Master of Urban Planning Supervised Research Project:

Riding with Robots

Determining the size of an autonomous vehicle fleet for use as an alternative to traditional transit in low-density neighbourhoods

Prepared by:
Scott Bagg

Supervised by:
Ahmed El-Geniedy

McGill University
School of Urban Planning

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Abstract

Shared-vehicle fleet services such as Car2Go, ZipCar, and Communauto have become increasingly attractive alternatives to personal auto ownership in recent years, often offering greater flexibility and convenience in comparison to transit services, and for many individuals, at a lower cost compared to personal auto ownership. Mobility-as-a-service providers including Uber and Lyft have likewise gained popularity, while automakers, big tech firms, and small-scale start-ups race towards the reality of fully autonomous vehicles (AVs), which inevitably have a role to play in the future of transportation. Leveraging the convergence of these trends gives rise to the potential for fleets of shared autonomous vehicle (SAVs) capable of providing safe, convenient, and efficient travel options in the places where it is simply not viable to operate transit.

This study contributes to the growing field of shared autonomous vehicle fleet research by developing a simple agent-based method for determining the fleet size requirements based on an input travel demand trip dataset for a specified study area. The developed model simulates the activity of AVs over a 24-hour period with the ability to generate additional vehicles as needed in order to satisfy a typical weekday of travel based on origin-destination survey data for the study area of la Ville de Saint-Jean-sur-Richelieu in Quebec, Canada. The model was designed for the "worst-case-scenario", which assumes that each vehicle can only be occupied by a single passenger, in order to determine the maximum fleet size required. Simulations are repeated at various proportions of transit and non-transit trip modes in order to assess fleet performance with increasing market penetration or AV ridership rates.

Considering the scenario that serves all transit trips and 25% of non-transit trips (50,765 total trips), the simulation results indicate that a fleet of 3,076 vehicles are required. Each autonomous vehicle in the fleet is thus capable of replacing approximately 6 personally owned vehicles, for a potential vehicle fleet reduction of about 84%. Assuming that vehicles can carry only one passenger (no ridesharing), the impact on vehicle miles travelled was found to increase by 66% in the transit plus 25% of non-transit trip modes scenario, due to the additional (unoccupied) travel required to reroute vehicles between trip assignments. Overall, fleet performance was found to improve as the number of trips served increases.

Policy makers, municipal planning offices, and transit agencies concerned with the potential impacts of autonomous vehicles may be particularly interested in the findings of this report as they anticipate and prepare for their imminent introduction.

Résumé

Depuis quelques années, l'arrivée des services de voitures libre-service tel que Car2Go, ZipCar et Communauto ont permis d'offrir une alternative attirante à l'achat d'un véhicule personnel ainsi qu'au système de transport collectif, et ce, pour beaucoup d'invidus, pour un coût inférieur à l'achat d'un véhicule. De plus, l'apparition de compagnie tel qu'Uber et Lyft ont grandement gagné en popularité pendant que les constructeurs automobiles, les grandes entreprises de technologie ainsi que les petites entreprises naissantes se tournent vers la nouvelle réalitée des voitures autonomes (VA) ayant ainsi un rôle à jouer dans l'avenir des transports. Ces tendances convergeantes amènent un potentiel de créer des flottes de véhicules autonomes libre-service (VALS) capable d'offrir un service sécuritaire, conviviale et efficace dans des secteurs qui ne serait pas viable d'opérer un système de transport public.

Cette étude se veut une contribution au domaine grandissant des véhicules autonomes libre-service. En développant une simple méthode en mode agent pour déterminer le volume d'une flotte par l'utilisation des données de la demande de transport pour une zone spécifique. Ce modèle simule, sur un période d'une journée, toutes les activitées des véhicules autonomes avec la capacité de rajouter des véhicules pour répondre à la demande basé sur l'Enquête Origine-Destination de la Ville de Saint-Jean-sur-Richelieu au Québec, Canada. Le modèle a été conçu pour simulé le pire scénario qui suppose que chaque véhicule peut être utilisé par un seul passager, et ce, dans le but de déterminer le nombre maximale nécessaire à la flotte. Des simulations ont été fait avec des taux variables d'utilisateurs et de non-utilisateurs de transport collectif dans le but de connaître les perfommances de la flotte.

Considérant que l'on rajoute 25% de non-utilisateurs aux utlisateurs qui utilisent déjà un transport collectif, il faudrait 3076 de véhicules autonomes libre-service. Pour chaque véhicule autonome, on considère qu'il peut remplacer de façon approximative 6 véhicules personnels signifiant une réduction de 84% de véhicules personnels. Supposant que chaque VALS peut transporter un seul passager, l'impact sur la distance parcourru augmente de 66% dans le scénario avec un rajout de 25% de non-utilisateurs, et ce, causé par l'augmentation de la distance parcouru sans passager. En général, les performances de la flotte augmente avec une augmentation de la demande.

Les élues politiques, les bureaux d'urbanisme municipaux ainsi que les agences de transport concernées par les véhicules autonomes devraient être intéressé par les résultats de cette étude étant donné qu'ils anticipent et prépare l'introduction imminente de ces véhicules.

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Introduction

The (In)efficiency of Coverage Transit Service

Recognizing that the travel options for some individuals are limited, and with motivations that extend beyond maximizing revenue (and ridership), transit agencies typically provide coverage services to ensure that a base level of accessibility is offered in areas of low travel demand (Walker, 2008), such as in low-density suburban neighbourhoods. Coverage services are generally characterized by low levels of service, often at frequencies of 30 or 60 minutes, and typically experience low passenger loads - in part due to the fact that the long wait times are unattractive to users with alternative travel options (i.e. personal automobiles). Furthermore, the cul-de-sac style of development common in many low-density suburban neighbourhoods makes provision of attractive service challenging, as indirect and meandering vehicle routings increase the total travel time, and users often must travel larger distances to access transit in comparison to residents living in denser metropolitan settings where transit is both more abundant and frequent (Ewing, 1999).

Noting this, operator wages, vehicle maintenance, and fuel costs remain relatively fixed for the service provider, irrespective of the location or the success of a given transit route. Thus the total cost of a given service is primarily dependent on the level of service provided rather than ridership. Review of bus performance data reveals that the variance in capacity utilization rates on coverage and high-demand transit services translate to vast differences in their respective costs per boarded passenger.

A low-frequency coverage service (30-60 minute headways) in a sprawling peripheral community of Metro Vancouver, for example, saw an average of 13 passenger boardings per revenue hour with an average cost per boarded passenger of $4.61 in 2014 (TransLink, 2015). In comparison, a higher frequency service (15 minute headway) with the same vehicle type operating in Vancouver's downtown peninsula had an average of 44 passenger boardings per hour of revenue service and an average cost per boarded passenger of $1.40 (TransLink, 2015). This example highlights the fact that providing even a bare-bones level of service comes at a high cost, while offering an unattractive travel option that discourages all but captive riders from using the system.

Economics aside, even with an unlimited budget, the provision of transit at a level of service that is attractive to non-captive users in low-density environments would most likely lead to very low capacity utilization rates and highly inefficient fuel consumption if constrained by traditional fixed-route and schedule services, negating their benefits. While recognizing the merits of coverage services, in reality, these offerings divert limited resources from successful core services where travel demand is strong, and where traditional services are in fact well-suited (Walker, 2008). Is there perhaps a more efficient and attractive way to satisfy the travel demand in low-density neighbourhoods?

Emerging Trends in Transportation

The use of shared-vehicle services (Car2Go, ZipCar, Communauto, etc.) is on the rise (Shaheen, Chan, & Micheaux, 2015), and automakers and tech-firms alike are heavily invested in autonomous vehicle (AV) technologies (Fagnant & Kockelman, 2013). Low-level autonomy for specific driving tasks are already integrated in a wide range of vehicles available for public purchase (Fagnant & Kockelman, 2013; Gill, Kirk, Godsmark, & Flemming, 2015). While regulatory barriers, liability concerns, and public perceptions of AVs may lag behind the pace of recent technological advances, automakers and researchers expect fully autonomous vehicles requiring no human input to be market-ready within 5-15 years (Gill et al., 2015; Levinson, Boies, Cao, & Fan, 2016; Lutin, Kornhauser, & Lerner-Lam, 2013).

The provision of safe and affordable mobility-as-a-service options, including shared autonomous vehicle (SAV) fleets, has the potential to reduce personal auto dependence by offering convenient and reliable alternatives to automobile ownership. Ultimately, these services have the potential to permit the shedding of the second vehicle for some households, and eliminate the need for personally owned vehicles altogether for others still, perhaps relegating vehicle ownership to those with specialized trip purposes that are not easily accommodated by AVs and to individuals that prefer or enjoy manual driving.

The introduction of AVs will undoubtedly have significant impacts on travel behaviour and landuse, for which planners, policy makers, and other stakeholders are urged to anticipate and prepare for. Interested readers are advised to consult the work of Fagnant and Kockleman (2013), which provides an in-depth overview of opportunities and barriers to AV introduction as well as policy recommendations for implementation, and the recent report completed by Levinson et al. (2016), which offers a comprehensive analysis of the predicted changes to transportation and landuse and the implications for policy and planning in light of new transportation technologies. Additionally, readers may find Guerra's 2015 publication dealing with long-range planning for AVs in metropolitan planning organizations similarly useful.

Study Objectives

Considering the shortcomings and high cost of coverage transit services, the growth of car-sharing and mobility-as-a-service offerings, and the impending widespread introduction of autonomous vehicle technologies, the study authors hypothesize that demand-responsive SAV fleets may be well suited to serve low-density neighbourhoods. Under such a scenario, a fleet of AVs could potentially replace the existing low-frequency transit services that currently operate in these environments at a high cost per boarded passenger. SAV fleets may be able to provide an improved level of service in areas where frequent transit cannot currently be justified, thus complementing and acting as a feeders to successful traditional transit corridors where travel demand is both strong and consistent. This research is particularly relevant given that an estimated 66% of Canada's population in 2006 resided within suburban contexts (Gordon & Janzen, 2013).

Specifically, the primary objective of this research project is to (1) determine – through simulation – the required size of an autonomous vehicle fleet needed to serve the specified input trip dataset. Based on the simulation results, the study also seeks to determine (2) the potential reduction in personal vehicle ownership that could be facilitated through the use of a SAV fleet (vehicle replacement rate), and (3) the impacts of SAV fleet use on vehicle miles travelled and energy/fuel consumption. The level of service provided (user wait time), and estimated vehicle maintenance requirements are also discussed.

The study methodology used is similar in nature to the agent-based models used in fleet sizing studies performed by Chen and Kockleman (2015), with the travel demand derived from origin-destination travel survey data in both cases. This being noted, the model developed for this study makes use of a more simplified trip generation method that assumes travel demand is known prior to simulation, representing an advanced booking rather than "live" trip requests, as in Chen and Kockleman's study. Additionally, the model used in this study assumes that all simulated trips are completed individually (i.e. one passenger per vehicle), irrespective of their current travel mode as listed in the OD survey. The ramifications of these assumption are discussed alongside the results.

The following provides a brief overview of the sections contained within this report. The first section delivers a summary of recent AV research with a focus on fleet sizing studies and the performance of SAV fleet, the potential benefits and implications of AV introduction, and barriers to their implementation. The methodology section describes the input travel demand dataset, an overview of the study area selected, the model framework and all assumptions, specific details of the techniques employed, as well as an overview of the various scenarios simulated. The results are then presented and analyzed at the fleet, vehicle, and trip level. An example highlighting the activity of a single AV over the course of the 24 hours simulated is also provided. Next, the study objectives are revisited and discussed in light of the results and ultimately, to assess the suitability of SAV fleets to serve low-density suburban neighbourhoods where frequent transit cannot be justified. Lastly, the recommended model improvements and next steps for further research are highlighted.

Literature Review

Completely Autonomous Vehicles: when, not if

Over the past several years, personal automobiles available to consumers have increasingly included options for low-level automation in specific contexts, including adaptive cruise control, parking assist systems, auto lane change, and collision avoidance (Fagnant & Kockelman, 2013; Levinson et al., 2016). Automakers and technology firms are also heavily invested in research to advance the implementation of completely autonomous vehicles requiring no direct human input (Fagnant & Kockelman, 2013). The vehicles used in Google's Self-Driving Car Project, for example, have driven more than 1.6 million kilometres with limited human control since 2009, travelling on public highways and city streets in Mountain View, CA and Austin, TX (Google, 2015).

