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Estimation of Car Trips Generated by the Arrival of Autonomous Vehicles in the Montreal Metropolitan Area

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Abstract/Résumé

In this article, we estimate the car trips generated by the arrival of autonomous vehicles (AV) in the Greater Montreal Area. Our research methodology is based on a simulation model which estimates new travel demand associated with AV by measuring differences in travel needs by age categories. Given the uncertainty regarding the evolution of critical variables such as future car occupancy rate, we evaluate different scenarios to assess a range of potential effects of VA on motorized travel. Thus, the results predict a 13% average increase in motorized trips based on overall results, and a 16% to 20% increase in trips based on a stable average vehicle occupancy rate in the coming years. Otherwise, the predicted increase in travel is between 2%, based on a 14% increase in occupancy, and 26%, based on a 5% decrease in occupancy. For each of the scenarios assessed in the analysis, we estimate the effects on external costs caused by automobile travel. According to our results, AV could reduce private and social costs by $ 5,059 billion in Quebec.

Keywords/Mots-clés: Autonomous Cars, Driverless, Self-Driving, Motorized Travel, Age

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1. Introduction and background

Several manufacturers have indicated that they expect to have fully automated vehicles by 2020-2025 (Gill *et al.*, 2015) and the arrival of AV on the automotive market is now expected by 2025-2030 (Anderson *et al.*, 2014; Litman 2014; Mosquet *et al.*, 2015). More specifically, Trommer *et al* (2016) predict that by 2035 the proportion of AV could reach between 17% and 42% in Germany and between 11% and 32% in the United States. The scenarios considered by the Boston Consulting Group (Mosquet *et al.,* 2015) predict, according to various hypotheses, an overall AV market penetration rate of 10% to 19% by 2035, and 20% to 43% by 2040. The results of Bansal and Kockelman (2017) predict an AV penetration rate of 24.8% to 87.2% by 2045, assuming respectively an annual price decrease of 5% to 10%, and a constant willingness to pay based on 2015 values.

In March 2016, the US Department of Transportation (NHTSA, 2016) announced an agreement with automakers requiring that over 99% of new vehicles have automatic emergency braking by 2022. Furthermore, the National Highway Traffic Safety Administration (NHTSA) told Google, in response to a request from the company, that a computer system operating an autonomous vehicle could be considered a driver (Shepardson and Lienert, 2016). This subtlety can clarify several regulations in favor of AV and facilitate their arrival on the roads.

It is in this context that this article aims to establish an estimate of the number of trips generated by the arrival of AV for the Montreal CMA using a travel simulation model that will be defined and explained in the following sections. The goal is not to accurately predict the future effects of AV, but rather to evaluate a range of potential effects on motorized travel in the Greater Montreal Area.

To do this, first, a theoretical framework on AV is presented. This framework includes the different levels of AV automation, as well as a literature review exposing possible effects (positive, negative, direct and indirect) resulting from an increased AV presence. Second, the travel simulation model used to estimate new motorized trips associated with AV is developed. Here, a range of travel needs by age group are used. Third, the results are presented and discussed. The results predict, most notably, an average increase of 13% in motorized trips as per overall results, and an increase of 16% to 20% in trips when applying a stable average vehicle occupancy rate in the coming years. The scenarios will be presented and detailed in this section of the article. The paper will end with the conclusion and research perspectives.

1.1 Levels of AV automation

Based on the levels of automation associated with technologies and human involvement, various definitions of automation have been proposed. The literature surrounding automation levels commonly use the definitions of Gasser and Westhoff, (2012), NHTSA (2013), and Smith (2013).

As Kyriakidis *et al.* (2015) did in their analysis, these definitions are summarized in the following table.

Table 1 — Levels of AV Automation

Source	Levels of AV Automation					
	0	1	2	3	4	5
NHTSA (2013)	No automation	Function-specific automation	Automation of combined functions	Automation with limited driving	Full Automation	
Gasser et Westhoff (2012)	Driver Only	Assisted	Partially Automated	Highly Automated	Fully Automated	
Smith (2013)	The driver monitors the driving environment			The system monitors the driving environment		
	No Automation	Driving Assistance	Partial Automation	Conditional Automation	High Automation	Complete Automation
Summary Classification	No Automation	Driving Assistance	Partial Automation	Conditional Automation	Complete Automation with Interventions	Complete Automation without Interventions

Sources: Gasser and Westhoff, 2012; NHTSA, 2013; Smith, 2013

These authors' definitions were thus used to establish a summary classification specific to this research. By doing so, the basic information can be extracted and combined into the essence of each definition.

1.2 Summary Classification

The summary classification above reflects the definitions from Gasser and Westhoff (2012), NHTSA (2013) and Smith (2013). Below, the Level 5 summary definition is explained in detail, since this level is the one that best applies to the model described in this paper:

Level 5 - Complete automation without interventions

The system controls braking, acceleration and steering under all road and environmental conditions faced by a human driver. As such, drivers do not necessarily have to be licensed or have the physical and cognitive ability to drive.

As reflected later, the objective of this research is to establish an estimate of the number of trips generated by the arrival of AV with Level 5 automation, using a simulation model which will be defined and explained in the next sections.

1.3 Hypotheses

For the various scenarios that will be used in the analysis, the following assumptions are made:

- All vehicles are fully automated without any interventions by the driver. Thus, the car system controls braking, acceleration and steering under all road and environmental conditions faced by a human driver. In this way, drivers do not necessarily have to be licensed or have the physical and cognitive ability to drive.
- Prices for this type of vehicle are affordable. The literature predicts that the initial AV-related premium over traditional similar vehicles could potentially decrease to $ 1,000 (Fagnant and Kockelman, 2015) following the large-scale arrival of AV[1].
- In Quebec, obtaining a learner's license is possible from the age of 16. It must be kept for a minimum of 12 months before a probationary license can be obtained. During this period, the driver must be accompanied by a person who has been licensed for at least 2 years. The probationary period then lasts 2 years.

[1] Higher fixed costs may also be offset by significantly lower variable costs (Arbib and Seba, 2017).

Given the nature of AV, it will be assumed that young people will be legally allowed to drive an AV without supervision from a parent / guardian from the age of 16.

