 2

Figure 6 shows a possible bus route along 407, starting at the Hamilton GO Train Station and ending at HWY 407 and Simcoe Street North, Oshawa. The distance between the two ends of the proposed RT line is 136 km.

Establishing a RT system requires an assessment of environmental impacts, land use impacts, costs, and pre-feasibility technical analysis. From the environmental perspective, bus fuel type plays a major role. Moreover, using the current, available fuel emission technologies, such as diesel particulate filters, selective catalyst reduction, exhaust gas recirculation, and variable geometry turbocharges will help decrease the levels of GHG emissions by the transit system. In addition, alternative fuels are promising for future decreases in emissions. Some of the economically available options are LNG, CNG, and electric buses. A report by the Federal Transit Administration [34] compares the release of particulate matters and NO_x by different fuel types in the transportation sector, for which CNG buses emit 90 percent less particulates and 30 percent less NO_x compared to untreated diesel. Therefore, in addition to the carbon reduction from increasing public transit share in transportation, using less carbon emitting buses will also help mitigate other environmental concerns.

The passenger capacity of a RT system depends on several parameters such as the number of stops, bus capacity, and frequency of service. A typical transit bus carries 60-80 passengers per trip, while an 18 meter long articulated bus can accommodate up to 270 passengers. The capacity of the proposed RT-EV system needs to be estimated to facilitate an economic analysis. Transit buses usually run on diesel, which may receive complaints regarding noise and air pollution (soot). A typical diesel bus costs around 300,000-$600,000. Natural gas buses are becoming popular, but are up to $70,000 more expensive. Hybrid buses that use a diesel or gasoline engine along with an electric motor cost nearly $714,000. Electric buses are not yet fully satisfactory in the mileage they can provide. The capital investment costs of a RT system vary by jurisdiction, and strongly depend on existing infrastructure, meeting the required environmental and safety regulations, and the capacity of the RT line. On average, the total capital cost can vary from $0.7 to $25 million per km. Aside from bus purchase costs; there are operating costs, which are typically estimated per hour. Examples of vehicle operating costs include New York City ($172 per hour), Los Angeles ($124 per hour), and Phoenix ($92 per hour) [15].

6.2.1 Rapid Transit examples

The City of Mississauga started construction of a BRT system in 2010, with the aim of improving local and inter-regional transit across the city. The 11 km-long busway now operational between Winston Churchill Boulevard and Renforth Drive with a total of 12 stops along the route. The project was estimated to cost $260 million with funding from several sources, which corresponds to an average $23.5 million per km.

In 2011, the Regional Municipality of York opened its first RT station located at Warden Avenue and Enterprise Boulevard in Markham, which was the first of 11 new stations along Highway 7. The investment for this project was a part of ‘Open Ontario Plan’. According to the Project Status Quarterly Report by York Region Rapid Transit Corporation, there are several ongoing rapid transit projects in York Region, including the remaining segments of Highway 7 East from Highway 404 to Warden Avenue.

The Transitway is an exclusive bus corridor providing rapid transit service across the City of Ottawa, which is also connected to O-Train (an eight km light-rail service). The Transitway is exclusively accessed by transit and emergency vehicles, and thus is unaffected by traffic delays. Ottawa's Transitway was Canada's first BRT line, opened in 1983, and currently carries up to 10,000 passengers and 185 buses per hour [35].

Calgary's RT system links the downtown to suburban areas via a two corridor, 47 km transit way, running every 10 min in rush hour periods and every 20 min during regular traffic periods. The city also uses light-rail transit. Lower cost per revenue hour is reported for Calgary's BRT than its LRT system [36] ($49 vs. $113, respectively). Other major Canadian cities have transit systems that can be categorized as BRT systems, although implementation has varied by local conditions. Dedicated bus routes are a major element in establishing a successful BRT system, and enforcing transit priority measures does not essentially cover the concept of a bus rapid transit system. In Canada, public transit is a responsibility of the municipalities, and the local governments assign agencies to plan, construct, and coordinate public transit investments. However, the federal government contributes to the development of public transit systems because these help the economy, the environment, and promote good public relations. The Government of Canada has funded several transit project under the Canada Strategic Infrastructure Fund including the Canada Line project in Vancouver, the Mississauga BRT project, and York Region's VIVA bus rapid transit project. Other examples of transit projects funded by the government are given in [36]. Internationally, successful RT systems include TransMilenio (Bogota), Metrobus (Pakistan), MIO (Cali, Colombia), and Metrolinea (Bucaramanga, Colombia).[19]

6.2.2 Assumptions, data use and results for Option 2

GO Bus now has 500 buses on the road carrying 55,000 passengers via 2,500 trips a day. Highway 407 is a major GO Bus route, connecting Guelph and Hamilton in the western Toronto region to Pickering and Oshawa in the eastern Toronto region [37]. GO Bus routes have grown from 24 daily trips in 2000 to 730 trips a day in 2014. On a weekday GO Bus makes 560 trips

[19] For comparison purposes globally 186 cities have BRTs serving 32 million people daily. In 2012 there were 1.8 million car-sharing members; 600 cities have bike sharing programs. Istanbul has 295 pedestrian streets (where cars are now prohibited); Helsinki recently announced plans to eliminate the need for cars by 2025 (making it the first car-free city) [from Tina Duong, thecityfix.com, 2014].

on Highway 407 (77% of all the GO Bus trips in the Toronto region), therefore, Highway 407 GO bus ridership is estimated at 42,300 passengers per day. These trips cover 37,400 km, resulting in an average of 67 km/trip.

The total distance between the Hamilton Go Station (on the Lakeshore West GO Train line) and Oshawa, on Highway 407 is 136 km. It will take approximately 2 h and 20 min for a BRT bus to travel this distance, assuming and average speed of 60 km/h. To estimate the number of buses required to operate on the HWY 407 BRT line, 15 min bus intervals are considered during rush hour (6 am – 9 am, and 3:00 pm – 6:00 pm), and 30 min intervals are used for other times of the day, starting at 5:00 am and ending at 1:00 am the next day (21 hours of operation per day). Therefore, 22 buses are required to operate on the BRT line. There are 108 total daily both ways and bus capacity is 55 passengers. Hence, the total daily ridership is estimated to be 5,900 passengers. 15 and 30 min headway are considered for the proposed BRT lines in Options 2 and 3. These assumptions are the same for all the proposed lines; however, adjustments may be required depending on the region and ridership estimations. Table 12 provides the data used in the cost and GHG estimates for Option 2, the results of which are given in Table 13. A comparison between using CNG or diesel buses is provided in Tables 12 and 13.