Amidst rapid technology developments in the AV field, the U.S. National Highway Traffic Safety Administration (NHTSA) released a preliminary policy document concerning AVs. The NHTSA's five-level definition for vehicle automation is provided, as presented in the 2013 policy brief:

> **No-Automation (Level 0):** The driver is in complete and sole control of the primary vehicle controls – brakes, steering, throttle, and motive power – at all times.
>
> **Function-specific Automation (Level 1):** Automation at this level involves one or more specific control functions. Examples include electronic stability control or pre-charged brakes, where the vehicle automatically assists with braking to enable the driver to regain control of the vehicle or stop faster than possible by acting alone.
>
> **Combined Function Automation (Level 2):** This level involves automation of at least two primary control functions designed to work in unison to relieve the driver of control of those functions. An example of combined

> functions enabling a Level 2 system is adaptive cruise control in combination with lane centering.
>
> **Limited Self-Driving Automation (Level 3):** Vehicles at this level of automation enable the driver to cede full control of all safety-critical functions under certain traffic or environmental conditions and in those conditions to rely heavily on the vehicle to monitor for changes in those conditions requiring transition back to driver control. The driver is expected to be available for occasional control, but with sufficiently comfortable transition time. The Google car is an example of limited self-driving automation.
>
> **Full Self-Driving Automation (Level 4):** The vehicle is designed to perform all safety-critical driving functions and monitor roadway conditions for an entire trip. Such a design anticipates that the driver will provide destination or navigation input, but is not expected to be available for control at any time during the trip. This includes both occupied and unoccupied vehicles.
>
> (National Highway Traffic Safety Administration, 2013)

Completely autonomous (Level 4) vehicles are currently used in a number of industrial applications, including autonomous trucks in RioTinto's Australian mining operations (RioTinto, 2015), and by Suncor in the Alberta tar sands (Gill et al., 2015). Level-4 technologies are predicted to become available to consumers within the next 5-15 years (Fagnant & Kockelman, 2013; Gill et al., 2015; Levinson et al., 2016; Levinson & Krizek, 2015), and estimates of the AV share within the US auto-fleet under various cost and consumer willingness-to-pay scenarios have been completed (Bansal & Kockelman, 2016). Even if the eventual introduction is delayed or if only low penetration rates are achieved, it is evident that AVs indeed have a role to play in the future of transportation.

Benefits and Impacts of AVs

Existing literature has already demonstrated that the potential benefits that can be provided by AVs are numerous, with significant investigation into potential safety improvements, congestion reduction, reduced parking requirements, and trucking/freight applications (Fagnant & Kockelman, 2013, 2014; Gill et al., 2015; Levinson et al., 2016; Li & Kockelman, 2016; Lutin et al., 2013). Most prominently, high AV adoption rates could drastically reduce the instance of car crashes (Fagnant & Kockelman, 2013). Driver error is estimated to be the primary factor leading to more than 90% of all crashes in the US (National Highway Traffic Safety Administration, 2008), contributing an estimated economic impact that more than triples the cost of congestion at $300 billion annually (Cambridge Systematics, 2011). The ability of AVs to sense and anticipate the actions of other vehicles (particularly if vehicle-to-vehicle and vehicle-to-infrastructure communication technologies are implemented) allows AVs to reduce fuel consumption through more efficient braking/acceleration, and to reduce congestion and intersection throughput through shorter headways, vehicle platooning, and coordinated route choice ((Fagnant & Kockelman, 2013)). However, even at low penetration rates (10%) it has been estimated that more than 1,000 traffic accident deaths could be avoided annually, in addition to tens of billions in potential economic gains (Fagnant & Kockelman, 2013). AVs also provide time-value benefits, as former drivers become passengers, enabling productive use of travel time (Badger, 2014; Gill et al., 2015).

Considering the SAV literature specifically, researchers have already begun investigating the travel implications, environmental impacts, valuation of safety benefits, operational frameworks, infrastructure implications (charging facilities), fleet sizing techniques, and frameworks for redistribution of unoccupied AVs, among other topics (Chen, Kockelman, & Hanna, 2016; Fagnant & Kockelman, 2013, 2014, 2015; Fagnant, Kockleman, & Bansal, 2015; Levin, Li, Boyles, & Kockleman, 2016). Kockleman, Fagnant, Chen, and others have contributed various agent-based simulations frameworks, including complex simulations that permit dynamic ride-sharing in order "to pool multiple travelers with similar origins, destinations, and departure times in the same vehicle" (Fagnant & Kockelman, 2015), as well as methods for pre-emptive redistribution of unassigned vehicles for more efficient trip assignment (Levin et al., 2016). Agent-based simulations completed for Austin, Texas at low SAV penetration rates of 1.3% of regional trips found that a single AV may be capable of replacing about 9 conventional vehicles without compromising travel patterns (Fagnant et al., 2015).

Unlike traditional transit services where every hour of operation costs the transit agency, a driverless system has the potential to offer round-the-clock service to customers at a relatively low marginal cost per trip served. In one study, researchers found that fleet operators "paying $70,000 per new SAV could earn a 19% annual (long-term) return on investment while offering SAV services at $1.00 per mile of a non-shared trip", while noting that this represented a rate less than 3 times that of the average taxi where the simulation was conducted (Fagnant & Kockelman, 2015). In addition to the fixed cost of acquiring the vehicle fleet, the operational costs are tied directly to vehicle miles travelled (VMT), and thus travel demand. As such, it is likely that an AV could be dispatched to serve a single trip during an off-peak period at a cost significantly lower than would be required to keep a traditional bus in service to serve the same individual. For example, the results of one study "suggests that the combined cost of charging infrastructure, vehicle capital and maintenance, electricity, insurance, and registration for a fleet of SAEVs ranges from $0.42 to $0.49 per occupied mile traveled," (Fagnant et al., 2015).

In addition to a potentially lower cost, the level of service and flexibility of such a service has many obvious advantages from the customer perspective. As previously touched on, transit services in low-density neighbourhoods often operate far below capacity and thus at a high cost per boarded passenger, particularly during off-peak travel periods. While it is not possible to predict how travel behaviour may change as a result of the introduction of AVs, it is possible that transit agencies may be able to reduce VMT and the cost of service provision in some circumstances by utilizing AV fleets. The full extent to which this may be possible will, however, greatly depend on the quantity of unoccupied ("deadhead") travel made by AVs as they are rerouted to serve another passenger (discussed further in the *Results & Analysis* and *Conclusions* sections).

KPMG estimates that even during peak travel periods less than 12% of all US personal vehicles are in use (KPMG & CAR, 2012). Simultaneously, the rapid increase in the use of car-sharing programs in North America (over 375,000 members in 2009 up from approximately 2,500 in 2001 (Shaheen, Cohen, & Martin, 2010)) highlight the growing potential for the use of shared-vehicle rental services. In comparison to today's car-sharing programs (i.e. Car2Go, ZipCar, Communatuo, etc.), Levinson and Krizek argue that next-generation services that utilize SAVs would be able to offer an even more attractive service and superior convenience, negating the need for users to locate and travel to an available vehicle prior to the trip or to locate a vacant parking space in proximity to the final trip destination (Levinson & Krizek, 2015). Instead, passengers can be picked up and dropped off directly at their origin and destination, leaving the task of finding a parking spot to the vehicle, or freeing up the vehicle in order to serve others if it is no longer needed.

Considering the aging demographic in Canada and the US (Robine & Michel, 2004), the high potential for AVs capable of providing mobility to the elderly and disabled (in addition to the young) who are unable to drive themselves is realized (Fagnant & Kockelman, 2013). However, while the use of SAV fleets have the potential to reduce auto-ownership (Fagnant & Kockelman, 2013), if consumers simply choose AVs as replacements for personal automobiles (and if AVs allow for a new demographic of automobile owners/users), AVs could in fact induce increased travel demand, congestion, and single-occupant travel - potentially negating their benefits (Fagnant & Kockelman, 2013; Gill et al., 2015; Levin et al., 2016).

Implementation Challenges

Obstacles to implementation include the requirement that AVs are able to safely and consistently operate under all driving situations including during adverse weather conditions such as rain, fog, snow, or icy roadways (Campbell, Egerstedt, How, & Murray, 2010). Furthermore, AVs must be capable of recognizing humans and other objects in the vehicle's path, a task that can be more challenging for an AV's sensors than for human drivers (Dalal & Triggs, 2005). Dependence on accurate and highly-detailed maps, as are

Google's self-driving cars, for example, provide another set of problems (Levinson & Krizek, 2015). However, a phased implementation strategy, beginning in mild climates and progressing towards regions with more adverse weather, coupled with the possibility to continuously crowd-source map updates in real time could mitigate many of these concerns.

With rapidly improving technology, the greatest challenges to widespread use of AVs are likely linked to public perceptions of autonomous vehicle safety, concerns surrounding job loss, litigation and liability concerns, privacy, and other social and political barriers (Fagnant & Kockelman, 2013). Noting the importance and legitimacy of these barriers, these topics are not the focus of this study, and readers interested in these topics are suggested to look elsewhere. Instead, this study is more technical in nature and is concerned with development of simple methods for determining the appropriate AV fleet size should barriers be overcome and the use of AV fleets becomes a reality.

Methodology

Data and Assumptions

Travel demand for the study is determined from the most recent Origin-Destination (OD) Survey results for the Montréal CMM (Agence métropolitaine de transport, 2015). The OD data represents an approximation of all travel occurring within the CMM on a typical weekday, obtained via telephone survey with a sampling rate of approximately 5% of the total population. The OD data contains information for each unique trip, containing demographic information (age, sex, home location, etc.) in addition to trip specifics (trip origin and destination (latitude/longitude coordinates), departure time, travel mode, trip purpose, etc.). Each unique trip is attributed an expansion factor that specifies the number of similar trips that occur with the same trip characteristics each day. The sum of the expansion factors thus represents the total number of daily trips.

A subset of this dataset was created by isolating all trips with an origin and/or destination "Municipal Sector code" (there are 108 municipal sectors within the CMM) matching that of the study area (see *Study Area Selection*, below). This subset of the OD data therefore represents an approximation of all travel to-, from- and within the study area over a 24-hour period for a typical weekday. The subset was further reduced by mode, removing all walking, cycling, paratransit, and school bus trips, which for the purposes of this study are assumed to retain their existing mode under the simulated scenarios.

The remaining subset contains 180,000 trips taken by the following modes: automobile (driver and passenger), transit (STM Metro, STM Bus, RTL bus, CIT bus, and "other" bus), motorcycle, and taxi. The composition of the daily trip data by mode is presented in, Figure 1, below. A plot of the count of trips over the course of the 24-hour simulation period is also provided in Figure 2. During simulations, the trip data is used in its compact (un-expanded form) to reduce processing time, with the expansion factor applied during the vehicle assignment phase.