- Public transport (PT) systems function similarly to today in terms of the quality and quantity of the service.[2]

2. Model

This research is an application of the simulation model developed by Truong *et al.* (2017) to the Quebec context. The model estimates new motorized trips associated with AV by measuring differences in travel needs across age groups, according to a scenario in which AV reaches the 5th level of automation.

The model's construction logic will now be presented, following the various steps leading to the final equation.

First, the total current daily trips by car (DT_C) are equal to the sum of driver trips (DT_D) and passenger trips (DT_P).

$$(1)\quad DT_C = DT_D + DT_P$$

This equation is used to obtain total trips, based on an occupancy rate of one individual per vehicle.

By way of illustration, a total of 80,000 trips completed by drivers, with a vehicle occupancy rate of 1.25 individual per vehicle, would be equivalent to 100,000 trips completed by drivers based on an occupancy rate of one individual per vehicle. Thus, this study considers a total of 100,000 daily trips, with a total of 80,000 driver trips and 20,000 passenger trips, to convert total travel to a single individual per vehicle basis. As reflected later, total current daily trips will then be divided by the new average occupancy rate of vehicles associated with the AV scenario, to obtain the total number of trips based on the various AV occupancy rate scenarios.

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[2] Despite the uncertainty surrounding this hypothesis, there is no choice but to issue it regardless. The effects of AV on public transport have not yet been studied separately.

Next, the quantity of new total daily trips ($NTDT$) is equal to the summation of the total new daily trips following the introduction of AV (*NDT*) and the total new daily trips resulting from the modal shift of PT and active transportation (AT) to AV.

NDT comes mainly from the growth in travel by young people (aged 16 to 19), people with driving constraints and seniors (aged 65 and over). This value is calculated from percentage changes in driver's license ownership by age group, and is based on three scenarios (low, medium and high). The average scenario predicts an increase of 253,735 trips. As mentioned earlier, the method for calculating these values will be specified in the following sections.

The new trips associated with modal transfers are calculated from the transfer percentages, α, estimated using data from the literature. Thus, α_{PT} represents the modal shift percentage associated with the public transport, while α_{AT} is associated with the modal shift from active transport. The new trips resulting from the modal shift of each mode are obtained by respectively multiplying each percentage by the sum of the daily trips: $\alpha_{PT}DT_{PT}$ for public transport and $\alpha_{AT}DT_{AT}$ for active transport.

$$(2)\quad NTDT = NDT + \alpha_{PT}DT_{PT} + \alpha_{AT}DT_{AT}$$

This model considers four different scenarios associated with modal shift. First, a zero modal transfer for both modes of transport, followed by a modal shift of 8.5% and 10% respectively for PT and AT to AV[3]. The different scenarios are presented in table 2.

Table 2 — Modal shift scenarios

	α_{PT}	α_{AT}
Scenario 1	0%	0%
Scenario 2	0%	10%
Scenario 3	8,5%	0%
Scenario 4	8,5%	10%

According to the 2013 origin-destination (OD) survey of the Montreal metropolitan area, the sum of daily trips by PT (train, bus and subway) was 477,000 (DT_{PT} = 477,000) and the sum of daily trips by AT (walking and cycling) was 247,000 (DT_{AT} = 247,000).

[3] These values were obtained from data in the literature and will be explained in the next chapter.

This means that the sum of trips from the modal shift of public and active transport to AV, according to the values of the last modal shift scenario (α_{CT} = 8.5% and α_{AT} = 10%) and the assumptions previously established, is 65,245 trips (0.085 * 477,000 + 0.1 * 247,000). Added to the total of the new daily trips that will be made following the introduction of the AV according to the average scenario (NDJ = 253,735), the amount of new total daily trips is thus 318,980 additional trips.

$NTDT$ = 253,735 + 0,085 * 477,000 + 0,1 * 247,000 = 318,980

The third equation establishes the percentage change in the average occupancy rate in the AV scenarios (AO_{AV}). This term comes from the multiplication of the variation of the average occupancy rate of the AV compared to the reference scenario (1+α_{AO}) by the occupancy rate of the reference scenario (AO_{REF}).

$$(3)\quad AO_{AV} = (1 + \alpha_{AO})AO_{RÉF}$$

In 2013, the average occupancy rate of vehicles in the Montreal Metropolitan Community (CMM) was 1.2 individual per automobile and therefore AO_{REF} = 1.2 (AMT, 2013). Using this method, if the reference occupancy rate is 1.2 individual per vehicle (AO_{REF} = 1.2) and a 10% occupancy increase is predicted when AV reach the fifth level of automation (α_{AO} = 0.1), AO_{AV} is equal to 1.32 ($AO_{AV} = (1 + 0.1) * 1.2 = 1.32$).

Thus, a 10% increase in average vehicle occupancy rates under an AV scenario corresponds to a rate of 1.32 in this model. In the model, 20 scenarios of variation were applied, ranging from -5% to + 14%. Consequently, it varies between 1.14 and 1.37 individual per vehicle. This data serves as the denominator in the final equation and allows the impact of negative and positive occupancy rate changes to be considered in relation to the reference scenario.

The fourth and last equation is the division of the sum of the terms of equations 1 and 2 by those of equation 3, resulting in the number of daily trips in the AV scenario (DT_{AV}):

$$(4)\quad DT_{AV} = \frac{DT_C + NTDT}{AO_{AV}} = \frac{DT_D + DT_P + NDJ + \alpha_{PT}DT_{PT} + \alpha_{AT}DT_{AT}}{(1 + \alpha_{AO})AO_{REF}}$$

The numerator of the final equation is therefore equal to the sum of the daily trips from the base scenario made by drivers, the daily trips from the base scenario made by passengers, the new daily trips resulting from the arrival of AV, and the variation from a modal shift of PT and AT to AV (or vice versa). The numerator is then divided by the average occupancy rate of cars in an AV scenario, making it possible to estimate the number of daily trips in an AV scenario.

In other words, the sum of the total current daily trips (DT_A) and the new daily trips associated with the introduction of AV ($NTDT$) is divided by the new average vehicle occupancy rate associated with the AV scenario, to obtain the number of total trips across various scenarios in terms of AV occupancy rates.