The total vehicle kilometer traveled by the proposed BRT buses is estimated to be 5.4 million-km/y, and the corresponding natural gas consumption will be 2.2 Mkg-NG a year. Assuming a NG price of $0.9/kg-NG and $87.5/h operation cost of a BRT bus, the annual fuel and O&M costs are estimated as 2.0 and $3.4 million a year. The $1.4 billion of capital cost given in Table 13 represents the purchase cost of the BRT buses (15 years fleet lifetime), the construction cost of 136 km of BRT line, and the cost related to installing 5,000 EV charging stations.

The GHG emissions estimations for Option 2 show a 50 kt-CO_2e emissions reduction in the proposed RT line, if CNG buses are used instead of diesel. On a per km basis, a natural gas bus emits 18 percent less GHG emissions than a new diesel bus[20] [38]. The lifecycle CO_2 equivalent emission from CNG buses is estimated as 1.5 kg-CO_2e/km, while this number is 1.8 kg-CO_2e/km for a new diesel bus. These numbers include both upstream, fugitive, and tailpipe emissions [23]. Lifecycle GHG emissions from transport fuels are provided in Annex 4.

[20] Fugitive methane emissions (during natural gas development and from the tailpipe) are considered in this review, and compared with an overall lifecycle perspective with other fuel options.

Table 12: Data used for cost and GHG emission estimation of Option 2

	NG bus	Diesel bus
# Buses	22	22
Fleet Renewal, 15 y	2	2
Purchase, m$	0.49	0.39
O&M, $/hr	87.5	87.5
BRT daily operation hours, h	21	21
BRT line, km	136	136
BRT line capital cost, m$/km	10	10
Bus Capacity	55	55
# bus trips per day, both ways	108	108
# of EVs	5,000	5,000
# of EV charging stations	5,000	5,000
Cost of EV charging purchase and installation, $	2,000	2,000
Ave Electricity price, $/kWh[21]	0.16	0.16
Fuel Consumption, kg-NG/km, or l/km	0.414	0.497
Fuel cost[22], $/kg-NG or $/l	0.9	1.35
CO2 emissions rate, kg-CO_2e/km (GWP-100)	1.446	1.756

Table 13: Cost, GHG emissions and ridership results for Option 2

	CNG bus	Diesel bus
Total km traveled (BRT buses), million-km/y	5.4	5.4
Total revenue hours, million-h/y	0.039	0.039
Total fuel consumption, Mkg-NG/y or Ml-diesel/y	2.2	2.7
Total Capital Cost, m$	1,391	1,387
Total O&M costs, m$/y	3.5	3.5
Total Fuel Cost, m$/y	2.0	3.6
Total costs, capital, O&M and fuel, m$	1,555	1,599
Total CO_2 emissions from BRT bus, kt-CO_2e	233	282
Total CO_2 savings compared to diesel bus, 30 year period, kt- CO_2e	50	NA
Daily ridership	5,940	5,940
Total Ridership, million passenger in 30 years	65	65
Fare, $/trip	23.9	24.6

[21] The price of electricity provided to a residential area is applied here; however, retail price of electricity at a public EV charging stations may differ. This number will be updated accordingly.
[22]The cost of CNG is considerably cheaper at a private on-site facility (than a public refueling station) that does not pay retail margin and O&M markup (nearly $0.90/kg).

6.3 Option 3: Expansion of the BRT-EV system to other cities

In this scenario, a larger operational area is considered for the RT system. The Highway 407 BRT system, proposed in Option 2, is expanded to other cities. This scenario is expected to receive interest due its link to future urban development and economic growth in the area. Residents will be encouraged to use electric or natural gas vehicles instead of gasoline/diesel cars, along with a trunk transit system (initially a BRT that, if ridership demands, could be adjusted to an LRT). In this scenario, electric vehicle charging stations will be developed at all major interchanges.

The proposed BRT lines are 450 km in length, with an estimated 35,600 daily ridership[23]. In addition to the BRT, 250,000 electric vehicles would be purchased and available at major interchanges. Figure 7 shows the map of the proposed BRT lines across HWY 407, and other major Toronto region routes.

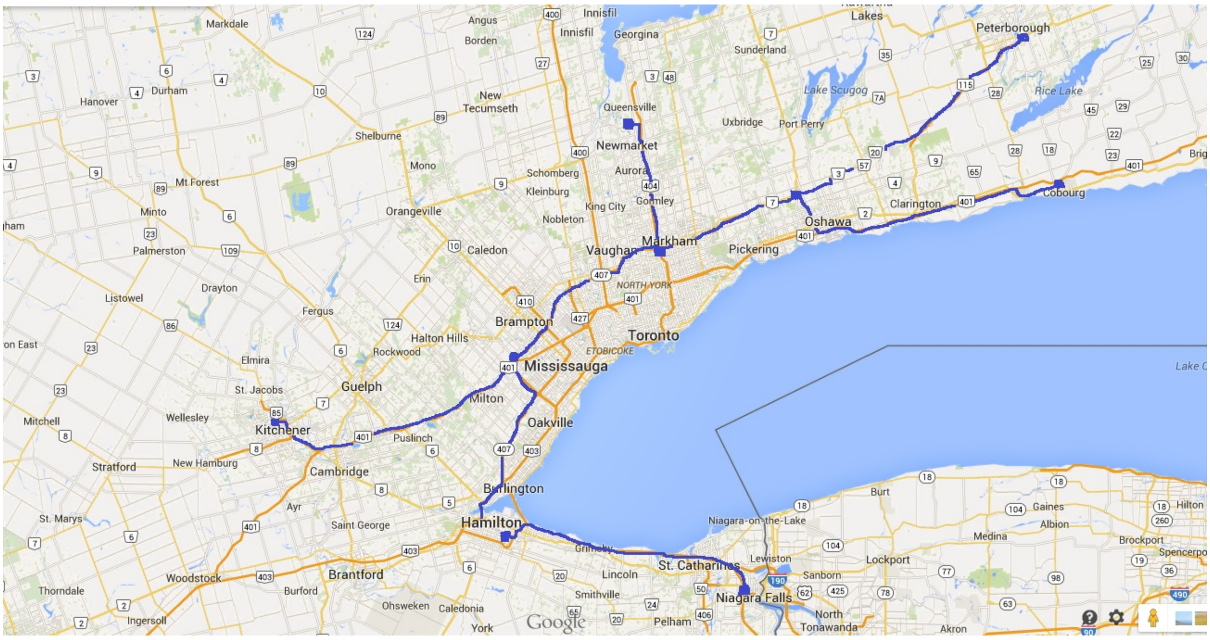

Figure 7: Proposed CNG-BRT lines across Toronto region

Table 14 gives the distances between each end of the BRT lines, estimated number of required buses, kilometers traveled per day, and daily ridership. Table 15 shows the assumptions, data, and estimated values for capital, O&M, and fuel costs.