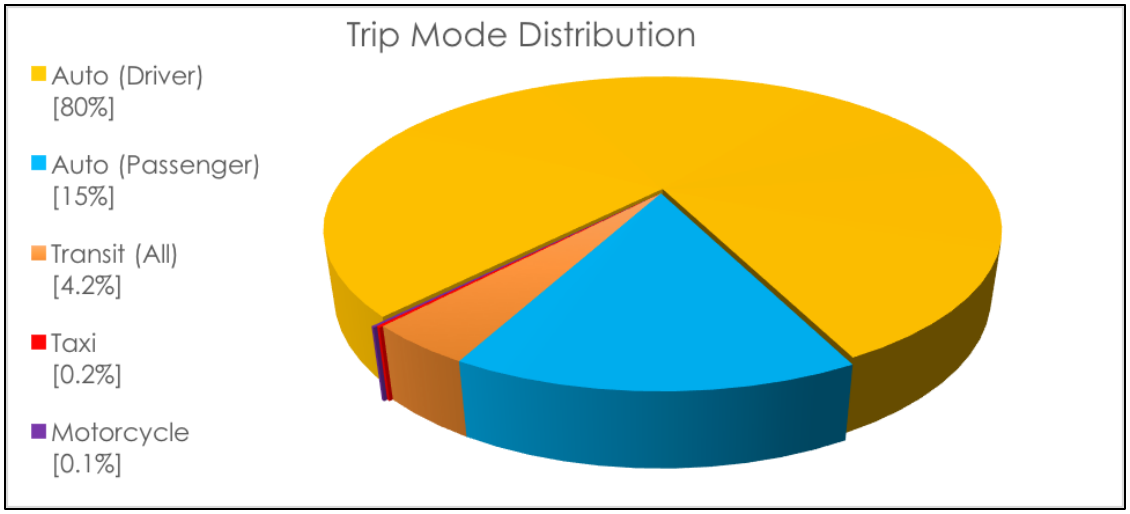

Figure 1 - Distribution of trip modes for Scenario 4 (All Trips)

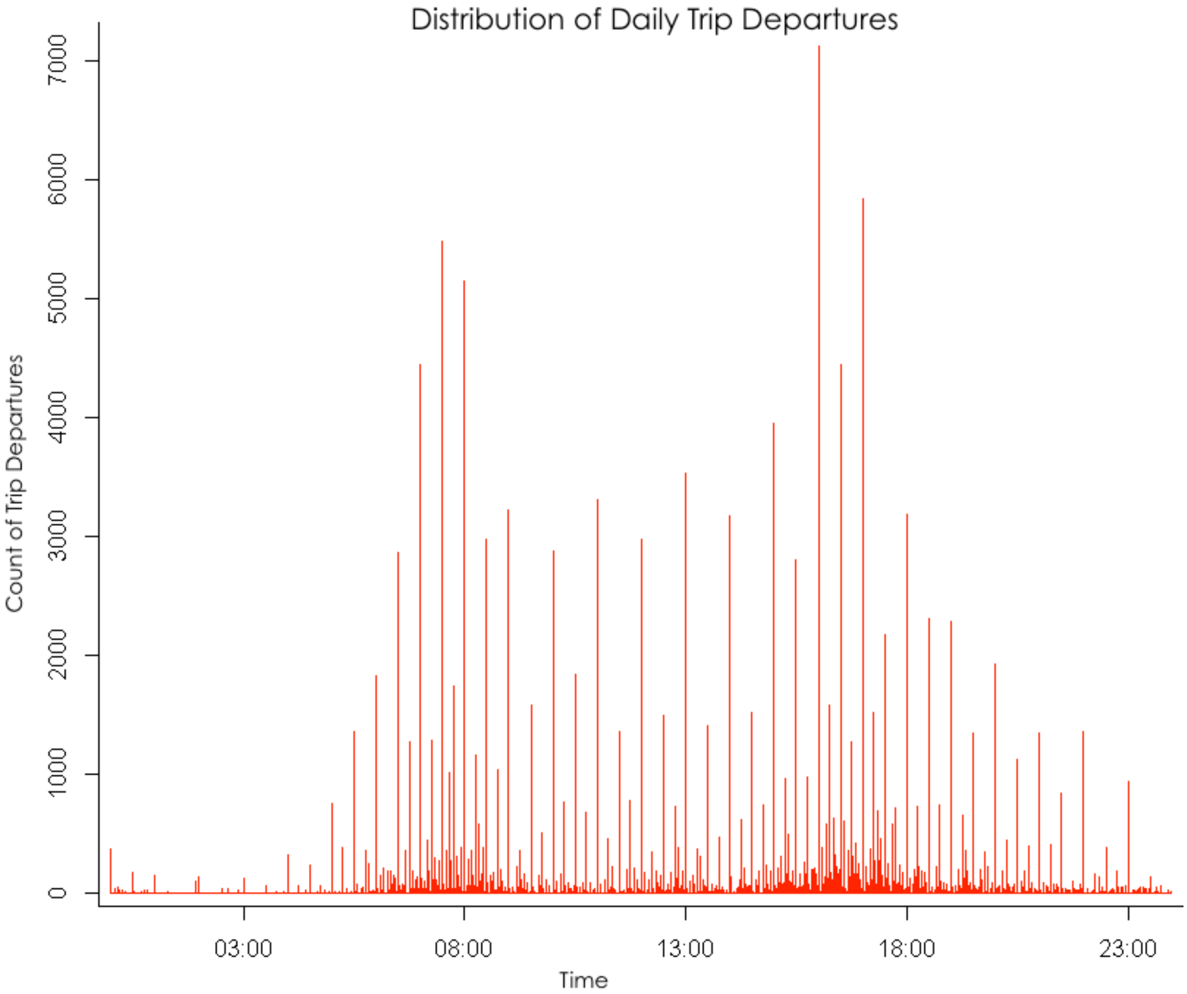

Figure 2 - Distribution of trip departures for Scenario 4 (All Trips)

Study Area Selection

Based on the objectives of the study, a number of criteria were developed to select an appropriate study area from among 12 potential locations (low-density satellite communities to the Montréal metropolitan core) within the Greater Metropolitan Montreal Region, where travel data was readily available. Selection criteria focused on sufficient population and travel demand, low levels of existing transit service, the degree to which the location is self-contained, and the existence of high-frequency transit hubs providing access to external regional destinations (i.e. Downtown Montréal/other communities and activity centres). A complete description of the selection criteria, justification for use, and the scoring methodology applied is available for further reference in Appendix A – Study Area Selection.

Potential Study Areas

The availability of Origin-Destination survey data was identified as a necessary component for the study to be completed, as it was used to generate the daily travel demand for used in the SAV fleet simulations. Access to OD data for the Montréal region was readily available, so potential sites were selected from within this region. Furthermore, the study is intended to be applicable to neighbourhoods where existing transit is provided at relatively low frequency in low-density neighbourhoods, and in order to simplify the simulations, within communities that are relatively isolated. With the above considerations in mind, the following potential sites were selected as potential case study locations:

- CIT Chambly-Richelieu-Carignan
- CIT Du Haut-St-Laurent
- CIT Laurentides
- CIT La Prequ'Île
- CIT Le Richelain
- CIT Roussillon
- CIT Sorel-Varennes
- CIT du Sud-Ouest
- CIT de la Vallée du Richelieu
- Ville de Saint-Jean-Sur Richelieu

It should be noted that the basic criteria were met for multiple potential study areas, and the model simulations could have been performed on almost any of the 12 potential locations. The selection criteria was therefore used to help determine the most appropriate location that would provide meaningful results while not becoming overly complex.

Saint-Jean-sur-Richelieu: An Overview

The selected study area, Saint-Jean-sur-Richelieu (SJSR), is located approximately 20 km south of the island of Montréal with a population of approximately 87,500 in 2006 (Statistics Canada, 2007). In 2001, from the former towns of Saint-Jean-sur-Richelieu (Old Saint-Jean), Iberville, Saint-Luc, Saint-Athanase, and the municipality of L'Acadie were amalgamated to form the Ville de Saint-Jean-sur-Richelieu, encompassing a total area of about 226 km^2 (Ville de Saint-Jean-sur-Richelieu, 2012). An overview map is presented in in Figure 3, below.

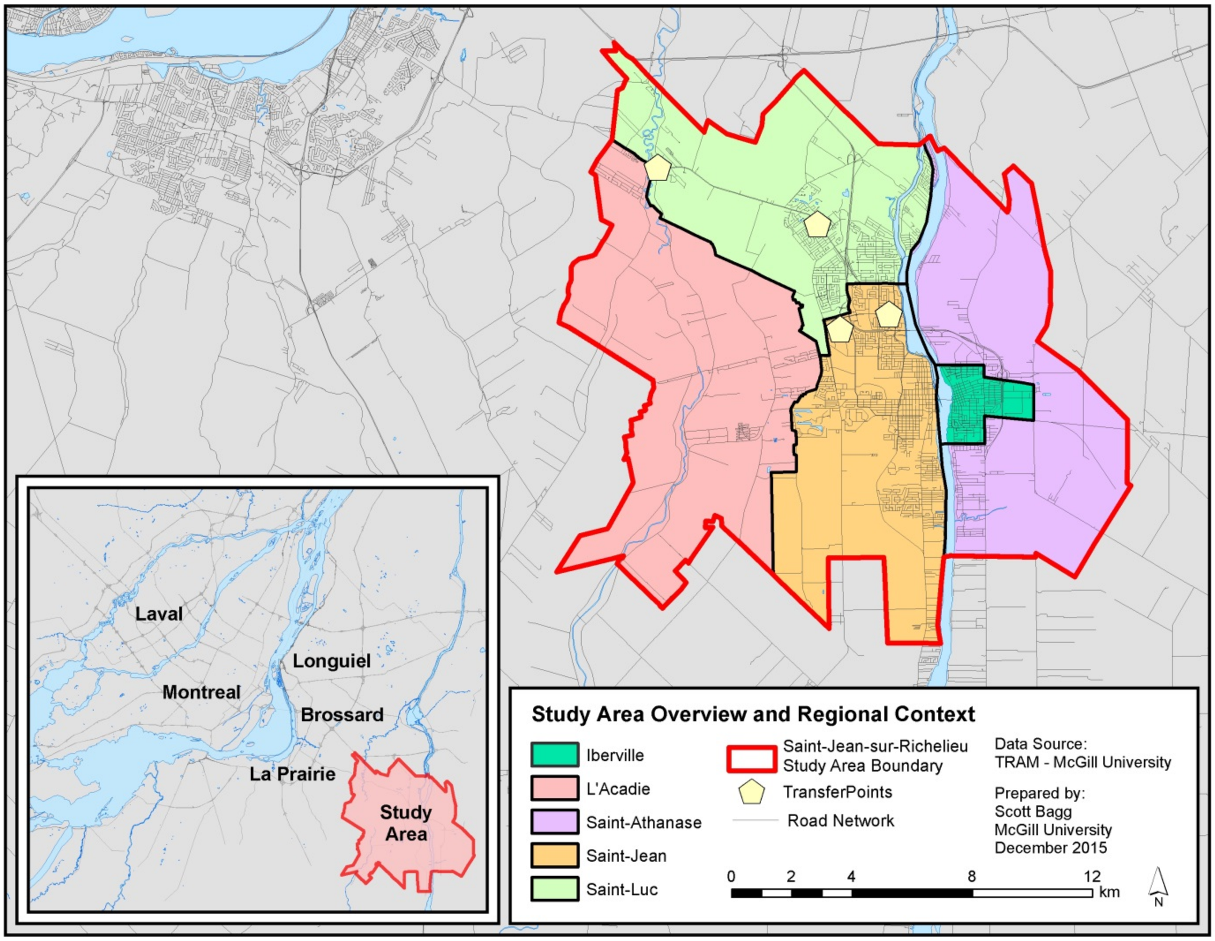

Figure 3 - Study area overview and the regional context

The majority of residents and the highest densities are clustered along the north and south shores of the Richelieu River, in Old Saint-Jean, Saint-Luc, and in Iberville (Statistics Canada, 2002, 2007). Table 1 provides a summary of the population by region within SJSR, accompanied their respective densities.

Table 1 - Population and density by region for 2001 & 2006

Sector	2001	Proportion of Total Population	2006	Proportion of Total Population	Density (persons/km2)
Saint-Jean	37,386	46.9 %	39,274	43.9 %	863.3
Saint-Luc	20,573	25.9 %	25,264	28.2 %	494.9
Iberville	9,424	11.8 %	9,989	11.2 %	1 915.8
Saint-Athanase	6,691	8.4 %	7,403	8.3 %	139.1
L'Acadie	5,526	6.9 %	5,562	6.3 %	80.2
TOTAL	**79,600**	**100 %**	**87,492**	**100 %**	**387.5**

Source: (Statistics Canada, 2002, 2007)

SJSR's existing transit services can be divided into two primary categories: high-frequency express regional services, and relatively low-frequency local services. The regional routes provide service to La Prairie, Longueuil, Vieux-Montréal, and Montréal Central Station, with more than 70 daily departures, and with frequencies as great as every 5 minutes during peak travel periods (Ville de Saint-Jean-sur-Richelieu, 2015b). In 2011, a significant majority of transit usage within SJSR was associated with the express regional services, totalling more than 1.2 million annual passenger trips served, and representing approximately 69.1% of all transit trips provided (Ville de Saint-Jean-sur-Richelieu, 2012).

The local routes are concentrated in the city's densest areas, primarily serving Old Saint-Jean, Saint-Luc, and Iberville. The peak frequency for local routes is 30 minutes on three of the five services, while the remaining two lines serve stops every 60 minutes. All local routes are operated at a frequency of 60-minutes during off-peak periods, for a as many as 15 to 25 daily departures (Ville de Saint-Jean-sur-Richelieu, 2015b). Over 54,000 local transit trips were completed in 2011, or 30.9% of the annual share (Ville de Saint-Jean-sur-Richelieu, 2012). For reference, a map highlighting the local transit services in SJSR is shown in Figure 4.