For example, based on the previous assumptions, the values obtained would predict a total increase of 317,409 trips:

$$DT_{AV} = \frac{100{,}000 \ + \ 318{,}980}{1.32} = 317{,}409$$

The inclusion of the average occupancy rate of cars is of paramount importance since it is likely that this rate will vary with the arrival of AV. This matter will be discussed in more detail in the section explaining the values used in the model. In addition, there is a possibility that AV can travel without passengers to park or pick someone up. These trips could be added to the number of trips induced by the arrival of AV, but will not be considered in the present research in an effort to remain conservative in the analysis, as these circuits remain too uncertain to be estimated and included. In this sense, a discussion note will be added in the discussion of the results to take into account the potential impacts that such trips might have. However, it is important to note that travel without passengers could have a significant impact on the results and greatly reduce the benefits of AV. Thus, this is an estimate of the lower limit of trips. Table 3 summarizes the variables in the final equation.

Table 3 — Description of variables

	Description of variables		
	Name	**Notation**	**Description**
Reference Scenario	Total daily trips (driver)	DT_D	Motorized trips made by drivers
	Total daily trips (passenger)	DT_P	Motorized trips made by passengers
	Average occupancy of vehicles	AO_{REF}	Individual/Car
	Total daily trips by PT	DT_{PT}	Trips made by public transportation (train, bus, metro)

	Total daily trips by AT	DT_{AT}	Trips made by active transportation (walking, biking)
Prediction	Total new daily trips associated with AV	NDT	New trips made following the introduction of AV
	Alpha of modal transfer from PT to AV	α_{PT}	Percentage transfer from public transportation to AV
	Alpha of modal transfer from AT to AV	α_{AT}	Percentage transfer from active transportation to AV
	Alpha of average occupancy rate of cars	α_{AO}	Percentage variation of average occupancy rate of cars in AV scenarios relative to reference scenario

Simultaneously, DT_{AV} will be compared to the total daily trips in the reference scenario (DT_D) to obtain the percentage change ($\Delta\%DT_{AV}$), i.e.:

$$(5)\ \Delta\%DT_{AV} = \frac{(DT_C - DT_D)}{DT_D} * 100$$

In this way, instead of obtaining a value in number of trips, a percentage of variation compared to the reference scenario will be obtained. This means that a total increase of 317,409 trips is equivalent to an increase of 217.4% over the baseline scenario.

$$\Delta\%DT_{AV} = \frac{(318{,}980 - 100{,}000)}{100{,}000} * 100 = 217.4\ \%$$

2.1 Estimation of the number of new trips

To estimate the increase in the number of trips by age group, the increases in each of three sub-segments are estimated individually, based on the possibilities that AV bring to the respective subgroups. The assessment is done by calculating the growth potential in driver's license holding rates by age category, which will then be multiplied by the percentage of trips based on the total number of licenses. In Montreal in 2013, a total of 1,296,000 automobile trips were completed during the morning peak period, out of 2,199,063 licenses (SAAQ, 2018a), which is equal to 59%. Thus, the value obtained resulting from the increase in the number of total licenses will be multiplied by 0.59 in each of the scenarios, accounting for the consideration that an increase in the number of licenses would lead to an equivalent increase in the number of trips per day. This value will be defined as the coefficient of equivalence of driver's licenses. The equivalence coefficient is the value by which travel could increase when driver's licenses increase by one.

The sub-groups will be composed of 16 to 19 year-olds, 20 to 64 year-olds and 65 years and over. This subdivision assumes that these subgroups will be affected differently by the growth of AV.

2.1.1 Estimation of the number of new trips for 16 to 19 year-olds

According to data from Statistics Canada (2001) in its 2001 census analytical series, 16 to 19 year-olds are predominantly "high school and college students". They therefore form a subgroup of their own, since certain characteristics (ie: school trips) specific to this age group differentiate them from the general labor force.

To assess the growth potential of the driver's license holding rate, the 20-24 age group was chosen as the reference rate, because it is the closest age group and very likely has the most similar travel behaviors. Indeed, the nature of the trips is similar, both groups being composed mainly of students who must travel to their school. In 2015-2016 in Quebec, 79% of young people aged 16 to 19 were considered full-time students compared to 45% of young people aged 20 to 24, and only 16% of those aged 24 to 29 (ISQ, 2017, SAAQ, 2017, Statistics Canada 2017b).

Currently 26.83% of 16 to 19 year-olds have a driver's license while this percentage increases to 55.50% for 20 to 24 year-olds (SAAQ, 2018a). For the purposes of the analysis, it is therefore assumed that, in a full level five automation environment, 16 to 19 year-olds could obtain a similar license holding rate at the current 20 to 24 year-olds rate. It is therefore estimated that travel for youth aged 16 to 19 in an AV context will be similar to the current travel of 20 to 24 year-olds, as barriers to obtaining a driver's license for 16 to 19 year-olds will decrease.

It is also assumed that high school students who travel by school bus will not see their travel increase, but an increase is still possible for other students and other reasons for travel (work and leisure). However, the financial constraints faced by young people aged 16 to 19 may prevent them from achieving the same level of self-mobility as the working population aged 20 to 64. According to 2016 Statistics Canada data, over 75% of 19 year-olds, 90% of 18 year-olds, 97% of 17 year-olds and 98% of 16 year-olds have incomes below $15,000 (Statistics Canada, 2016). In addition, in 2012, the average hourly wage for full-time employees went from $11.15 for 15-19 year-olds to $15.70 for 20-24 year-olds, to over $21.00 for 25-29 year-olds. Added to the much lower employment rate of 15-19 year-olds (43.5%) compared to 20-24 year-olds (70.3%), it is likely that their financial situation would not allow them to obtain AV despite a potentially affordable price (ISQ, 2014). As a result, the three scenarios use the current 20 to 24 year-olds license holding rate of 55.5% for 16-19 year-olds. The medium and high scenarios then increase the detention rates for the 20 to 24 year-olds age group to account for previously described differences between the two age groups, while the low scenario does not increase the rate for the 20 to 24 year-olds age group.

The estimated total number of license holders in each age group will be obtained by multiplying the number of individuals per age group in 2017 by the new hypothetical license holding rate, which is the current holding rate for the 20 to 24 population of 55.5%.