[23] This number is in addition to the current GO bus ridership along Highway 407.

Table 14: Proposed BRT lines across 407

From	To	Distance, km	# Buses	# daily trips	Km-traveled/day	Ridership/day
Oshawa, Simcoe St North and HWY 407	Hamilton GO Station	136	22	108	14688	5940
HWY 401 and HWY 407 in Milton	Kitchener GO Station	65	12	108	7020	5940
Hamilton GO Station	Niagara Falls	76	14	108	8208	5940
HWY 407 and HWY 404	East Gwillimbury GO Station	34	8	108	3672	5940
Oshawa, Simcoe St North and HWY 407	Peterborough	67	12	108	7236	5940
Oshawa, Simcoe St North and HWY 407	Cobourg	71	12	108	7668	5940
Total		449	80	648	48492	35640

Table 15: Assumptions and data used in Option 3: BRT line across Toronto region

	CNG bus	Diesel bus
# of Buses	80	80
Fleet Renewal, 15 y	2	2
Purchase cost, m$	0.485	0.39
O&M, $/hr	87.5	87.5
BRT daily operation hours, h	20	20
BRT line, km	449	449
BRT line capital cost, m$/km	10	10
# of Stops	16	16
Bus Capacity	55	55
# bus trips per day, both ways	648	648
# of EVs	250,000	250,000
Average Cost of EV purchase, $	18,000	18,000
# of EV charging stations	250,000	250,000
Cost of EV charging purchase and installation, $	2,000	2,000
Ave km traveled by EV per day	44.3	44.3
Ave EV electricity consumption, kWh/km	0.2	0.2
Ave Electricity price, $/kWh	0.16	0.16
Fuel Consumption, kg-NG/km, or l/km	0.414	0.497
Fuel cost, $/kg-NG or $/l	0.9	1.35
CO_2 emissions rate, kg-CO_2e/km (GWP-100)[24]	1.446	1.756

[24] Accounts for lifecycle GHG emissions. It is worth noting that emissions control technologies such as oxidation and three-way catalysts helps reducing CO, NOx and particulate matters. These technologies are used in both modern diesel and CNG buses.

The GHG levels are also calculated and given in the Table 16. Operation and maintenance costs of the BRT system depends on fuel type, length of the line, daily trips, weather conditions, and maintenance schedules. Therefore, for each BRT option, costs should be further estimated with input from potential manufacturers.

The Regional Municipality of Durham assumes a \$125/h operating cost for a proposed BRT line in their Long Term Transit Strategy (LTTS), which includes labour (driver, staff, maintenance) and fuel costs [39]. Fuel expenses are calculated separately (usually about 30% of the O&M costs): an \$87.5/h operating cost is assumed for the proposed RT lines.

Table 16: Extended Highway 407 BRT line data and estimation for 2020-2050

	CNG bus	Diesel bus
Total km traveled (BRT buses), million-km/y	17.7	17.7
Total km traveled by public EVs, million-km/y	4,000	4,000
Total revenue hours, million-h/y	0.24	0.24
Total fuel consumption, Mkg-NG or Ml-diesel	7.3	8.8
Total EV electricity consumption, GWh	808	808
Total Capital Cost, million \$	14,568	14,552
Total O&M costs, million \$/y	20.7	20.7
Total Fuel Cost, million \$/y	6.6	11.9
Total Electricity cost, million \$/y	129	129
Total costs, capital, O&M and fuel, million \$	19,267	19,410
Total CO_2 emissions from BRT bus, kt-CO_2e	768	932
Total CO_2 emissions from EVs, kt-CO_2e	1940	1,940
Total CO_2 savings, 30 year period, Mt-CO_2e	29.8	29.6
Daily BRT ridership	35,640	35,640
Total BRT Ridership, million passenger in 30 years	390.3	390.3
BRT Fare, \$/trip	13.8	14.2
EV trip cost, \$/km	0.1	0.1

Capital cost of a BRT line varies depending on existing infrastructure (bus stations and platforms, HOV lanes), and the need to build new stations, road widening, and installing traffic signals. For a BRT line, with service frequency of 5 min, maximum station distance of 800 m, and with new enhanced BRT platforms and dedicated lanes, the capital cost is estimated at $10 million/km, according to Durham Region's LTTS report [39].

The proposed Option 3, intends to enhance transportation between municipalities in the Toronto region, with stops only at the major interchanges on the HWY 407 route. There are already GO bus and GO train stations in place at some of the major interchanges along the route; however there is a need to build new, on-route BRT stops, EV parking facilities, and possibly dedicated BRT (or HOV) lanes. Therefore, for the cost estimate, the capital cost of the BRT line is $10 million/km. This number is subject to change, as more detailed cost estimates become available.

Covering 17.7 million-km/y, the extended CNG-BRT system provides fast, and easily accessible service to nearly 36,000 passengers a day, and 250,000 Toronto region residents participating in the EV car sharing program. The economic and GHG emissions savings of Option 3 are substantial, which are estimated as 30 Mt-CO_2e for a 30 year period from 2020 to 2050. The related GHG reduction cost savings (assuming $20/tCO2e) will be $ 600 million. The $14.6 billion estimated capital cost (Table 16) is the sum of the costs of BRT line construction and bus purchase ($4.6 billion), public electric vehicles purchase and the cost of EV charging stations ($10 billion). The lifetime of both BRT buses and EV are considered to be 15 years.

Developing an integrated transportation system, where personal (car) trips are not driven by a slow and inconvenient public transit systems, requires an understanding of future driver's ideas on car ownership and adaptability to possible changing modes of transportation. Research shows that the new generation will still strive for car ownership as they see cars a symbol of status (although this is declining). A new generation of customers is demanding 'media integration' and car sharing. Integrated in-car media connectivity enhances economic development (considering the significant amount of a time commuters spend in cars, buses and trains). McKinsey [40] estimates a global EUR 5 billion economic benefit from connected mobile passengers.