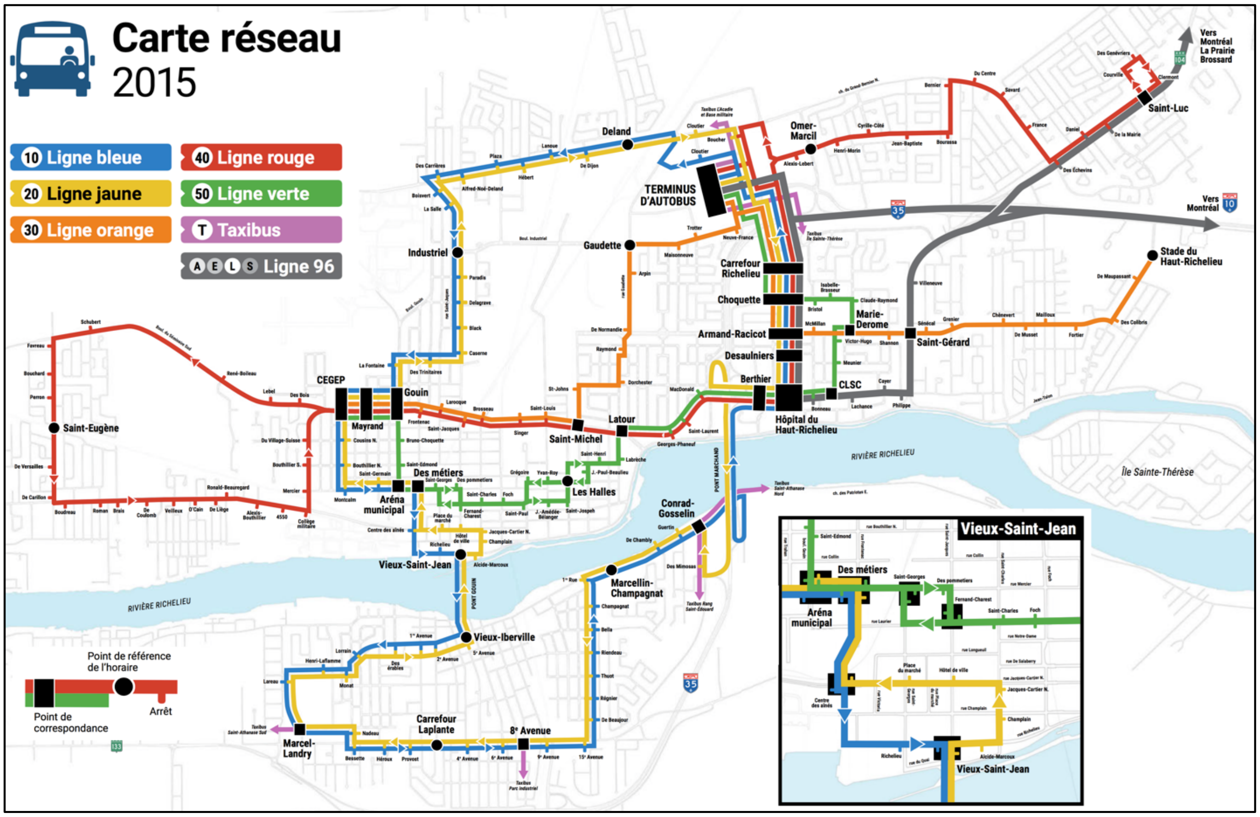

Figure 4 - Map of existing transit services in the study area (Saint-Jean-sur-Richelieu, 2015)

Since 2005, SJSR has also offered subsidized TaxiBus services for individuals residing within the extents of the municipal boundaries that live outside of the core transit network coverage area. TaxiBus users must board at specific waypoints, and are driven to a bus stop or one of the transfer points within the core-network (Saint-Jean-sur-Richelieu, 2015). In 2011, 15,411 rides were provided via TaxiBus (Ville de Saint-Jean-sur-Richelieu, 2012). Additionally, adapted transport is provided to individuals with disabilities and reduced mobility. In 2011, more than 80,500 adapted transport trips were completed in SJST; consisting of a majority of about 72,000 passengers served by contracted (subsidized) taxi, and an additional 8,600 individuals served by wheelchair accessible minibus (Ville de Saint-Jean-sur-Richelieu, 2012).

Model Framework and Assumptions

In order to determine the number of AVs required to accommodate the approximated daily travel demand for each model scenario (see *Model Scenarios*), a relatively simple program was developed using the R programming language to simulate travel throughout the day using a 1-minute time discretization. It is important to emphasize that travel demand is known prior to simulation. This means that vehicle assignment is handled as an advanced booking system, and that vehicles are dispatched to trip origins pre-emptively, rather than in response to a new trip request.

An important assumption made is that all trips are handled individually, meaning that each trip is served by a single AV, irrespective of the reported mode of travel in the OD survey. Accordingly, trips with a mode reported as automobile passenger, for example, require their own vehicle as do trips where the reported mode is automobile passenger or transit user. While acknowledging that this does not represent the most likely travel patterns of users of a future AV service (assuming that individuals that travel together today would do so in the future and that AVs could be designed to have sufficient capacity to accommodate more than one passenger), utilizing this method provides the maximum fleet size requirements to serve all trips independently. As such, this method offers a highly conservative estimate of required fleet size. The ramifications of this assumption and the impact on the results are further discussed in the *Analysis* section.

As the proposed AV fleet is not intended to act as an outright replacement of all transit services, instead complementing frequent transit services along high-demand corridors (by serving local contexts where high levels of transit service is not justified), it is assumed that the AV service will provide local service only. Accordingly, all simulated trips that commence (or terminate) outside the boundaries of the study area are assumed to use existing transit services (or other travel modes) for travel outside of the study area. Specifically, it is assumed that individuals making these “external” trips will connect to higher frequency transit services via major transit hubs to connect to origins and destinations in the Montréal Metropolitan core and other regional destinations. While noting that some such services exist today, this is not the case for all external connections. Acknowledging this, the chosen method was deemed acceptable for the purposes of this study as transit service are subject to change.

Trip Routing

To determine trip routing, distances, and travel times, the study makes use of the Network Analyst extension in ESRI's ArcMap software suite. First, a network dataset was created from a street network shapefile for the Montréal CMM. The street network layer's attributes include travel speed and the length of each road segment, which are used to determine the travel time (in minutes) along all road segments within the CMM. It is important to note that the street layer shapefile contains a variable indicating whether or not streets permit only one-way traffic, however, the permissible direction cannot be easily attributed to the network dataset. As such, one-way street restrictions are not included in the network dataset (travel is permissible in both directions on all road segments). The full impact of this assumption on the results has not been estimated, but is assumed to be minimal.

Next, the origin-destination pairs for all trips considered were mapped from the latitude and longitude coordinates provided in the OD data. For internal trips (trips originating and terminating within the study boundaries), the coordinates for both the origin and destination are used as provided. However, some modifications were necessary for "external" trips (as only the local or "internal" portion of the trip is carried out by AV), as described below.

For trips with origins inside the study area boundaries that terminate elsewhere, the origin coordinates are retained while the coordinates of the destination are modified to reflect the Transfer Point that is closest to the trip origin (determined using the Closest Facility tool within the Network Analyst tool set). For trips with origins that are outside the study area boundaries, the Closest Facility tool is first used to locate the transfer point closest to the trip destination (within the study boundaries). Then, the shortest networked path (by travel time) is computed from the external origin to the transfer point. Adding the travel time to the original trip departure time provides an approximation of when the individual would reach the transfer point, and is thus set as the adjusted trip departure time (for the trip portion completed by AV). The adjusted origin coordinates are similarly updated to reflect the location of the transfer point location.

With the origins and destinations of external trips adjusted, the shortest path (by travel time) was then computed for all internal trips and the local portion of all external trips. The results were then exported and the calculated travel time and associated trip distances were attributed to each unique trip ID.

Vehicle Rerouting

As the vehicles are assumed to be shared by all users involved in the given scenario, a key component in the simulations involves rerouting available vehicles from completed trip destinations to upcoming trip origins. Thus in order for the model to determine the appropriate vehicle for an upcoming trip (i.e. the closest available vehicle), the travel time and distance to reach subsequent trips must be known. To reduce the complexity of the trip reassignment module of the simulation, the list of all latitude and longitude pairs for trip origins and destinations were reduced to a list of unique locations. Using this list, the trip dataset was updated to contain simplified location IDs for all trip origins and destinations.

Next, the travel time and distance from all unique trip destinations to all unique trip origins was determined using the Network Analyst OD cost matrix tool. In effect, this allows the model to quickly reference and compare the time (and distance) to reach all upcoming trips once the trip currently assigned to it is completed, without unnecessarily re-checking the cost (time) of reaching vehicles at the same location.

Simulation Vehicles

During simulations, each vehicle in the fleet is assigned a unique vehicle identifier (vID), and has attribute variables (updated each timestep) to monitor important metrics throughout the simulation. Key vehicle attributes include:

- vStatus (indicates the given vehicle's status current status: "available" (0); "active" (1); "charging" (2));
- numCharge (number of recharge cycles completed);
- ReleaseTime (indicates the timestep at which to return the status to 0 (available) when the active trip or recharge cycle is completed);
- TripCount (count of completed trips);

- vXY (vehicle location ID, tied to latitude / longitude coordinates);
- VMT (total distance travelled in km)
- OTT (occupied travel time in minutes; accumulated while carrying passengers);
- UTT (unoccupied travel time in minutes; accumulated while rerouting from a completed trip to an assigned trip)

Simulation vehicles are based off of the Smart ForTwo all-electric EV. The vehicle's travel range on a single charge is specified as 110 km, and the battery capacity is treated as a driving "allowance" based on this range. The recharge time for the vehicle is listed as 4.5 hours to regain a full charge from a battery with 20% capacity remaining, and 7 hours to recharge completely from zero capacity. During simulations, vehicles that have reached the 20% capacity threshold after completing a trip have their status set to "charging" (2), and are made unavailable for trip assignment until released 4.5 hours later. While charging, the vehicle remains at the location of its last completed trip. Rerouting to a vacant parking space or to a charging/maintenance facility is suggested as an improvement to the model for future study, as discussed in the *Next Steps* section of the report.

Trip Simulation

For each of the different model scenarios, two full simulations were completed, beginning at 12:00 AM and carried out using a 1-minute timestep for a total of 1440 iterations over the 24-hour simulation period. The first, or "Seed Day", simulation was carried out to determine the required vehicle fleet, and commences with a fleet of zero vehicles. The second or "Fleet Test" simulation begins with the full fleet "created" during the seed day simulation with each vehicle's location carried over from their positions at the end of the seed day. The cumulative attributes holding each vehicle's VMT, occupied/unoccupied travel time, number of recharges, etc. were reset for the Fleet Test. The process for both the Seed Day and Fleet Test simulations are the same, composed of the following components, repeated for all 1440 iterations:

1) **Release Phase**
    - Identifies and isolates vehicles that have completed their assigned trips and/or finished recharging
    - Resets vehicle status to "available" (0) for the associated vehicles
2) **Initiate Recharging**
    - Vehicles that have expended 80% or more of the battery (measured using distance travelled, as outlined in the "Simulation Vehicles" section above) since their last full charge are identified and isolated
    - For the isolated vehicles:
        - The vehicle status is set to "charging" (2)
        - ReleaseTime is set to 4.5 hours (270 iterations) from the current timestep
        - numCharge (recharge count) is incremented by 1
3) **Upcoming Trip Check**
    - A check is performed to identify and isolate all trips scheduled to depart during the next timestep
    - If no trips are found, model advances to *Step* 6
    - If trips are found, the isolated trips are added to a temporary "next trips" dataset
4) **Trip Expansion Phase**
    - Duplicates of the unique next trips are created according to their respective expansion factors
    - Once expanded, the order of the next trips dataset is shuffled to randomize the order in which they are assigned vehicles[1]
5) **Vehicle Assignment Phase**
    - For each of the expanded next trips, a lookup function returns the reroute times to all available vehicles
    - The vehicle with the shortest travel time to reach the trip under consideration is assigned
        - If multiple vehicles are present at this location, a vehicle is selected at random to avoid favouring the first listed vehicle, thus more evenly distributing trips among vehicles and
    - This is repeated until all trips are assigned

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[1] All of the next trips are scheduled to depart during the same 1-minute timestep. Randomizing the order of expanded next trip set reduces unnecessary bias to the first-listed unique trip.