The 2017 population is used to account for population changes between 2013 and 2017. The percentages of licenses by age group have remained more or less identical, whereas sociodemographic changes make the number of individuals per age group vary considerably between years, with a decrease of almost 19,000 for young students aged 16 to 19 and 20,434 for those aged 45 to 54, versus an increase of 44,324 for 55 to 64 year-olds and 75,600 for retirees 65 and older. Furthermore, it is still better to use the 2013 driver's license holding rates since most other variables come from the 2013 OD study.

2.1.2 Estimation of the number of new trips for 20 to 64 year-olds

Using a technique similar to that of Wadud *et al* (2016), the percentage of license holders aged 45 to 54 is used as a reference for other age groups between 20 and 64 year olds. In their research, Wadud *et al.* (2016) estimated the increase in trips for the population aged 62 and over by linearly extrapolating the decline in license ownership rates between 44 years old, being the highest rate, and 62 years old, where the decrease accelerates. Thus, instead of seeing a steep decline in trips from age 62 linked to the decrease in cognitive functions, the authors estimated that the rate of increase remains the same before and after 62 years (Wadud *et al.,* 2016).

For the purposes of this study, to determine the increase in driving by drivers in the active population, it is assumed that the difference between the highest rate (82%) and the rates of the other groups illustrates inferior travel needs, which could increase with an increase in the quality of the vehicle supply. The highest rate is the percentage of license holders in the 55 to 64 year old age group.

Three scenarios are thus proposed (See Table 4 and Figure 1):

- Low: no change in trips. Holding rates for the five age groups between 20 and 64 will remain the same as in 2013;

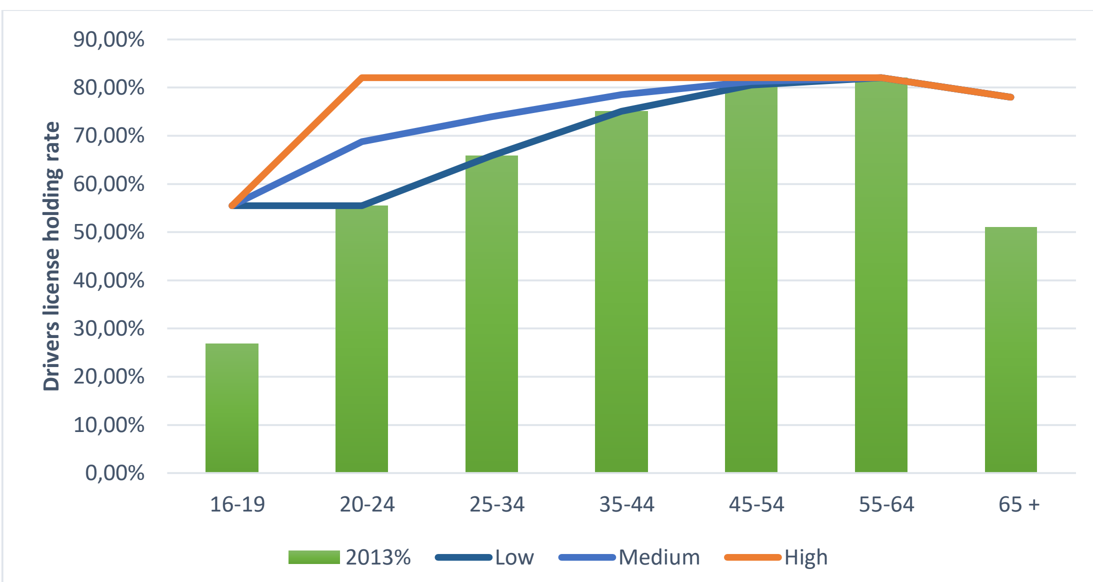
- Medium: average rate between the highest rate of 82% and the current rate of each group.

- High: use of the highest rate for all groups in the labor force.

Table 4 — Detention rate and variations in the number of drivers licenses by age category according to the scenarios

	Scenarios					
	Low		*Medium*		*High*	
	New %	Variation	New %	Variation	New %	Variation
16-19	55,50 %	44,805	55,50 %	44,805	55,50 %	44,805
20-24	55,50 %	-1966	68,78 %	35,082	82,06 %	72,129
25-34	65,87 %	9791	73,96 %	57,848	82,06 %	105,905
35-44	75,06 %	27,155	78,56 %	48,359	82,06 %	69,562
45-54	80,51 %	-16,451	81,28 %	-12,008	82,06 %	-7565
55-64	82,06 %	36,371	82,06 %	36,371	82,06 %	36,371
65 and up	78,00 %	220,083	78,00 %	220,083	78,00 %	220,083
Total		319,788		430,539		541,290

Figure 1 – Driver's license by age category according to the scenarios



2.1.3 Estimation of the number of new trips for 65 year-olds and over

According to the Quebec Medical Association (*Collège des médecins*, 2013), people over the age of 65 have an increased risk of having a medical condition that may affect their ability to drive (declining cognitive functions, Alzheimer's and visual or hearing impairment). In this sense, hearing, vision, cognition, and mobility are four functions that deteriorate with age and are important for adequate driving (Statistics Canada, 2015).

The statistics from the table "Proportion of people 65 years and older with a driver's license who drove a vehicle in the previous month and whose main mode of transportation is to drive a vehicle, depending on their level of functional capacity, 2009" by Statistics Canada (2015) were used. This table ranks license holders 65 years old and older by functional ability levels.

Level 1 percentages will be used as a reference for the share of driver's licenses held by people aged 65 and over, since this level establishes the share of highly functional individuals who use the car as their primary mode of transportation. In an AV context, this age group remains less mobile as a majority of them no longer work. In fact, only 10.3% of the population aged 65 and over had a job in 2017 in Quebec (Statistics Canada, 2018). By way of comparison, this rate is 45.7% for the 60 to 64 age group and 72.2% for the 55 to 59 age group (Statistics Canada, 2018). However, it is hypothesized that the decrease in trips as a function of the deterioration of their cognitive abilities will be considerably counterbalanced by level 4-5 automation. Thus, the table shows that 76.5%, 76.3%, 78.7% and 79.3% of the population aged 65 and over who hold a valid driver's license can be considered to benefit from vision, from hearing, from cognition, and from level 1 mobility, respectively (Statistics Canada, 2015). The weighted average of these percentages will thus be used to obtain the final value of 77.98% for the retiree age group.