Car sharing benefits both local governments and the environment, and surprisingly the car original equipment manufacturers (OEMs) will not suffer from this emerging market as vehicle traveled kilometres likely remains the same as current levels. Nevertheless, car sharing seems to have more appeal to younger drivers and city-core residents, e.g., 38 percent of young Germans residing in cities with a population over 100,000 indicate greater use of car sharing over the next 10 years. Car manufacturers are investigating the market potential (e.g.; BMW & SIXT with driveNow and GM's cooperation with RelayRides). In a study by Frost and Sullivan, a potential revenue of up to EUR 7 billion in 2020 is estimated from ten million car-share users and a fleet of 150,000 cars [40]. Car sharing provides enormous potential benefits, especially if integrated with a Rapid Transit system that dramatically increases the effective range of shared vehicle programs.

- Manufacturers and operators can capture a new market opportunity in densely populated cities.
- Cities can benefit from smaller car fleets (every car from a car sharing pool replaces up to three cars from the existing fleet), although the average kilometers traveled is not expected to decrease. 20 percent of car sharing households tend to give up their second or third vehicle.
- The environmental benefits from a smaller fleet of cars along with a higher market penetration of electric vehicles. The layered benefits of car sharing are presented in Figure 8.

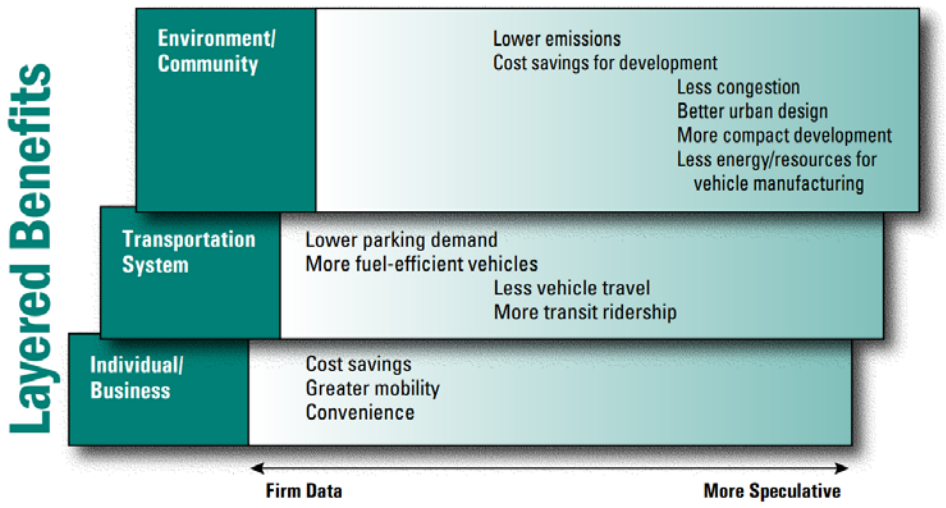

Figure 8: Layered benefits of car sharing. Source [41]

7. Sustainability Potential of Alternative Transportation Options

The sustainability potential of Toronto's transportation projects are measured using a methodology developed by the authors, which is based on the physical and socio-economic impacts of each individual project. For details of the methodology and descriptions of the options see Annex 5 and Hoornweg et al. [42]. The results are shown in Figure 9, along with the costs associated with each project. Option 3, as proposed in this study, has the largest sustainability potential among assessed options, mainly due to reduced GHG emissions and the large number of users.

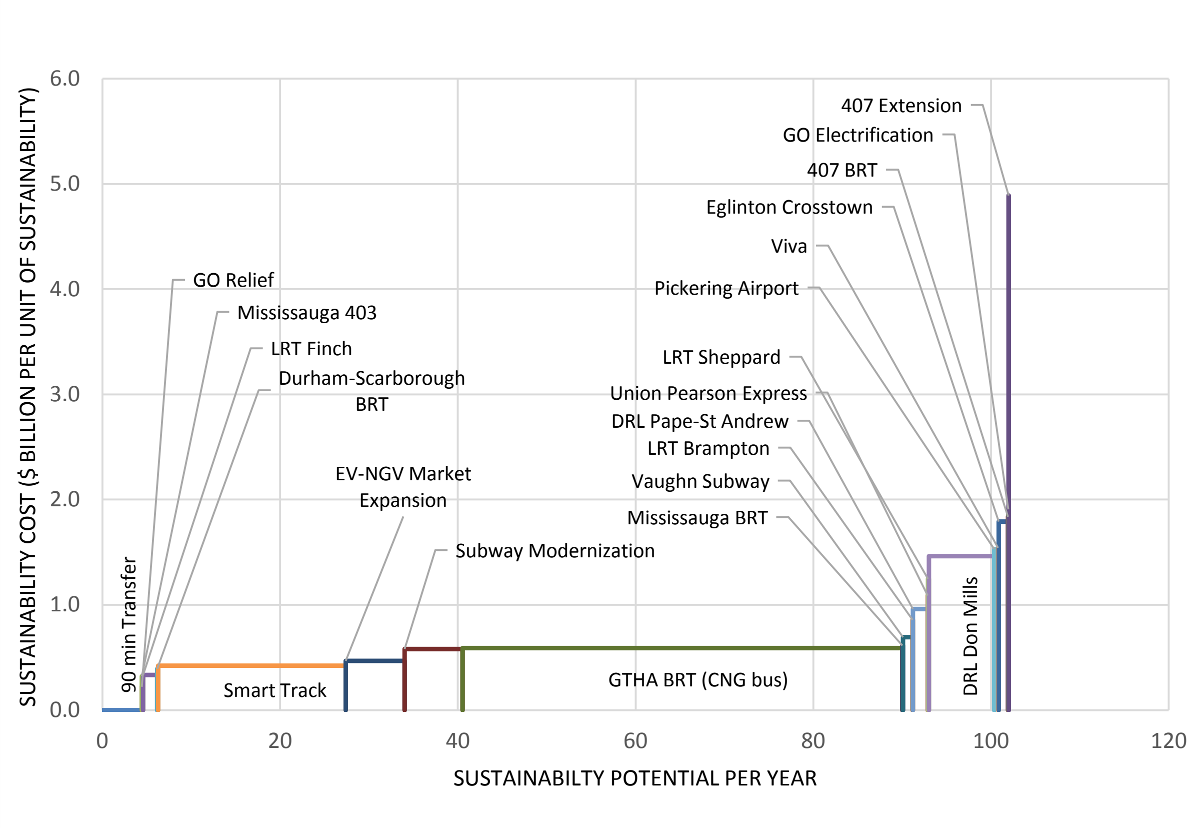

Figure 9: Sustainability potential of Toronto's transportation projects

8. Recommendations

In this report, three options are proposed to improve transportation in the Greater Toronto Area. Option 1 is increased market share of electric and natural gas vehicles. Option 2 is a Rapid Transit corridor along Highway 407 (with truck use in non-peak hours). Buses (and trucks) operate on natural gas. Linked parking lots are equipped with EV charging stations. Option 3 expands the Transit corridor across the Toronto region, and adds 250,000 publically available EVs through a car sharing program.