- If unassigned next trips remain but there are no available vehicles, additional vehicles are added to the fleet and assigned to the remaining trips[2]
    - Newly added vehicles are introduced at the origin location of their first assigned trip with zero distance travelled and zero recharges

6) Fleet Snapshot

- A copy of the vehicle fleet with all attributes is saved to file for temporal analysis

7) Timestep Increment

- The timestep is incremented
- If no vehicles have been assigned during the current iteration, the iteration terminates and the model returns to *Step 1*

8) Determine Wait Time (if any)

- The time required to reroute the assigned vehicles to their newly assigned trips is added to the vehicle's release time to determine if it can reach the assigned trip's origin before its scheduled departure time
- If the vehicle cannot reach the origin before the scheduled trip departure time, a wait occurs and the trip departure time is updated accordingly
- The difference between the actual and scheduled departure time is recorded for all assigned trips in the level of service log

9) Initiate the assigned trips

- All assigned trips are initiated and the status of the associated vehicles are set to "active" (1)
- Each vehicle's release time is set as the trip departure time plus the trip time (including boarding (3 minutes) and alighting (1 minutes) time)
- Each vehicle's cumulative attributes are updated (TripCount, VMT, OTT, UTT) using the times/distances associated with rerouting the vehicle and the assigned trip
- Set each vehicle's location to the destination of its assigned trip (where it will be when the vehicle is released)
- Terminate the iteration and return to *Step 1*

In addition to the fleet snapshots saved to file during each timestep that allow for temporal analysis, the input code and console outputs are saved to text file for review and analysis.

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[2] This occurs during the seed day simulation *only*.

Model Scenarios

Various scenarios are simulated to determine the AV fleet size required to accommodate trips made by various mode-shares. The following scenarios were devised:

1. Transit only
2. Transit + 25% of all other trips
3. Transit + 50% of all other trips
4. All trips

In order to obtain a more accurate sample for scenarios 2 and 3, all non-transit trips were expanded prior to sampling. This ensures the samples include most (if not all) unique trips, rather than a simpler sample of the unexpanded trip set (which would eliminate a significant portion of the unique trips).

This sampling method involved first splitting a copy of the "all trips" dataset into transit and non-transit groups. The non-transit trips were then expanded using the OD expansion factor, and random samples were generated at rates of both 25% and 50%. Next, the count of each unique trip in each sample was used to attribute new expansion factors to each unique trip present in the given sample. The samples were then reduced to their compact (unexpanded) forms, and recombined with the transit trip group for use in the simulations.

Excluded Trips

Trips listed with the following modes are excluded from all model scenarios:

- Walking
- Cycling
- Paratransit
- School Bus

Additionally, some trips within the OD data for the CMM were listed with the same origin and destination coordinates, or with origins/destinations beyond the CMM boundaries (outside the network dataset). All such trips were removed.

The following (Table 2) presents counts of the trips that were excluded from simulation by exclusion category, shown for scenario 4 (all trips).

Table 2 - Count of excluded trips (expanded) for Scenario 4

Trip Type	Count	Walking	Cycling	Paratransit	School Bus	Ex - CMM	Same O/D	TOTAL*
Local	150271	15468.4	2703.6	389.8	10458.1	0.0	1848.7	30718.5
Local → External	35237	18.1	0.0	0.0	394.2	4179.7	0.0	4611.4
External → Local	35249	18.1	30.7	28.3	403.3	4440.7	0.0	4991.2
Total	**220758**	**15505**	**2734**	**418**	**11256**	**8620**	**1849**	**40321**
Percent of Total	100%	7.0%	1.2%	0.2%	5.1%	3.9%	0.8%	18.3%
Total Retained	**180437**							
Percent Retained	81.7%							

*Note that some trips were counted in multiple exclusion categories; total is therefore less than the sum of all individual exclusions.

Results & Analysis

Results Summary

The results of the model simulations demonstrate that SAV fleets are capable of accommodating the typical travel demand within the study area at the various trip intensities of the scenarios tested. A summary of the key findings are presented in Table 3, below. More detailed analyses follow, grouped into fleet, vehicle, and trip statistic categories.

Table 3 - Summary of key findings by scenario

Scenario	Number of Trips Simulated	Required Fleet Size	Replacement Factor	VMT Ratio[3]	Trips with Delayed Departures
Transit Only	7587	586	N/A	N/A	7.5%
Transit + 25%	50765	3075	6.26	1.66 : 1	2.4%
Transit + 50%	93943	5893	6.53	1.51 : 1	1.8%
All Trips	180299	11022	6.77	1.45 : 1	1.7%

Fleet Statistics

The simulation results for each scenario indicate that the fleet size required in each case is approximately one-sixth the size of the fleet of personally owned vehicles within the study area, as shown in Table 4, below. The vehicle ownership statistics were determined using the reported vehicle ownership for all households within each scenario's trip dataset, multiplied by the expansion factor. This statistic does not account for the transit vehicles or taxi services which are used to complete the trips today, suggesting that the replacement factor is conservative.

Furthermore, readers are reminded that the model assigns a single vehicle to every trip, which - as previously discussed - likely does not accurately reflect real-world passenger behaviour. Thus, it is expected that modifications to the model that allow multiple

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[3] Conservative estimate does not include the VMT required to serve transit modes; refer to *Fleet Statistics* section for further details.

passengers to occupy a given vehicle would further reduce the fleet size required under all of the simulation scenarios.

Table 4 - Required feet size and replacement factor

Scenario	Fleet Size	Vehicle Ownership	Replacement Factor
Transit Only	586	-	-
Transit + 25%	3075	19254	6.26
Transit + 50%	5893	38506	6.53
All Trips	11022	74586	6.77

The impact of the shared AV fleet on VMT is extremely important. While it has been demonstrated that the fleet size requirements are greatly reduced when a shared AV fleet is employed to provide transport, by the nature of the SAV fleets functioning, a proportion of travel includes some level of unoccupied travel as vehicles relocate themselves between occupied trips in order to serve other users. Simultaneously, there is potential to reduce VMT (if only slightly) in some respects, as intelligent, connected vehicles will not need to search for parking if another passenger awaits, and when the vehicle is not immediately needed, AVs will be able to locate and travel to a suitable parking location (or charging/maintenance facility) in a manner that is equally or more efficient than human drivers.

The extent to which VMT will be affected remains highly contested within the literature, and also depends on assumptions for travel patterns and behaviour in a world of self-driving vehicles, which cannot be easily predicted. As previously noted, it is possible that those who are non-drivers today (the elderly, mobility-challenged, or children, for example), may soon have a new option for travel, generating trip demand that was not previously possible.

The VMT of the SAV fleet simulated can be determined with a high level of confidence (given the model assumptions and the trip dataset), while estimating the present day VMT equivalent that is associated with providing the same trips is more difficult. This is partially due to the fact that the VMT associated with provision of transit cannot be determined accurately without additional data, and because the primary trip mode indicated in the OD survey does not necessarily cover all segments of the trip. Furthermore, for trips completed by multiple modes there is no indication of what portion was completed by the primary mode.

To illustrate this point, consider a trip that originates in SJSR study area and terminates on the island of Montréal, but is listed in the OD with a primary mode corresponding to the STM's metro (subway) service. As the Metro network does not extend to SJSR (approximately 35 km from the island of Montréal), the trip cannot have been completed by metro alone, and must in fact represent linked trips that include a segment on the metro. What proportion of the route was completed by car (driver or passenger)? By transit? Which route was taken? Did the individual need to find a parking space? Without additional information, these questions cannot be answered with any degree of certainty.

For a true comparison, the VMT for all of the transit trips simulated should include the sum of the VMT incurred by each of the utilized services over the course of the day. Unfortunately, even this would not provide a fair comparison as many of the transit services used serve more than just the population simulated, making it virtually impossible to estimate the VMT associated with the only the transit services taken by the individuals accounted for in the OD survey.

With no way of accurately determining the VMT associated with the present day transit trips, it was decided to exclude the transit trips in the VMT impact analysis. While this means that no VMT comparison can be made for the Transit Only scenario, this method is conservative. Exclusion of the VMT incurred by transit vehicles from the present day VMT estimate inherently leads to less favourable AV fleet performance (i.e. a greater proportional increase in VMT). As such, the estimates of the present day VMT include only non-transit modes, excluding trips completed as automobile passengers, as this would incorrectly double-count the VMT incurred by both drivers and passengers of the same vehicle.

VMT is calculated as the shortest path (determined by ArcMap's Network Analyst tool) between the stated origin and destination coordinates in the OD survey. Notably, this method assumes that vehicles travel directly from origin to destination (i.e. no additional travel for parking, taxis do not accumulate VMT while travelling between trips, etc), again favouring a conservative overestimate of the increase in VMT incurred by the SAV fleet.

Considering these limitations, the VMT accumulated by the SAV fleets in each scenario is presented below, in Table 5. These figures are also compared to the estimated VMT equivalent in order to provide the associated VMT ratio. In all cases, the VMT ratio is greater than 1, indicating that the AV fleet indeed increases the total amount of travel compared to the status quo in order to complete the same number of trips. An important finding, however, is that as the total number of trips served increases, the VMT ratio decreases. This may indicate that as the number of trips (and the vehicle fleet size) increases, the distance a vehicle must travel before reaching its next assigned trip decreases, on average, for improved fleet performance overall, suggesting that fleet performance could be improved if additional users partake in the shared ride service. Furthermore, we can also speculate that this ratio could be further decreased if the model is improved to allow for vehicle occupancies greater than one (discussed further in the *Conclusions* and *Next Steps* sections).

Table 5 - Fleet VMT comparison and Recharge statistics

Scenario	**Fleet VMT (km)**	**Equivalent VMT (km)**	**VMT Ratio**	**Vehicles Recharged**[4]	**Prop. of Fleet Recharged**
Transit Only	43,453	*N/A*	*N/A*	203	34.6%
Transit + 25%	235,702	142,159	1.66 : 1	1346	43.8%
Transit + 50%	431,509	286,694	1.51 : 1	2081	35.3%
All Trips	830,967	573,260	1.45 : 1	4434	40.2%

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[4] Count of vehicles recharged one or more times throughout the duration of the simulation.

The fleet statistics also include a count of the recharge cycles completed by all vehicles in the fleet during the simulation, as shown in the above, Table 5. Across all scenarios, a single vehicle is recharged no more than once per day, and approximately 56 - 65% of the fleet complete the simulation on their initial charge. The maintenance and battery lifespan implications are discussed in the following section, *Vehicles Statistics*.

Vehicle Statistics

Next, the results are discussed in the context of individual vehicle attributes. As is shown in Table 6, the average number of trips completed by each vehicle increases from approximately 13 under the Transit Only scenario, to about 16 trips per vehicle per day in all other cases. A similar trend exists for the maximum number of trips served by a single vehicle.

However, the average distance travelled remains relatively consistent across all scenarios, ranging from approximately 73 – 77 km per vehicle. And yet despite the similar mileage, the vehicles in the Transit Only scenario covered a significantly greater proportion of travel without passengers on-board, as indicated by the average occupied to unoccupied travel ratio of 1.65 : 1. This means that on average about 38% of travel is unoccupied in the Transit Only scenario, pointing to significant distances associated with vehicle relocation between passenger trips. For the remaining scenarios, the rate of occupied to unoccupied travel ranges from about 5:1 to 6:1, indicating that unoccupied travel (trip rerouting) is significantly reduced when the number of trips served increases. On average, approximately 84 - 86% of all travel occurs with a boarded passenger in these scenarios.

Table 6 - Vehicle travel and usage statistics

Scenario	**Trips Served (avg)**	**Trips Served (range)**	**avg VMT (km)**	**VMT range (km)**	**Occupied to Unoccupied Travel Ratio (avg)**
Transit Only	12.95	2 – 26	74.2	14.5 - 133.3	1.65 : 1
Transit + 25%	16.51	2 – 32	76.7	16.7 - 144.9	5.15 : 1
Transit + 50%	15.94	2 - 35	73.2	13.9 - 155.4	5.96 : 1
All Trips	16.36	3 – 33	75.4	11.2 - 163.8	5.80 : 1

In terms of the wear and tear on vehicles and the expected longevity of the fleet, similar trends exist among all 4 scenarios, primarily due to the fact that in all cases the average vehicle accumulates about the same mileage each day, albeit at diferent occupancy rates.