2.2 Modal transfer of public and active transportation to AV

The relative attractiveness of other modes of transport will also change. On the one hand, improving car travel will make public and active transport relatively less attractive. On the other hand, autonomous vehicles could make PT more responsive and more affordable if it too becomes self-sufficient (Davidson and Spinoulas, 2015). By acting as a low-cost driverless taxi, AV could also attract PT and AT users who would find it an economical and flexible alternative (Millard-Ball, 2016). In addition, the potential decrease in accidents and abrupt lane changes by motorists could also increase the attractiveness of AT by increasing comfort on the roads.

Thus, given the change in the relative attractiveness of these types of transport, this study attempts to estimate the modal shift of public and active transport to AV using data from studies by Childress *et al* (2015), Davidson and Spinoulas (2015) and Truong *et al* (2017).

First, Childress *et al* (2015) measured AV effects using a model based on transport network activities and travelers' choices. The scenarios evaluated by the authors explore how driverless cars can influence travel demand through more efficient use of road infrastructure and changes in perceived trip lengths, parking costs and vehicle operating costs. The third scenario evaluated by the authors is the one that best fits the assumptions adopted by the current paper. This scenario assumes full market penetration, reduced parking costs, a 30% increase in road capacity and a 35% reduction in the value of time for all AV trips. According to this scenario, relative modal shares would increase from 2.6% to 2.4% for PT and from 8.6% to 6.8% for AT. This represents decreases of 7.69% and 20.93% respectively (Childress *et al.,* 2015).

Next, Davidson and Spinoulas' (2015) research uses similar scenarios to calculate the possible effects of the arrival of the AV in Brisbane, Australia on the kilometers traveled and the modal transfers induced. The authors use a model that makes it possible to vary the behavioral parameters by market segment (time value, tolls, public services of destination, etc.). They use Monte Carlo simulations to plot values from probability distributions. Each parameter can be set to a random variable and can effectively simulate all aspects of the trip choice. The third and last scenario considers that a penetration of the AV market of around 75% is possible by 2031. When coupled with a 50% reduction in car operating costs, since these will likely be all-electric, this results in a decrease in PT and AT market share of 13.6% and 11% respectively (Davidson and Spinoulas, 2015).

Overall, Childress *et a*l (2015) and Davidson and Spinoulas (2015) respectively predict decreases of 7.69% and 13.6% for PT and 20.93% and 11% for AT. On average, this represents a decrease of 10.65% and 15.97%. Truong *et al.* (2017) used a decrease between 0 and 4.18% for PT and between 0 and 10% for AT. Their AT values comes from the lower bound of the two articles previously cited, while the values for PT comes from assumptions and calculation in the VISTA data between 2007 and 2010 in Victoria.

For the AT modal shift, the 10% presented by Truong *et al* (2017) will be used, since this value is aligned with the two cited studies (Childress *et al.,* 2015, Davidson and Spinoulas, 2015). This value is considered in this model by setting α_{AT} to 0,1.

The calculations were not recreated to obtain a specific value for public transit in Montreal since these calculations are based on uncertain assumptions. An average of the three articles was used instead, namely Truong *et al.* (2017), Childress *et al*. (2015) and Davidson and Spinoulas (2015). This results in an alpha value of modal shift from PT to AV of 8.5%. This value is considered in the model by setting α_{PT} to 0.085.

2.3 Average occupancy rate of automobiles

The scientific literature is divided about how AV will influence the number of individuals per vehicle (Truong *et al.,* 2017, Santos *et al*., 2011, Stephens *et al*., 2016).

Current trends in car sharing show declining occupancy rates in Quebec in recent years. Between 1998 and 2013, this rate went from 1.23 to 1.20, a decrease of 2.5% (AMT, 2013). Assuming that this downward trend of 2.5% over a 15-year period will continue at the same rate, an average occupancy rate of approximately 1.17 in 2028 and 1.14 in 2043 can be established, a decrease of 5%.

Stephens *et al.* (2016) estimate that the average occupancy rate for cars in the United States could be between 1.6 and 1.7 in a level 4 or 5 scenario, not considering car sharing, and between 1.6 and 1.9 with an increased car sharing presence. In 2009, the occupancy rate was 1.67 (Santos *et al.,* 2011), and thus the variation is between -4% and 14%. Therefore, in this analysis, various average car occupancy rates will be tested, with the percentage change in the average occupancy rate of cars from the baseline scenario varying between -5% (current trend by 2043) and 14% (according to the article cited above).

3. Results

This travel simulation model produced 240 results from three scenarios associated with changes in the number of driver's licenses (low, medium, high), 20 average occupancy rates for automobiles (between -5% and +14%) and four modal shift variations (α_{PT}, α_{AT}). The overall results are presented in the appendix (see Appendix A, B and C).

Eighty results were obtained per scenario, which are briefly presented using tables 5, 6 and 7. The tables present 20 results per scenario, i.e. five occupancy rates and four variations of the modal shift.

Table 5 - Percentage of variation in motorized trips in a medium AV scenario

			α_{AO}				
	α_{PT}	α_{AT}	$-0{,}05$	0	$0{,}05$	$0{,}1$	$0{,}14$
1	0	0	22 %	16 %	10 %	5 %	2 %
2	0	0,1	24 %	18 %	12 %	7 %	3 %
3	0,085	0	25 %	19 %	12 %	8 %	4 %
4	0,085	0,1	26 %	20 %	14 %	9 %	5 %

Table 6 - Percentage change in motorized trips in a low AV scenario

			α_{AO}				
	α_{PT}	α_{AT}	$-0{,}05$	0	$0{,}05$	$0{,}1$	$0{,}14$
1	0	0	18 %	12 %	6 %	2 %	-2 %
2	0	0,1	19 %	13 %	8 %	3 %	-1 %
3	0,085	0	20 %	14 %	9 %	4 %	0 %
4	0,085	0,1	22 %	16 %	10 %	5 %	2 %

Table 7 - Percentage change in motorized trips in a high VA scenario

			α_{AO}				
	α_{PT}	α_{AT}	$-0{,}05$	0	0,05	0,1	0,14
1	0	0	26 %	20 %	14 %	9 %	5 %
2	0	0,1	28 %	22 %	16 %	11 %	7 %
3	0,085	0	29 %	23 %	17 %	12 %	8 %
4	0,085	0,1	31 %	24 %	18 %	13 %	9 %

The average variation in percentage of motorized trips for all 240 results is 13%.