With current trends in passenger vehicle markets, there will be nearly 5.7 million cars on Toronto region roads in 2050. A market penetration of 15 percent for EVs, 5 percent for NGVs, and 15 percent for NG-heavy duty trucks (Option 1) will reduce GHG emissions by 68 $MtCO_2e$ from 2016 to 2050. Gasoline and diesel consumption will be reduced by 29 billion litres, providing an estimated savings of $34 billion (as well as greater energy security as critical energy sources are more localized).

Highway 407 connects the municipalities in the Toronto region from Hamilton to Oshawa (construction is still ongoing with eventual connection to Highway 115). A direct RT line that traverses the Highway will attract more riders, especially if the service is convenient and price-competitive. Option 2 highlights the environmental benefits and cost savings of a RT system powered by CNG. Daily ridership is estimated at 6,000 passengers, and GHG emissions reduction (only from the RT line) is 230 $ktCO_2e$ during 30 years of operation. The RT system has stops at major interchanges, where EV charging stations are located.

Transportation in Toronto region can be better integrated. For example, by expanding the proposed RT system (Option 2) to major cities around the area, and linking with province-wide car sharing programs. Option 3 expands the RT system across the Toronto region, and integrates with 250,000 publically available EVs in a car sharing program. 80 CNG buses would operate on six major RT lines, serving 36,000 passengers a day. The car sharing program would serve 1.2 million[25] residents of the Toronto region. EVs, which would be available at public parking lots throughout the BRT system, are estimated to cost $0.1/km[26] to operate. Total GHG emission reductions through Option 3 are estimated to be 30 $MtCO_2e$ from 2020 to 2050.

The three proposed Options have considerable economic and environmental benefits. The optimum approach is moving forward in an integrated manner and implementing both Options 1 and 3. GHG emissions would be substantially decreased by 98 $MtCO_2e$ from 2016 to 2050. Fuel savings of $51 billion would accrue. In addition, cost savings from reduced greenhouse gas emissions and increased health benefits are considerable.

[25] Every car from a car sharing pool replaces up to three cars from the existing fleet. Ontario's average personal vehicle occupancy was 1.69 passengers per vehicle in 2009 ([7] NRC, 2011, *Canadian Vehicle Survey Summary Report 2009*, Natural Resources Canada, Government of Canada, Ottawa.

[26] Only vehicle and EV charging stations purchase costs and cost of electricity are considered. Vehicle maintenance and insurance would increase the price of the car sharing program (similar to existing options).

According to Environment Canada, medical costs associated with hospital admissions for respiratory illnesses are, on average, approximately $3,000 per admission [43]. Toronto's level of particulate matter (especially particles smaller than 2.5 micrometers which especially affect respiratory health) is nearly twice the limit set by the World's Health Organization (WHO) (19 vs. 10 $\mu g/m^3$ respectively). Exposure to high concentrations of PM2.5 and larger PM10 is a significant health risk and poses a considerable health care burden. Air pollution now gives rise to 1,300 premature deaths and 3,550 hospitalizations each year in the City of Toronto alone [44]. As shown in Figure 10, in city of Toronto, PM2.5, O_3 and NO_2 are responsible for 69 percent, 13 percent, and 14 percent of premature mortality, and about 33 percent, 29 percent, and 35 percent of hospitalizations from air pollution, respectively. These pollutants are mostly emitted from the transportation sector. Heavy duty trucks are responsible for more than 77 percent of PM2.5 and 55 percent NO_x emissions in Toronto [44]

Moving toward alternative fuels will help reduce air pollution and associated health burdens. For example, a CNG truck emits 70-90 percent less carbon monoxide than an equivalent diesel vehicle. Similar reductions of 90 percent and 99 percent for particulates and sulphur dioxide respectively are possible [45-47].

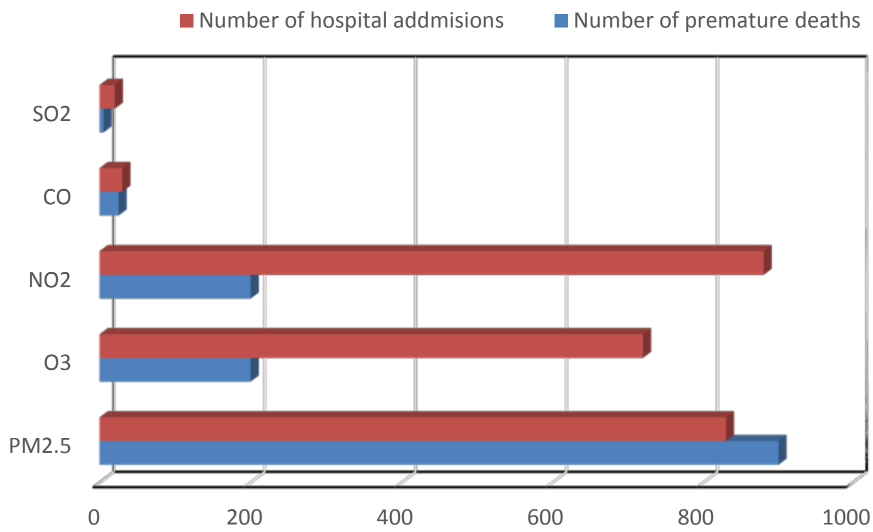

Figure 10: Pollutant Contributions to Air Quality Burden of Illness, Toronto, 2009 (Adopted from Ref. [44])

In addition to the environmental and health benefits associated with the transportation options proposed here, there are other user benefits. These include automobile ownership and maintenance savings and decreased number of vehicle accidents. Table 17 highlights $26 billion in estimated user benefits for the RT (CNG) system of Option 3. Including fuel cost savings from Options 1 and 3 (a total of $51 billion), Toronto region would benefit from $76 billion in savings, if transportation is improved as proposed here.