Based on the vehicle specifications for the Smart ForTwo EV, the vehicle's battery should power-control checks and battery maintenance every 20,000 km of travel (or once annually). With an average daily mileage of 75 km, this means that most vehicles will be due for heavy maintenance every 267 days, on average. While noting this, as a service vehicle it is likely that more frequent general maintenance (and cleaning) will be required. See the *Next Steps* section for additional discussion on this point.

The ForTwo electric drive's battery is marketed with a 4-year, 80,000 km warranty (Smart Canada, 2015). Using the conservative assumption that vehicle usage on weekends will be the same as on weekdays (for which the simulations were completed), within 4 years, the average AV is expected to have travelled as much as 110,000 km. Conversely, if weekend travel is assumed to be 30% lower than on weekdays (for an average weekend VMT of 52.5 km/vehicle-day), the average AV can be expected to travel about 45 km less each week. Under such a scenario, the vehicles might more realistically be expected to accumulate 100,000 km over 4 years.

In either case, it appears that vehicles will exceed their battery warranty in less than 4 years. Using the more conservative estimate (weekend travel rate equivalent to weekday travel), vehicle batteries are predicted to reach 80,000 km of travel and thus require replacement approximately every 3 years[5]. When reduced weekend travel is assumed (52.5 vehicle km per weekend day), battery lifespan increases by approximately 100 days. A full breakdown of the expected battery lifespan and heavy maintenance requirements are presented in Table 7, below.

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[5] For the purposes of this study it is assumed that batteries must be replaced when the warranty expires. However, in practice the useful life of the battery may exceed the warranty period.

Table 7 - Expected maintenance and battery lifespan

Scenario	Recharge Cycles (avg)	Days of Service until Battery Maintenance (avg)	Conservative Battery Lifespan (yrs)	Battery Lifespan with Reduced Wknd Travel[6] (yrs)
Transit Only	0.346	270	2.95	3.24
Transit + 25%	0.438	261	2.86	3.14
Transit + 50%	0.353	273	2.99	3.28
All Trips	0.402	265	2.91	3.19

As battery densities increase and the price of batteries are reduced over time, these figures may change in coming years. It should be noted, however, that there is a large environmental impact associated with the end of life and disposal of batteries. A full life-cycle analysis of the SAV fleet is thus recommended, which should be compared to the life-cycle cost of the vehicles (personal automobile, taxi, and/or transit) for which they are intended to replace.

Trip Statistics

Assessing the performance of individual trips, just 1.7 – 7.5% of all trips served incurred delays to their scheduled departure time across all scenarios. For trips that were delayed, the average wait time was approximately 1 minute, and no trips were delayed by more than 6 minutes. Considering that the existing local transit within the study area is provided at frequencies of 30 and 60 minutes only, the level of service improvements that a SAV fleet could provide are particularly impressive. The level of service and trip delay details are presented in Table 8, below.

Readers are reminded that the simulation is based on scheduled travel demand similar to advance bookings, rather than on-the fly response to live trip requests, which would likely lead to greater wait times, or a larger fleet to maintain service levels. The transition to a live trip request model that more accurately depicts the likely implementation of a SAV service is thus recommended, as discussed in the *Next Steps* section.

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[6] Assuming weekend travel requires only 70% of weekday vehicle VMT

Table 8 - Level of Service and Trip Delays

Scenario	Total Trips	Trips with Delayed Departures	Average Wait Time (min)[7]	Maximum Wait Time (min)
Transit Only	7587	7.5%	1.697	5.87
Transit + 25%	50765	2.4%	0.861	5.55
Transit + 50%	93943	1.8%	0.762	5.95
All Trips	180299	1.7%	0.786	5.82

A Day in the Life of an AV

This section is intended to provide readers with a better understanding of the typical activity of an AV within the fleet. The following example tracks the activity of a vehicle in Scenario 2 (Transit + 25%), highlighting the vehicle's location over the course of the simulation period in addition to the trip origins and destinations. Figure 5 provides an overview at noon (midway through simulation) and midnight (simulation complete). At the start of the simulation, the AV is located Saint-Luc, and proceeds south to its first assigned trip origin (denoted by the orange circle with subscript 1o), where a passenger boards, before travelling to the trip destination represented by the pink circle with subscript 1d, also denoted as a transfer point.

Closer examination reveals that the origin for the next assigned trip (2o) is also located at the same transfer point, meaning that the AV will not need to be relocated before commencing the next trip. It can also be noted that in instances where the vehicle must be relocated, the relocation distance is typically small. Among all of the necessary vehicle relocations in this example, the maximum unoccupied distance travelled did not exceed 2 km for a single relocation event.

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[7] Average wait time and maximum wait time are calculated using only the portion of trips that were delayed.

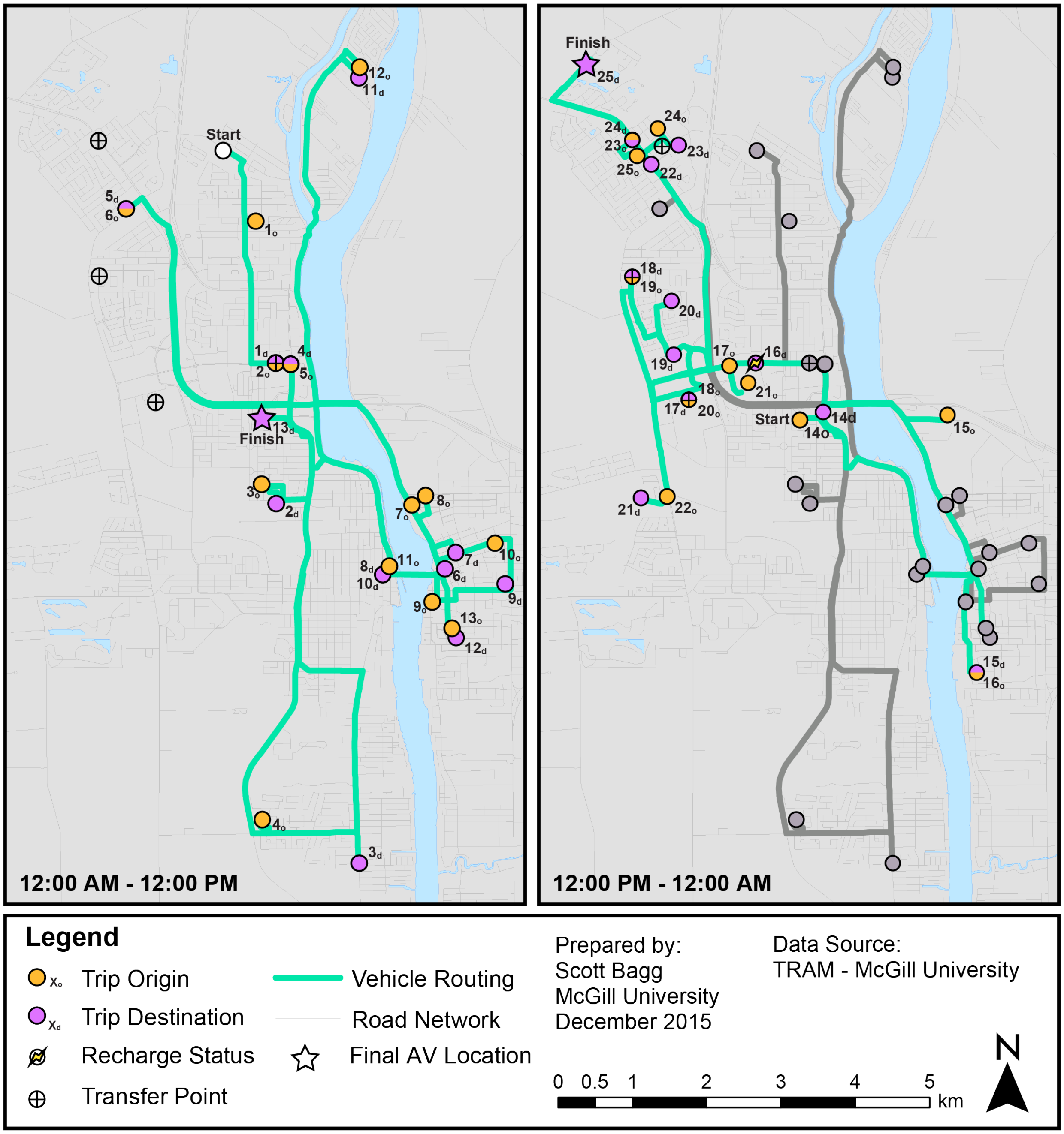

Figure 5 - AV activity progression over the course of simulation

By noon, the vehicle in this example has completed 13 trips, with an average trip distance of 4.6 km, and an average rerouting distance of 317 m. After completing its 16th trip at approximately 1:00 pm, the battery has dropped below 20%, at which point the vehicle is made unavailable for trip assignment while the battery is recharged (at its current location), as indicated by the lightening bolt recharge status indicator. After regaining a full charge about 4.5 hours later, the vehicle status is returned to available and subsequent trips are assigned.

At the end of the simulation, the vehicle has provided 25 passenger trips, with an average occupied trip distance of 3.68 km, each requiring about 600 m of unoccupied travel to move between trip destinations and subsequent origins. To achieve this, the AV covered about 108.7 km in total, approximately 92 km of which were travelled while carrying a passenger, and approximately 16.7 km was travelled while unoccupied. This points to an occupied to unoccupied travel ratio of 5.5. Within this count, five of the 25 trips served (20%), required no trip rerouting, as the origin of the next trip served took place at the destination of the previously served trip.

Conclusions

Fleet Impacts

The fleet size required to serve the daily trips completed by transit mode (Scenario 1) within the study area is found to be 586 vehicles. The actual vehicle fleet used to serve SJSR's local transit is estimated to be 9 conventional (60') buses during the peak travel period and 6 conventional buses during the off-peak periods (See Appendix B: Estimating SJSR's Local Vehicle Fleet Size), in addition to as many as 41 contracted TaxiBus that provide public transit service to residents outside the service area of the main five bus lines (Ville de Saint-Jean-sur-Richelieu, 2012).

This constitutes a significant fleet size increase, largely attributed to the assumed single occupant restriction, and to a lesser extent, the fact that the transit only scenario includes all trips that indicate transit as the primary travel mode. This assumption may lead to an over-inflated approximation of the transit users in SJSR due to the fact that the primary mode is often associated with a transit service located outside the study area (e.g. STM Metro or RTL bus), and assumes that these users also use SJSR's transit for the portion of their trip within the study boundaries – which may or may not be the case. Acknowledging these limitations, the results indicate that the operational saving on a per vehicle basis would need to be very significant in order to justify a conversion from a traditional bus fleet to a SAV fleet (refer to *Impacts on Fuel Economy and Energy Consumption)*. However, considering that a large proportion of transit's operational costs are linked to operator wages, the fact that the driver is removed from the equation when AV fleets are employed might tip the scales in favour of the SAV fleet. The potential job loss implication constitutes an important but separate topic that is not discussed in this report.

Considering Scenario 2 (Transit + 25%), which was found to require a larger AV fleet of 3,075 vehicles, the results indicate that each AV in this case is capable of replacing about 6.26 personally owned vehicles. This indicates that if on-demand, automated transit vehicle services are able to attract just 25% of today's trips presently completed by non-transit mode, there is potential to significantly reduce the personal automobile fleet. Of additional note, while the number of SAVs in the fleet increases by a factor of approximately 5.25 from Scenario 1 to 2, the associated number of trips served increases by a factor of 6.70. This highlights the fact that the number of trips served by each vehicle increases from approximately 13 trips per vehicle per day in Scenario 1 (Transit Only), to about 16.5 trips per vehicle per day in Scenario 2 (Transit + 25%). Together, these findings indicate a non-linear relationship between the number of trips served and the fleet size, and that overall the SAV fleet can be said to perform more efficiency as the number of trips served increases.

The results also indicate that in serving only the transit trips, on average approximately 38% of each vehicle's daily VMT occurs with no boarded passengers. However, when the number of trips served is increased to include 25% of non-transit trips, the proportion of unoccupied travel drops off significantly - to less than 16% of daily VMT for the average fleet vehicle. This once again highlights the trend that individual vehicle productivity improves as the number of trips served increases.