- The medium scenario shows variations from 2% to 26% with an average of 13%.

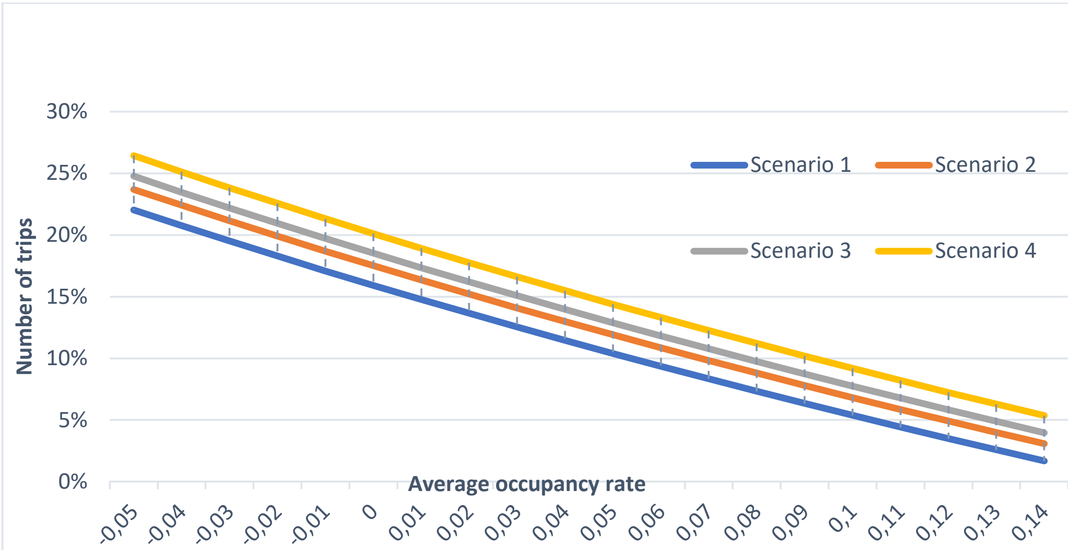
- The low scenario shows variations from -2% to 22% with an average of 9%.

- The high scenario shows variations from 5% to 31% with an average of 17%.

3.1 Modal shift and change in average occupancy rate of automobiles

The percentage changes in car trips for various modal shift scenarios in a medium scenario are summarized in Figure 2. If the arrival of AV does not destabilize the current average occupancy rate of cars, these results predict an increase in travel from 12% to 16%, 16% to 20% and 20% to 24% in a low, medium and high scenario. Otherwise, the increase in average scenario trips is between 2%, based on a 14% increase in occupancy, and 26%, based on a 5% decrease in occupancy. For the other scenarios, the variation of trips is between -2% and 22% for the low scenario and between 5% and 31% for the high scenario. The lower limit of the results is characterized by no modal shift and a 14% increase in the occupancy rate of the vehicles. Conversely, the upper limit is characterized by a modal transfer of 8.5% of PT to AV, and of 10% of AT to AV, as well as a 5% decrease in the occupancy rate of the vehicles.

Figure 2 — Variations in car trips of various modal shift scenarios in a medium scenario

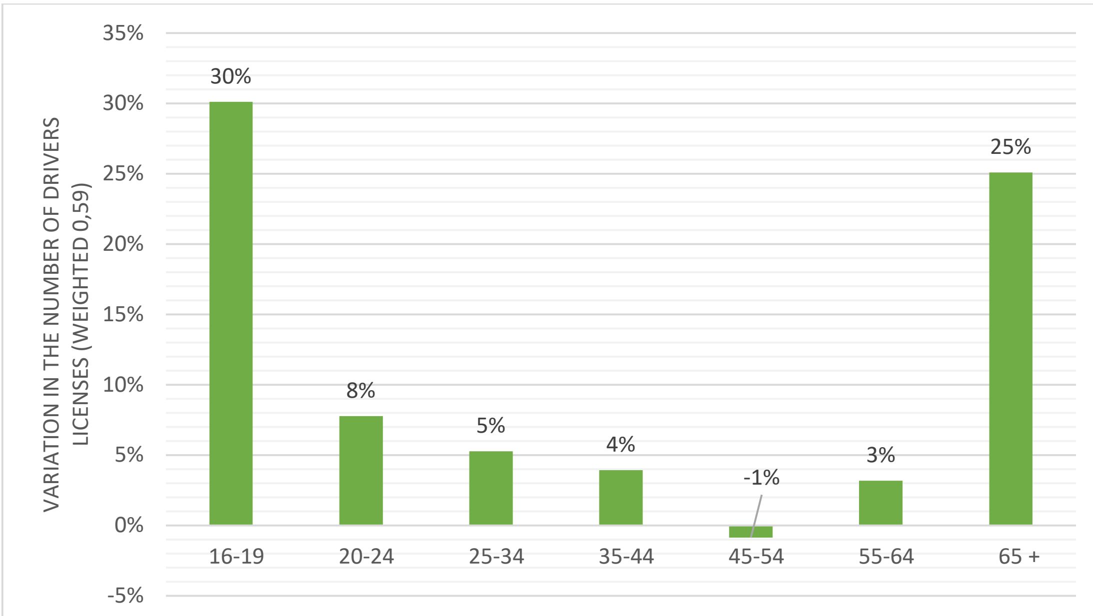


Still applying a zero variation in the occupancy rate and an average scenario of variation in the number of driver's licenses, PT modal shift of 8.5% and AT modal shift of 10% led to a 4.19% increase in travel. 2.6% come from the modal shift from PT to AV, and 1.6% from the modal shift from AT to AV.

3.2 New daily trips associated with AV

Figure 3 shows the percentages of new trips generated by AV in the medium scenario compared to the baseline scenario and by age group. These values are obtained by dividing the increase in trips (increase in driver's licenses multiplied by the driver's license equivalence coefficient of 0.59) by the estimation of the number of trips in the reference scenario (sum of driver's licenses multiplied by the equivalence coefficient). As previously indicated, this scenario uses the average rate between the highest driver's license rate, 82%, which comes from the literature, and the current rate for each age group between 20 and 64 years old.