Table 17: Summary of cost benefits of the BRT (CNG) system across Toronto region (Option 3)

	Unit	Value
Auto Operating Cost	$/km	0.0531
Safety benefits	$/km	0.07
Health benefits		NA
Total personal km traveled saved	million km	207,222
Auto Operating cost savings	billion $	11.0
Total Safety benefits	billion $	14.5
Total Health benefits	billion $	
Total User's Benefits	**billion $**	**25.5**

9. Conclusions

This analysis highlights several urban mobility issues for the Toronto region: not only is congestion an enormous drag on the region's current economy and the main cause of local air pollution, but improved mobility is likely the best option for greater productivity and future economic development. The transportation sector now represents the area's largest source of greenhouse gas emissions – introducing the natural gas fueled and electric vehicle 'Option 3' outlined in this report would reduce GHG emissions by about 30 Gt/year. Urban mobility is changing quickly. Autonomous vehicles, car-sharing, inter-modal, and 'communicating vehicles', need to be encouraged and integrated into a new transportation system. Toronto region needs to shift from a largely passive approach to transportation, to a mind-set that views urban mobility as a key service to enhance regional quality of life, connectivity, economic development, and wealth generation, e.g., increased land values.

This review – an initial overview – highlights the need for an integrated approach to local mobility. No single technology, fuel option, or infrastructure investment will deliver sufficient results. Natural gas is better in some situations, electric vehicles in some others, and in some cases we are best served by keeping existing energy systems. An integrated approach is needed, and arguably a rapid but incremental approach that accommodates technological shifts. The approach also needs to consider the needs and opportunities region-wide. By moving forward as an integrated urban region enormous economic gains are possible. Also both sides of the financial ledger need to be addressed. Much of what is proposed in this report is costly, but already today, about a third of our personal (regional) wealth is directly attributable to our existing transportation network. And we now have a chance to double that.

This report takes a retrospective view – where would we like to be in 2050? The report intends to contribute to an at-times already boisterous conversation. We are at a cross-road. Behind us is unprecedented good fortune. Ontario’s economy owes much to the North American vehicle ownership model and cheap electricity. Most of us know that road is ending. We are still fortunate though; we have one of the world’s lowest carbon sources of electricity, access to relatively cheap natural gas, manufacturing prowess, excellent agencies and an environment that rewards pragmatism and global replicability. We also have a few potentially powerful partners like Montreal, Vancouver and rural and northern Ontario. Moving forward this Century we can probably replicate our good fortune of the 20th Century. Time to move.

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Annex 1: Lifecycle greenhouse gas emissions of several electricity generation systems (average values)

Electricity Generation Plant	Coal-fired	NG	Solar PV	Nuclear
CO_2 emissions, g/kWh	888	499	85	29

Table Adapted from Ref. [48]

Annex 2: Equations used for cost and GHG emissions of Option 1

Electricity consumption by EVs

$$E_{EV} = VKT_{EV} \times e_{EV}$$

where E, VKT and e are total electricity consumption, total vehicle kilometer traveled and electricity consumption per km traveled (kWh/km), respectively.

Natural gas consumption by passenger NGV

$$M_{NG,passenger} = (\text{VKT} \times FC)_{NG,passenger}$$

$$M_{NG,HDT} = (\text{VKT} \times FC)_{NG,HDT}$$

where M and FC are total NG consumption, and NG consumption per km traveled, respectively.

Cost of vehicle fuel (electricity and natural gas)

$$\text{COF} = E_{EV}\left(0.5COE_{public} + 0.5COE_{in-home}\right) + M_{NG,passenger}\left(0.7C_{NG,public} + 0.3C_{NG,in-home}\right) + M_{NG,HDT} \times C_{NG,fleet}$$

where, COF, COE, and C are total cost of fuel, unit cost of electricity (\$/kWh), and unit cost of NG (\$/kg), respectively. The subscripts, $in-home$, and $public$ refer to public or in-home vehicle charging/refueling options.

Annex 3: Equations used for cost and GHG estimations of Options 2 and 3

Total capital cost

$$\text{Total capital cost} = (\text{N}_{\text{Buses}} n_{\text{Fleet renewal}} \text{C}_{bus}) + (\text{L}_{BRT\ line} \text{C}_{BRT\ const}) + N_{EV}\left(C_{\text{EV}} + C_{EV,Charging}\right) n_{\text{Fleet renewal}}$$

where N is the number of buses or EVs, n is the fleet renewal frequency, L is the length of the BRT line in km, and C is the specific cost.

$$\text{O\&M cost} = \text{Daily bus operation cost} \times \text{O\&M} \times 365 \times (2050 - 2020)$$

$$\text{Toal fuel consumption} = \text{No. trips per day} \times \left(\frac{\text{BRT line}}{100}\right) \times \text{Fuel consumption} \times 365 \times 30$$

$$\text{Total fuel cost} = \text{Total fuel consumption} \times \text{Fuel cost}$$

$$\text{Total ridership} = \text{No. trips per day} \times \text{Bus capacity} \times 365 \times 30$$

$$\text{Trip cost} = \frac{\text{sum of capital,O\&M and fuel cost}}{\text{Total ridership}}$$

Annex 4: Lifecycle GHG emissions from transport fuels

Table A1: Lifecycle GHG emissions from transport fuel, gCO_2e per fuel unit

	Upstream emissions	Tailpipe CO_2	Total
Diesel, gCO_2e/l	815	2,716	3,531
Gasoline, gCO_2e/l	703	2,245	2,948
CNG, gCO_2e/kg	710	2,782	3,492

Table A2: Lifecycle GHG emissions from transport fuel, gCO_2e per energy unit

	Upstream emissions	Tailpipe CO_2	Total
Diesel, gCO_2e/MJ	22.9	76.5	99.4
Gasoline, gCO_2e/MJ	21.6	69.1	90.7
CNG, gCO_2e/MJ	15.0	58.9	73.9

In the GHGenius model for lifecycle assessment of transportation fuels, the Natural Resources Canada uses the following fuel economy values for Canada:

	Light duty gasoline vehicles	Buses	Heavy duty trucks
City fuel consumption, l/100km	10.13	49.73	44.34
Highway fuel consumption, l/100km	7.23	49.73	34.93
Fraction of km in city driving	0.55	1	0.5

Therefore, average GHG emissions of gasoline and diesel vehicles on a per km basis are estimated as:

	Light duty gasoline vehicles	Buses	Heavy duty trucks
GHG emissions, gCO_2e/km	260	1,756	1,400

Annex 5: Possible transportation projects in Toronto

Numerous planning reviews are available for metropolitan Toronto's transportation sector. Preliminary budgeting and planning assessments are often available for proposed key infrastructure projects. The transportation planning authority Metrolinx published a comprehensive transportation Master Plan in [49]. The Toronto Transit Commission and Province of Ontario (various agencies, including Ministry of Transportation) have proposed several significant initiatives. Thirteen key activities were examined (Figure A1) to provide a demonstration of the SCC method:

90 Minute Transfer

The Toronto Transit commission (TTC) is considering a switch from its longstanding single-continuous-trip transfer system to time-based transfers. The ability to pay one fare and transfer as needed between buses, streetcars and subway trains is an integral part of TTC planning. The majority of TTC customers transfer at least once per journey. The TTC currently issues paper transfers to riders who pay fares with cash, tickets, or tokens and whose trip requires a change of vehicle. The existing transfer policy is purposely limited - transfers are only valid for a continuous one-way trip. Transfers must be used to transfer to the next available train or vehicle from a valid transfer point, which is usually a subway station or an on-street bus or streetcar at an intersecting route. Stopovers or return trips are not permitted, and the transfer can only be used by the passenger to which it was issued and on the day that it was issued. Under a time-based transfer system, transfers would allow riders to potentially re-enter the system within the prescribed time limit. TTC officials estimate an unrestricted-use time-based transfer valid for 2 hours would cost the TTC $20 million a year in lost revenues, while a 90-minute transfer would cost around $12 million a year. [50].

407 Extensions

Highway 407 known as the 407 ETR (Express Toll Route) is privately operated and tolled. The government of Ontario regulates and sets toll rates and retains partial revenue generated from highway 407 tolls. The Highway 407 East extensions will be built in two phases: a 22 km extension to Harmony Road in Oshawa, as well as the West Durham Link, is scheduled to open in 2015; a further 43 km extension to Highway 35 and Highway 115, as well as the East Durham Link, is scheduled to open in 2020.

Union Pearson Express

The Union Pearson Express (UP Express) [51] is an airport rail link service under construction in Toronto running between Canada's two busiest transportation hubs: Union Station in downtown Toronto and Toronto Pearson International Airport. The project is to be completed in time for the 2015 Pan American Games [52]. The UP Express is a division of Metrolinx. UP is to be a distinct service from its sister division with a unique visual identity, vehicles and fares, but will nonetheless share some common resources, including tracks, signals and maintenance facilities [51]. An airport rail link was one of the priority projects identified in Metrolinx's regional transportation plan, The Big Move.

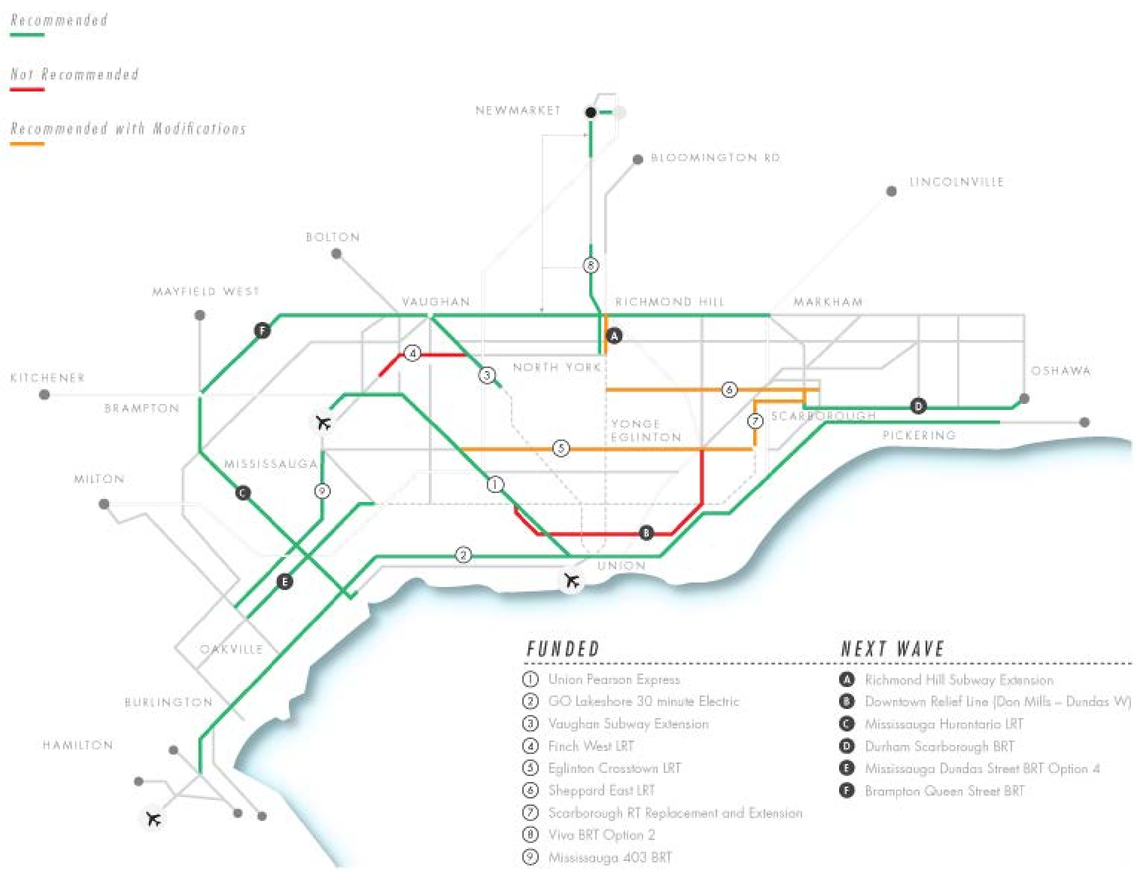

Figure A1: Possible transportation projects in Toronto [53]

The UP Express will travel from Union to Pearson in 25 minutes [3] departing every 15 minutes, seven days a week. It is expected to carry 5,000 passengers per day, replacing approximately 1.2 million car trips in the first year alone. Construction began in 2011, some of which is being accommodated as part of the Georgetown South Project, expanding a rail corridor the UP Express will share with GO Transit and Via Rail [51, 52] . Initially, the UP Express will use diesel multiple unit (DMU) trains. The DMUs will be convertible to electric power, which will occur with the electrification of the Kitchener line and the UP Express at a future unspecified date [54]. The decision to not use electric trains at launch has become a source of opposition and legal challenges from the Clean Train Coalition (CTC). So too the proposed $30-plus cost per passenger trip.