The number of trip departures that experience delays also decreases when non-transit trips are included; reduced from 7.5% of all trips in the Transit Only scenario to 2.4% and 1.7% when 25% and 50% of non-transit trips are included, respectively. This being noted, for existing transit users in SJSR, where the frequency of local services is at best 30 minutes, this represents a significant improvement as approximately 92.5% of transit trips can be served with no required wait.

Furthermore, across all scenarios the average and maximum experienced wait times do not exceed 2 and 6 minutes, respectively. These findings suggest that on-demand autonomous mobility services are capable of offering highly convenient services to the large majority of users. This level of convenience is likely to be viewed as a more attractive alternative to transit, particularly for non-captive transit users that typically favour the convenience of the personal automobile.

Impacts on VMT

VMT comparisons were not completed for transit trips due to data limitations. However, in general, a conservative analysis of the simulation results point to an increase in VMT over today's driving behaviour, ranging from 45% to 66% increases in total distance travelled. While not a positive outcome, this is not entirely surprising, considering that the model allocates one vehicle per passenger, and that vehicles inherently incur additional travel in order to reach their next assigned trip. Given this, is it plausible that a shift to multiple occupancy vehicles would be able to reduce or eliminate the increases in VMT? How might such a shift be realized?

Considering scenario 2 (Transit + 25%), with an estimated 66% increase in VMT, it can be assumed that all trips completed by transit users (who already use shared vehicles) and automobile passengers (who currently share their rides with automobile drivers) can be assigned to shared vehicles. In this scenario, transit trips account for 15.0% of the daily trips, and approximately 11.3% of the total fleet VMT[8]. Automobile passenger trips account for an additional 13.6% of the daily trips, and approximately 10.6% of VMT. Combined, assigning these trips to shared vehicles would reduce the fleet VMT by 51,606 km, for a total fleet VMT of 184,096 km. This correlates to an adjusted VMT ratio of 1.30 (compared to the unadjusted result of 1.66).

What this indicates is that in order for the net VMT of the AV fleet to remain the same as the estimated present day VMT, if existing transit users and automobile passengers accept sharing their rides, daily fleet VMT would need to be reduced by an additional 30% by incentivizing just 15% of automobile drivers that are assumed to utilize a single occupant AV to opt for a shared double-occupant AV. Whether or not this is possible in reality is up for debate, but appropriately valued incentives (via fare and membership discounts, or through the issue of travel credits, for example) are likely capable of attracting at least a proportion of the individuals necessary to reduce the VMT ratio to 1.

Impacts on Fuel Economy and Energy Consumption

In addition to VMT, another important consideration is the impacts of an SAV fleet on energy use and fuel consumption. The use of smaller, more efficient vehicles compared to

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[8] Note that this calculation does not account for the additional VMT associated vehicle rerouting, ensuring that VMT reduction estimates are conservative.

the existing transit fleet (as well as many personally owned vehicles) could lead to reduced overall energy use to meet transportation demand. While a true life-cycle analysis should be completed to comprehensively compare an SAV fleet to the business as usual case (including the extraction, production, use, and end of life of the vehicles and related infrastructure in both cases), a quick analysis of the operational energy needs provides some insight into the potential energy impacts.

In reality, the fuel economy of transit vehicles varies from bus to bus, route to route, and season to season due to external factors (state of repair, terrain, topography, weather and climate, for example), conservative estimates can be used to gain a general comparison to the energy use of the simulated SAV fleet. At best, conventional, hybrid and liquefied natural gas (LNG) buses were found to have fuel economies that ranged from 3-8 mpg equivalent under various scenarios of testing that considered different passenger loads, vehicle speed profiles, and route slope, among other characteristics (Wayne, Clark, Nine, & Elefante, 2004). To be conservative, the upper bound of 8 mpg (or 29.4 L/100 km) will be used for transit vehicles. For comparisons to the AV fleet, the Smart FourTwo electric drive's fuel economy equivalent will be used, taken as 1.9 L/100 km[9] (Smart Canada, 2015).

Using these energy consumption estimates, a single AV would need to travel about 15.3 km to consume the same amount of energy required to travel just 1 km by conventional diesel bus. In effect, this means that a VMT ratio as great as 15:1 could be accommodated without affecting energy consumption, in operational terms, when considering only the replacement of transit buses. Of course, such an increase in VMT would not be desirable as this would be associated with increased traffic congestion, but this does indeed demonstrate that there are likely energy consumption savings to be made so long as VMT does not increase significantly. Additionally, this estimation is sensitive to the energy consumption rates of the AV vehicles used, so if more energy intensive vehicles are ultimately selected, the extent of the energy savings will be reduced.

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[9] Calculated from the specified gasoline fuel consumption equivalent of 1.9 L/100 km of city driving, using Smart's stated energy equivalent of 8.9 kWh of energy per litre of gasoline.

AV Fleets as a Replacement to Local Transit

In summary, assuming that vehicles permit only single occupancy, the results of the simulations do not indicate that autonomous vehicle fleets can more efficiently provide local transit service within the study area, with a considerably larger vehicle fleet, and a high proportion of unoccupied travel. However, even using single-occupant vehicles, the results indicate that if SAV fleet services can be made attractive to both existing transit users and a proportion of non-transit users, the performance of the fleet can be greatly improved with respect to fleet size per passenger-trips served, the additional VMT incurred, and the occupied to unoccupied travel ratio. Furthermore, the ability of a shared AV fleet to reduce the total number of vehicles required to meet daily travel demands has been found to be substantial in all scenarios where any proportion of non-transit trips are included.

It has also been demonstrated that the level of service can be dramatically improved in neighbourhoods where only low levels of transit are presently justifiable. While this is good news for the vast majority of Canadians that live in low-density suburban neighbourhoods, it is stressed that this finding should not be used to justify the continued development of sprawl in the future. Conversely, the author believes that the findings of this study highlight the potential for improved transit (or mobility-as-a-service alternatives) that are attractive enough to improve the travel options for individuals that presently deem transit a restrictively inconvenient mode of travel for all but captive users. Ultimately, it is believed that shared vehicle fleet services may become more cost-effective, safe, environmentally friendly, and convenient than personal auto ownership, fuelling a transition from auto dependence to a system of shared vehicles that can serve all but specific trip purposes, and an overall reduced energy demand and environmental impact associated with transportation.

What remains clear is that AV technologies are imminent, and it is no longer a matter of if, but when they will become available to consumers. The introduction of AVs is likely to be very disruptive in terms of their impact on landuse and travel behaviour. Although the extent of those impacts are difficult to predict, it is up to planners, engineers, governments, and other stakeholders to anticipate change and plan accordingly such that whatever level of transition occurs is done safely, and that the benefits of their introduction can be fully realized while minimizing the potential negative consequences. In time, safe, financially attractive and convenient AV fleet services have the potential to reduce the need for personal automobile ownership, and if ride sharing is properly incentivized, impacts to VMT and congestion can likely be mitigated.

Next Steps

Moving forward, continued development of real-world autonomous vehicle technologies, additional research in the shared autonomous vehicle field in general, and improvements to SAV fleet model simulations, will bring a future that includes AVs as part of the transportation system closer to a reality.

The model used in this study was developed from the ground up, and much was learned throughout study process. As a result, refinements and additional features for more realistic simulation have been identified. The following provides suggestions to improve the simulations completed in this study, in addition to related research topics that are suggested for further exploration into the impacts of SAV fleets.

Repeat Simulations in Additional Locations

Perhaps most simply, completing additional simulations using the same model but within other contexts (locations / trip datasets) either within the Montréal CMM or in entirely new locations could prove highly beneficial. Comparing the results in different locations might strengthen the conclusions drawn from the results of the initial simulations in SJSR, or highlight weaknesses in the model to handle particular situations.

Multiple Passengers per Vehicle

While significantly more complex to develop and implement, the model's realism would be significantly improved with the ability to allow for multiple passengers to occupy a single vehicle. The optimal vehicle capacity for SAV fleets, or a mix of various capacities (2 and 4 passenger varieties, for example), is up for debate, and remains a topic for future research.

Implementing a multiple passenger allowance into the model could be achieved in a variety of different ways. For example, the expanded trips of a given unique trip could be favoured for grouping in common vehicles. Or, similarly trips associated with the same household ID could be favoured to be matched together. Although an improvement, this method may prove somewhat limited by the "representative" nature of the OD trip data that utilizes expansion factors, often exceeding 20.

While this expanded set of trips is said to represent individuals (all sharing the same trip departure time, origin, and destination), and could be easily grouped into separate vehicles, more than anything it highlights one of the shortcomings of using the simplified OD dataset to model daily trip activity at the local scale. More realistic (or actual) trip data for a population that is of higher resolution (i.e. a higher number of unique trips with lower expansion factors) would allow for much more accurate simulation, while noting that this would increase the simulation complexity further, as well as the cost and effort of collecting the OD survey data.

Dynamic Ride Sharing

Another - albeit further complicated - option would be to incorporate dynamic ride sharing; or more specifically, allowing vehicles to deviate from an ongoing trip – perhaps limited by a set amount of time or a proportion of the total trip duration – in order to pick up another passenger with a similar destination. Other researchers, including Kockleman and Fagnant, have already completed preliminary research in this field, however, their overall methods varied (particularly with respect to how available vehicles were redistributed). This being noted, the incorporation of dynamic ride sharing into the model used in this study would allow for a comparison of results found in other studies, allowing for greater insight into the potential implications on VMT and fleet size requirements in particular,

One problem with implementing such a scheme into the model is that it is difficult to predict when (or who) might be willing to share their ride with a stranger (which constitutes a research field in its own right). Existing shared ride services (e.g. Uber, Lyft, and some shared taxi services) around the world demonstrate that such schemes are viable, and it is likely that monetary incentives (or travel credits) would increase the willingness of passengers to accept a shared ride.

In order to implement a dynamic ride-sharing system, the willingness of all simulation participants to share a ride must either be known or assigned values. Although a large undertaking, stated preference surveys (or future OD studies) could attempt to determine individual likelihood of accepting a shared ride. A simpler option could be to complete scenarios with varying percentages of shared rides, and to then randomly select the trips that are involved. In any case, a better understanding of the impacts of dynamic ride sharing at all extremes (i.e. 0 – 100% shared ride simulations) would be beneficial to AV researchers, policy makers, and other interested stakeholders.

Vehicle Fleet Management

Another shortcoming of the model utilized in this study is that of inactive vehicle management. That is, there is no limit to the number of permissible vehicles at a given location, and vehicles that are unassigned simply remain at their previous destination until a new trip is assigned - perhaps hours later. Looking ahead, future research could examine the temporal ("fleet snapshot") data to identify key locations where numerous vehicles are grouped throughout the day in order to determine appropriate maintenance, charging, and storage facilities. Vehicles could be routed to such facilities when they sit idle for a prescribed amount of time or when a threshold capping the permissible number of vehicles at a given location is exceeded. It should be noted that introduction of fleet management strategies within the model will undoubtedly have further impacts on VMT, while simultaneously improving the model's approximation of real-world use.

Landuse Impacts

Along a similar vein, if widespread use of shared AVs become prevalent, it is possible that personal automobile ownership rates will decline, and overall vehicle fleet sizes may decrease. Even with modest fleet size reductions (or the possibility of fleet size expansions), the impacts on parking infrastructure and landuse in general is an area requires significant attention. Perhaps some existing infrastructure may be suitable for reuse as AV storage, charging, and maintenance facilities, while oversupplied on-street parking might be made available for improved pedestrian and cycling facilities, reclaimed as green space, or reimagined entirely. Conversely, if AV fleets are introduced without a simultaneous reduction in personal automobile ownership, parking facilities may no longer be deemed adequate, requiring a different set of interventions. While likely outside the scope of future modelling, the potential impacts of AVs are widespread, and particular attention and research focus should be paid to the impacts on landuse.

The Cost of AV Fleets

Given the relative infancy of AV technologies, estimates of the added cost of AVs over standard vehicles range from under $3,000 to over $70,000 by the time they are made available to consumers (Fagnant & Kockelman, 2013). As such, estimates for vehicle procurement cannot be made with accuracy at this time. it is suggested that future research be completed to assess the annual cost (including operations and maintenance costs and average vehicle replacement) of existing vehicle fleets for which an AV fleet might replace.