Figure 3 — Percentage of new trips per day by age group - Medium scenario



The 16 to 19 year-olds age group had the largest increase at 30%, followed by the 65 years and over age group with 25%. These two groups have the same results for each of the three scenarios. Age groups between 20 and 64 have much smaller increases given their higher driver's license rates in the baseline scenario. Finally, the 45 to 54 year-olds age group has a decrease of 1%. This is due to the fact that their population will decrease between 2013 and 2017, and that their current rate of license holding approaches the highest rate. Overall, new trips associated with AV could be responsible for a 7% increase in daily trips compared to the reference scenario.

These results suggest that the increase in car trips across the various scenarios would be caused mainly by new trips rather than by modal changes. This can be explained by the low AT and PT modal relative shares (compared to the modal share of vehicles) which are respectively 7.23% and 22.28%. Without considering a modal shift, only the improved mobility that AV offer to those who are too young to drive, who do not have a driver's license, and to the elderly would still lead to a significant increase in car trips. This reaffirms the importance of exploring the increase in vehicle travel, both from commuter modal shifts and from new trips.

The impact of car occupancy on changes in car travel is clearly a major factor affecting these results. As shown in Figure 2, car travel decreases almost linearly with the increase in car occupancy. For example, if the average occupancy rate of cars is reduced by 5% compared to the current situation, car trips increase from 18% (low scenario) to 26% (high scenario), ignoring new trips. In addition, trips increase between 22% (low scenario) and 31% (high scenario) when modal transfers from both AT and PT are included.

In addition, while the average occupancy rate of cars increases by 14%, the average scenario estimates a decrease of 2% to 5% in car trips, depending on whether only new trips are considered, or both new trips and modal changes.

4. Discussion

Given the downward trend in car occupancy rates in Montreal, the motorists' preference for single-owner cars (Litman, 2017) and the trips between parking and pick-up of passengers, the car occupancy rate is expected to decrease. It is thus likely that the number of trips by car will increase considerably.

However, an increase in the car occupancy rate is possible although unlikely. Indeed, even if the shared AV are more numerous than has been estimated, driverless trips can occur due to the ability of AV to park and board passengers on their own and thus decrease average occupancy of vehicles.

In addition, it must be reiterated that travel without passengers can have a significant impact on the results, and greatly reduce the benefits of AV. Thus, this study represents an estimate of the lower limit for the number of trips. Indeed, there is a possibility that AV can travel without passengers to go park or pick up a passenger. These trips could be added to the number of trips induced by the arrival of AV, but are not considered in the present research, which aims to remain conservative in the analysis. These passenger-less trips remain too uncertain to be estimated and included.

For example, by estimating at least one additional empty trip per motorized trip, a significantly higher number of new trips following the introduction of AV may be considered, namely an increase of at least 1,529,280 compared to the number of current daily trips. This value is obtained by multiplying the current number of daily trips by the average of the increase in trips under the average scenario, assuming an unchanged occupancy rate (18%).

Overall, the results show that a 1% increase in the occupancy rate would result in an average decrease of 0.95% in car trips (between -1.04% and 0.88%, respectively, based on an occupancy rate between -4% and 14%). This suggests that carpool and car occupancy studies are also needed to better understand the impact of AV on car travel (Truong, 2017).

The analysis presented in this paper is limited to the impacts of AV on the number of trips by car. The possible impacts of AV on the variation in kilometers traveled are also important, but have not been addressed in this paper. The focus was on the number of trips since the kilometers traveled depend on many uncertain factors such as the location of households based on automation levels. However, it is likely that increased car travel will also increase mileage, especially if the arrival of the AV leads to urban sprawl.

When estimating the new trips generated by AV, the possible new trip taken by people aged 16 to 65 whose driving conditions are restricted were not accounted for. This can be addressed in future work, assuming they can travel by AV as well as healthy drivers of the same age.

Additionally, it was hypothesized that PT would function similarly to today in terms of quality and quantity of service. This hypothesis should be improved in future research by integrating the effects of AV on PT. Despite the uncertainty surrounding this hypothesis, there is currently no choice but to apply it since these effects have not yet been studied separately.

4.1 External costs of motorized transportation

External transportation costs are the costs imposed onto third parties by users of transportation, such as pollution, and are therefore not accounted for by users without government intervention (Maibach *et al.,* 2008). For example, the Quebec governement intervenes by imposing a tax on gasoline, which makes it possible to directly attribute to motorists a portion of the external costs that they impose on society. In this sense, the social cost represents the external costs plus the private consumer transportation cost. It is important to note that for all trips, the private marginal benefit is greater than the private marginal cost, otherwise the trip would not have happened (Becker *et al.,* 2017). Car users pay only the private costs of their trip, i.e. the purchase of the car, fuel, insurance, etc., but do not pay the costs they impose on third parties. Taking the externalities into consideration, many of these trips should not have been completed in the light of a social optimum.

Becker et al (2017) divide the external costs of motorized transport into six categories:

1- Accidents
2- Air pollution

        i. Impacts on the health of individuals and vegetation and damage to buildings
3- Noise pollution
        i. Health impacts and inconvenience costs by number of individuals affected and noise level
4- The effects upstream and downstream
        i. Indirect costs of transport generated by vehicle production and disposition, transport infrastructure and energy production
5- Other secondary effects
        i. Land use, biodiversity loss, water pollution, etc.
6- Climate change
        i. Cost of GHG emissions per vehicle

On average, according to research by Becker *et al.* (2017), each resident of the European Union is thus taxed 750 euros per year in external transport costs, in addition to paying for their private transportation. More specifically, a European car generates on average around 1600 euros in annual external costs (Becker *et al.,* 2017).

Transport Canada (2008) estimates the external costs of road transportation in Quebec at $7266 billion, which represents 20% of total costs (external and private costs). According to their estimates, accidents, delays caused by congestion, air pollution, GHGs and noise pollution are respectively responsible for 54% (3924 billion), 17.5% (1272 billion), 16% ($ 1162 billion), 12% ($ 872 billion) and 1% ($ 73 billion) of these external costs.

Returning to the results of this study, the average increase in motorized trips under the average scenario predicts an average increase of 18%. Thus, all elements kept equal, the external costs of road transport in Quebec could increase to $ 8574 billion. However, AV can be expected to influence these costs by modifying the impacts of their various contributing causes.