Richmond Hill Subway Extension

The planned Yonge subway extension will extend 6.8 kilometres north from Finch Station to the Richmond Hill/Langstaff Urban Growth Centre at Highway 7. It will include up to six stations. This urban centre will be a major transit hub where transit riders will be able to connect to GO Trains, GO Buses, TTC Subway, YRT\Viva buses, the future 407 transit way, and other transit services [55].

Downtown Relief Line

The Downtown Relief Line (DRL) is a proposed subway line in Toronto. Fully built, the line would form a shallow U-shape, running east-west through downtown (parallel to but south of the Bloor–Danforth subway line) and bending north on either side of downtown to meet stations on the Bloor–Danforth line (with possible extensions northward). The DRL is the latest of several plans for an east-west downtown subway line dating to the early 20th century. Most of these proposed routes were along Queen Street, but current proposals favour a more southerly route through the Railway Lands and Union Station. The main rationale for the DRL is to reduce congestion on the Toronto Transit Commission's (TTC) Yonge Line, particularly at Bloor-Yonge Station, the main interchange with the Bloor–Danforth line. Planners see this as urgent because of the proposed extension of the Yonge Line to Richmond Hill, north of the city [56]. In addition, the growth of downtown population and connecting high-density "shoulder areas" of downtown such as Liberty Village, City Place, the Entertainment District, Distillery District, and West Don Lands lack efficient higher order transit options and are experiencing an influx of high-rise transit-oriented development [57]. Four DRLs alignments are proposed:

- From Pape to St. Andrew
- From Pape to Dundas West through St. Andrew
- From Don Mills at Eglinton through Pape to St. Andrew
- From Don Mills at Eglinton through Pape and St. Andrew to Dundas West

Two most likely DRL lines are denoted here as DRL Don Mills and DRL Pape in the tables and graphs.

Pickering Airport

Pickering Airport is a proposed international airport to be built directly north-east of Toronto in Pickering, Ontario, Canada, approximately 65 km east of Toronto Pearson International Airport. It would serve the Greater Toronto Area and the Golden Horseshoe, and would (likely) be operated by the Greater Toronto Airports Authority (GTAA). Cost estimates of are approximately $2 billion; anticipating up to 11.9 million passengers per year by 2032.

The original plans for the airport were developed during the 1970s as part of a widespread federal government plan to improve air travel across Canada. Lands were expropriated in 1972, but opposition to the expansion plan was widespread. The plans were shelved in 1975 when the Government of Ontario stated it would not build the roads or sewers needed to service the site. A "Needs Assessment Study" was completed by Toronto region for the federal government in 2010. After a "due diligence review" Transport Canada released a report in 2011 [58]. A decision to proceed with airport planning and construction was announced on June 11, 2013.

Smart Track

The SmartTrack line [59] is a Regional Express Rail 'surface subway' planned to connect major hubs in the GTA (Airport Corporate Centre in the west, southeast to Union Station and northeast to Markham in the east). The planed service year is 2021, and the line will have 22 stops at major interchanges. The SmartTrack is expected to help reduce congestion in both the current subway lines and road traffic. The 53 km surface subway line will use the already in-use GO train lines; however with the same fare as the TTC subway lines. The SmartTrack was a part of John Tory's plan for the city of Toronto's mayoral election in Fall 2014. Part of the attraction of the SmartTrack is its use of existing alignments and tracking and potential (relative) speed of implementation compared to subways requiring extensive tunneling. The estimated capital costs are $5.3 billion.

GO Electrification

GO train is a major part of Toronto region's public transit system. Currently the trains run on diesel as fuel. Metrolinx began a review in 2009 on the feasibility of electrification of the entire GO rail system. Economic, environmental, social, health, and technological considerations led to the final conclusion as the feasibility of the project [60]. Metrolinx, following the staff recommendations, has started the project in Phases, of which electrification of Union Station-Pearson Airport line is the first. The capital costs are estimated as $0.9 billion.

Rapid Transit Network Plan

Rapid Transit Network Plan is a complimentary to the existing Viva services and aims at identifying new Viva services to expand York Region's transit network. The plan was initiated to decrease traffic congestion, increase transit ridership, and increase schedule reliability, and will be in place from 2014 to 2017. The estimated capital costs are $132 million, and an average $37.4 million of operation and maintenance costs are expected [61].

Toronto – York Spadina Subway Extension (Vaughan Subway)

Currently, Toronto's subway lines are only within the City's boundaries. Construction of an extension to the University-Spadina line started in 2010 and is planned to be in service in 2016. The Toronto - York Spadina Subway is an 8.6km extension from Downsview Station northwest (last station on University-Spadina line) through York University within the City of Toronto and north to the Vaughan Metropolitan Centre, in The Regional Municipality of York. Six stations are being constructed and 2,900 parking spaces will be available to encourage ridership. The estimated project costs are $2.6 billion, which are funded by the federal and provincial governments and the City of Toronto [62].

Mississauga LRT Projects

Metrolinx, along with the cities of Mississauga and Brampton are investing in expanding and improving public transit in the area with a light rapid transit line from the Port Credit GO Station in Mississauga to the GO Station in Downtown Brampton. This Hurontario-Main LRT will be designed to address congestion and improve traffic along the corridor; 5-8 years of construction is expected [63].

GO Relief Projects

GO trains can serve some of the TTC riders during peak hours by increasing train frequency. For example, a GO train trip can be scheduled to move TTC riders on the Danforth Subway Line from Main subway station to downtown directly. An estimated 5,000-20,000 TTC riders can use this service by getting off the subway at Main Station, walk, or ride a TTC bus, to Danforth GO Station, take the peak hour GO train that is scheduled between Danforth and Union Station, and get to downtown in only 10 min. With this project, a considerable passenger load is diverted from the TTC at Yonge and Bloor lines. The cost to operate 12 additional trips on the 10-km line between Union and Main Street every morning and evening peak would be about $1.4 million per year [64]. Similar ideas can be applied from Kennedy (east of Toronto) and Kipling (west of Toronto) subway stations to Union Station. These projects are marked as 'GO Relief' in tables and graphs.