Working backwards from the determined number of AVs required to replace the fleet in question, researchers would be able to determine the vehicle cost at which the fleet could theoretically be replaced by AVs within the same monetary budget. Consider the following hypothetical example based on the results from Scenario 1 (Transit only), where a fleet of 586 AVs is deemed adequate to meet the local trip demand currently served by the municipal transit agency. Using the 2015 budget allocated to operations for SJSR's public transportation (approximately $11.8 Million[10] (Ville de Saint-Jean-sur-Richelieu, 2015a)), and considering that approximately 25% of their vehicle fleet (9 of 40 conventional buses) are dedicated to local transport, it is assumed that 25% (approximately $2.95 Million) of this operating budget can be assigned to the fleet.

Based on these assumptions, the annual operations and maintenance cost can be estimated as approximately $5,000 per vehicle. Is this realistic? Using the Smart ForTwo's specified energy consumption rating for city driving at 16.91 kWh/100 km of travel[11] (Smart Canada, 2015), and the assumption of 75 km of daily travel per vehicle, the daily energy requirements are found to be approximately 12.7 kWh. Assuming an equal vehicle usage for

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[10] Not including vehicle procurement.

[11] Calculated from the specified gasoline fuel consumption equivalent of 1.9 L/100 km of city driving, using Smart's stated energy equivalent of 8.9 kWh of energy per litre of gasoline.

all 365 days of the year, the total energy required per vehicle can be estimated to amount to about 4629 kWh.

Using Hydro Quebec's 2015 "Rate M" electricity rate for industrial, commercial, and institutional customers of 4.87¢ / kWh (Hydro Quebec, 2015), the cost to power a single vehicle each year can be estimated as $225.43. In this hypothetical situation, approximately $4,774 per vehicle remains budgeted for maintenance and cleaning throughout the year, which may or may not be adequate.

As this relatively simple example demonstrates, this information would be particularly useful in assessing the feasibility of replacing a local transit fleet with AVs, or in determining the required trip fare or membership rate for a given service to break even. Additional research into the specific costs required to maintain and operate an AV fleet, in addition to the associated facilities and infrastructure that are also required should be completed to better understand the economic impacts of AV use.

Overcoming Barriers

It is likely that AV technologies will soon compose a share of the transportation fleet. However, the process through which they are implemented, and the associated policies and regulations administering their use are at this point virtually non-existent in most jurisdictions. Continued and growing research in the field of automated vehicles must focus on both the more technical implications in addition to those which are more social and political in nature. In order to best prepare ourselves for a world with driverless cars, both the technical and socio-political barriers to AV implementation must be confronted and the opportunities as well as the risks must be thoroughly assessed to ensure the highest level of public safety and to minimize and mitigate negative outcomes (e.g. potential job loss).

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Appendix A: Study Area Selection

Population Served

The population within the study area must be of an appropriate size to provide meaningful results. A population that is too small may lead to results biased by the small sample size, while a population that is exceedingly large may unnecessarily increase the computational complexity of the study. Ideally, the study will render results that can be translated to provide ball-park estimates for autonomous fleet requirements in other Canadian cities. For the above reasons, the use of a study area with a population size similar to a multitude of other Canadian cities was deemed to be desirable, noting that various local factors will affect the specific requirements for any given area.

Thus, the target population size was determined from the average of Canadian cities and metropolitan agglomerations with populations greater than 10,000 and less than 1 million inhabitants. Applying these conditions yields a subset of 141 Canadian cities/agglomerations with an average population of 85,839 inhabitants (Statistics Canada, 2007).

For each of the potential study areas, the population within each of the transit service areas under consideration was compared to the average value, (*Equation 1*). Scores were then attributed to each site, with higher scores given to areas with populations closer in absolute terms to the average population target.

$$PopScore_i\,(\%) = \frac{|Pop_i - Pop_{AVG}|}{Pop_{AVG}} \cdot 100\,\% \qquad (1)$$

PopScore$_i$	**Score**
< 20%	5
< 40%	4
< 60%	3
< 80%	2
< 100%	1
>= 100%	0

Population Density

Variance in population density across Canadian cities and agglomerations varies widely within the 10,000 – 1,000,000 population subset (i.e. 1 – 1274 persons/km^2), with an average density value of 192.6 persons/km^2 ((Statistics Canada, 2007)). Each of the potential study areas had similar densities (average density of 331 persons/km^2), with all but one site exceeding the national average. Ideally, use of more detailed data (i.e. proportion of single-family detached and semi-detached homes) would allow for better identification of the type of neighbourhoods that the proposed autonomous transit service is intended to target – those with a very high proportion of single-family detached and semi-detached homes where traditional transit service is typically not justifiable at high levels of service.

Initially, the target density value was determined using the same method as for the population value (i.e. using the national average). However, given the large variance in population densities across Canadian cities of the target population, the similar densities of the potential sites, and literature highlighting the shortcomings of pure population density measures for classification of neighbourhood types (Gordon & Janzen, 2013), it was decided to not attribute scores for population density.

Existing Level of Transit Service

Likely the most important criteria, the existing level of transit service (LoS) was subdivided into five sub-conditions, for which score of 1 or 0 was assigned when the condition was either met/not met. A sum of the sub-scores provides the total score for the existing level of transit service, with a maximum possible score of 5 points. Since this study is directly targeting areas where traditional transit services are offered at low a LoS, the following conditions were devised (assessed during peak 6-9 am and 4-7 pm):

- Less than 5% of all bus stops are served every 5 minutes
- Less than 10% of all bus stops are served every 10 minutes
- Less than 20% of all bus stops are served every 20 minutes
- More than 50% of all bus stops are served every 30 minutes
- More than 75% of all bus stops are served every 60 minutes

Self-Containment

To reduce the complexity of the study and to simplify the modelling framework, selection of a study area that is relatively self-contained was deemed to be desirable. In cases where the study area is not self-contained (i.e. multiple municipalities are in close proximity to each other) there may be significant travel between the two locations that would be problematic to simulate in a model focusing on a single municipality. While this does not mean that an AV fleet is necessarily unsuitable in these locations, in order to more accurately determine the fleet requirements the geographic scope of the model would need to be increased to include all of the overlapping regions for simultaneous simulation.

Scores for this criterion were determined from visual analysis of each of the potential study areas in ArcMap, and as this criterion is somewhat subjective, a weighting of 0.5 was applied to minimize the overall importance in the final score. Scores range from 0 to 4, where a score of 4 represents a study area that is completely self-contained, and where 0 represents an area where the developed areas within the study area are in high proximity to developed areas of adjacent municipalities.

Transit Hubs

While the above criterion attributes higher scores for areas with self-contained local travel, this criterion seeks to address inter-city travel to and from areas outside the study area. Since the proposed autonomous transit service is not intended to replace all travel, and instead is suggested to complement and strengthen use of transit services along high demand corridors (i.e. to external metropolitan centres, Downtown Montréal, for example), the presence of transit hubs from which high frequency trips to external destinations was determined for each potential study area. For the purposes of the study, all travel to - and from - external destinations is routed through these transit hubs. Locations with transit hubs are assigned a positive score of 1 or 2 (when 2 or more hubs are present).

Travel Demand (O-D Survey)

Similar to target population, the total number of trips for the study area must be large enough to provide a simulation that is not biased by low O-D survey sampling rates (5%), and yet not so large that computational complexity is increased unnecessarily. Considering the trip demand for the potential study areas range from approximately 15–450 thousand trips per day, the ideal range was set to be 125-175 thousand trips. Scores were thus assigned as follows:

Total Daily Trips (000s)	**Score**
< 75 *OR* > 225	1
75–100 *OR* 200–225	2
100 – 200	3

Data, Scoring, and Results

Tables containing the raw values and converted scores for the previously described criteria for each of the potential study areas considered are presented below:

Study Area	**Population**	**Pop. Density**	**Existing Level of Transit Service (Peak)**					**Self Contained**	**Transit Hubs**	**Travel Demand**
			5 min	**10 min**	**20 min**	**30 min**	**60 min**			
	Persons	***Pers/km^2***	***Percentage of Stops***					***0 – 4***	***No.***	***Annual***
CIT CRC	39,748	240	2.0%	8.5%	27.3%	33.2%	51.8%	2	1	59,537
CIT HSL	23,654	37	0.0%	0.0%	2.0%	11.8%	51.0%	2	0	14,249
CIT Laur	327,332	337	0.6%	6.9%	21.1%	35.0%	89.0%	1	4	444,400
CIT Presq	61,886	458	0.2%	0.8%	3.5%	20.7%	51.9%	1	3	88,199
CIT Riche	42,831	349	3.6%	32.1%	56.2%	78.1%	95.0%	2	2	67,128
CIT Rous	47,490	643	1.1%	17.3%	53.8%	76.7%	82.0%	2	1	81,490
CIT SV	76,031	235	1.2%	5.1%	64.9%	76.8%	84.8%	1	2	63,523
CIT SO	96,761	354	1.4%	10.2%	17.1%	23.7%	74.0%	1	2	96,944
CIT VdR	120,419	336	2.7%	15.9%	23.0%	48.3%	94.1%	2	3	100,315
SJSR	87,492	387	3.5%	10.3%	19.4%	75.2%	100.0%	3	3	164,551
TARGET	**85,839**	**N/A**	**< 5%**	**< 10%**	**< 20%**	**> 50%**	**> 75%**	**4**	**1 +**	**125–175**

Study Area	**Population**	**Pop. Density**	**Existing Level of Transit Service (Peak)**					**Self Contained**	**Transit Hubs**	**Travel Demand**	**Total Score**	**Rank**
			5 min	**10 min**	**20 min**	**30 min**	**60 min**					
CIT CRC	3	N/A	1	1	0	0	0	1	1	1	8.0	8
CIT HSL	2	N/A	1	1	1	0	0	1	0	1	7.0	9
CIT Laur	0	N/A	1	1	0	0	1	0.5	2	1	6.5	10
CIT Presq	4	N/A	1	1	1	0	0	0.5	2	2	11.5	3
CIT Riche	3	N/A	1	0	0	1	1	1	2	1	10.0	6
CIT Rous	3	N/A	1	0	0	1	1	1	1	2	10.0	6
CIT SV	5	N/A	1	1	0	1	1	0.5	2	1	12.5	2
CIT SO	5	N/A	1	0	1	0	0	0.5	2	2	11.5	3
CIT VdR	3	N/A	1	0	0	0	1	1	2	3	11.0	5
SJSR	5	N/A	1	0	1	1	1	1.5	2	3	15.5	1
MAX	**5**	**N/A**	**1**	**1**	**1**	**1**	**1**	**2**	**2**	**3**	**17**	**/10**

Appendix B: Estimating SJSR's Local Vehicle Fleet Size

This section describes the method used to determine the fleet size of Saint-Jean-sur-Richelieu's local transit fleet (excluding taxibus, paratransit services, and the express regional services), as this information was not publicly available. Once determined, the peak- and off-peak fleet sizes were used in combination with the bus schedules to estimate the VMT of the associated fleet.

First, the routings of the five local transit services (10 – Bleu; 20 - Jaune; 30 – Orange; 40 – Rouge; and 50 – Vert) (Ville de Saint-Jean-sur-Richelieu, 2015b) were mapped using the free online google maps editor. For each service, waypoints were created for all bus stops served, and the specific routing was modified to mimic the specified routing on SJSR's transit website. Once completed, the networked travel distances determined by the google maps editing software were recorded in Microsoft excel for further analysis.

Next, the weekday transit schedule for SJSR was consulted to determine the total number of daily trips completed for each if the five local services, in addition to their respective peak and off-peak frequencies, and recorded in the excel table. Using the schedule data and circuit length for each service, the number of buses required during the peak and off-peak periods was determined, and recorded.

Finally, the VMT for each service was estimated using the circuit distance and number of daily trips completed for each respective service. Of important note, this estimation estimates the in-service VMT only (i.e. no unoccupied deadheading), as the specific operations of the transit agency is not known. The results are presented in Table 9, below.

Table 9 - SJSR Transit Fleet and Daily VMT Estimation

		Peak Period		**Off-Peak Period**			
Service	**Circuit Distance (km)**	**Frequency (min)**	**Vehicles Required**	**Frequency (min)**	**Vehicles Required**	**Daily Trips**	**Daily VMT (km)**
10 – Bleu	22.2	30	2	60	1	19	421.8
20 - Jaune	23.9	30	2	60	1	25	597.5
30 - Orange	23.5	60	1	60	1	15	352.5
40 - Rouge	33.4	30	3	60	2	23	768.2
50 - Vert	18.2	60	1	60	1	15	273.0
TOTAL	**121.2**	**-**	**9 buses**	**-**	**6 buses**	**97**	**2413**