For example, since the effectiveness of accident prevention in automated systems may continue to increase, Stephens *et al.*'s study (2016) assumes as an upper limit that partial automation could reduce accidents by 50%. In Quebec, the external costs associated with accidents could therefore also be reduced by 50% to $ 1962 billion, and to $ 2315 billion when considering the increase in travel by 18%.

Then, Fagnant and Kockelman (2015), who base their results on a comprehensive literature review, estimate that delays caused by congestion could decrease by 60% and fuel savings could reach 25% with an AV penetration rate of 90%. These estimates reduce the impact of delays and air pollution on external costs to $600 billion and

$1029 billion respectively. Again, these values are obtained after considering the 18% average increase in trips.

Finally, the literature review presented in Section 1 generally concludes that the effects on greenhouse gases and noise pollution are uncertain. This study therefore only considers that the increase in trips and their value respectively reaches $1029 and $86 billion. In total, according to these estimates, external costs could decrease to a minimum of $ 5059 billion. This represents a 30% decrease from 2008 estimates.

5. Conclusion

The purpose of this paper was to estimate the number of trips generated by the arrival of AV at Level 5 automation using a trip simulation model.

To properly evaluate the potential effects, a simulation model was created based on the potential variation in travel needs for different age categories and the modal shift of public and active transportation to AV. Three possible scenarios were considered (namely low, medium and high), and variations were applied to the average occupancy rate of vehicles to evaluate a range of potential effects on motorized travel. Thus, overall, a total of 240 scenarios were evaluated. The results showed that AV have the potential to result in an overall average increase of 13% in daily commuting in Montreal. If the car occupancy rate remains unchanged in the medium scenario, the new trips generated by AV could create a 16% increase in car travel. Travel would increase by 20%, including transfers from public and active transport to AV.

The analysis presented in this paper is limited to the impacts of AV on the number of trips by car. The possible impacts of AV on the variation of kilometers traveled are also important, but have not been addressed in this paper. The focus was instead on the number of trips, since the kilometers traveled depend on many uncertain factors such as the location of households as per levels of automation. However, it is likely that an increase in the number of car trips also leads to an increase in kilometers driven.

Despite the large number of scenarios evaluated and the uncertainty in the data used, it is believed that this article contributes to the reflections of planners and decision-makers in order to maintain timely and informed regional plans based on potential increases in the number of AV. Planners, as well as the general public, must be careful not to expect this technology to solve traffic congestion, traffic accidents or pollution problems by itself. Indeed, this model predicts that AV are likely to modestly increase vehicle trips. Additionally, increased travel time productivity could lead to increased peak hour congestion due to the reduced value of congestion avoidance.

This type of potential effect illustrates the limitations of this research. Indeed, despite a constant concern for the multiplier effects of AV variables, it is possible that, in the end, these effects have been underestimated or overestimated. Furthermore, in future research, other models might consider separating results by nature, by origin, and arrival of trips, since these variables could partly explain the effects of AV.

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APPENDIX A

RESULTS, LOW SCENARIO

		α_{AO}									
α_{PT}	α_{AT}	-0,05	$-0{,}04$	$-0{,}03$	$-0{,}02$	$-0{,}01$	0,00	0,01	0,02	0,03	0,04
0%	0%	18%	16%	15%	14%	13%	12%	111%	10%	8%	7%
0%	10%	19%	18%	17%	16%	14%	13%	12%	11%	10%	8%
8,5%	0%	20%	19%	18%	17%	15%	14%	13%	12%	11%	10%
8,5%	10%	22%	21%	19%	18%	17%	16%	15%	14%	13%	11%
α_{PT}	α_{AT}	0,05	0.06	0,07	0,08	0,09	0,10	0,11	0,12	0,13	0,14
0%	0%	6%	5%	4%	3%	2%	2%	1%	0%	-1%	-2%
0%	10%	8%	7%	6%	5%	4%	3%	2%	1%	0%	-1%
8,5%	0%	9%	8%	7%	6%	5%	4%	3%	2%	1%	0%
8,5%	10%	10%	9%	8%	7%	6%	5%	4%	3%	3%	2%

APPENDIX B

RESULTS, MEDIUM SCENARIO

		α_{AO}									
α_{PT}	α_{AT}	-0,05	−0,04	−0,03	−0,02	−0,01	0,00	0,01	0,02	0,03	0,04
0%	0%	22%	21%	20%	18%	17%	16%	15%	14%	13%	11%
0%	10%	24%	22%	21%	20%	19%	18%	16%	15%	14%	13%
8,5%	0%	25%	23%	22%	21%	20%	19%	17%	16%	15%	14%
8,5%	10%	26%	25%	24%	23%	21%	20%	19%	18%	17%	15%
α_{PT}	α_{AT}	0,05	0.06	0,07	0,08	0,09	0,10	0,11	0,12	0,13	0,14
0%	0%	10%	9%	8%	7%	6%	5%	4%	3%	3%	2%
0%	10%	12%	11%	10%	9%	8%	7%	6%	5%	4%	3%
8,5%	0%	13%	12%	11%	10%	9%	8%	7%	6%	5%	4%
8,5%	10%	14%	13%	12%	11%	10%	9%	8%	7%	6%	5%

APPENDIX C

RESULTS, HIGH SCENARIO

		α_{AO}									
α_{PT}	α_{AT}	-0,05	−0,04	−0,03	−0,02	−0,01	0,00	0,01	0,02	0,03	0,04
0%	0%	26%	25%	24%	23%	21%	20%	19%	18%	17%	15%
0%	10%	28%	27%	25%	24%	23%	22%	20%	19%	18%	17%
8,5%	0%	29%	28%	27%	25%	24%	23%	22%	20%	19%	18%
8,5%	10%	31%	29%	28%	27%	26%	24%	23%	22%	21%	20%
α_{PT}	α_{AT}	0,05	0.06	0,07	0,08	0,09	0,10	0,11	0,12	0,13	0,14
0%	0%	14%	13%	12%	11%	10%	9%	8%	7%	6%	5%
0%	10%	16%	15%	14%	13%	12%	11%	10%	9%	8%	7%
8,5%	0%	17%	16%	15%	14%	13%	12%	11%	10%	9%	8%
8,5%	10%	18%	17%	16%	15%	14%	13%	12%	11%	10%	9%