Optimizing CAV Driving Behaviour to Reduce Traffic Congestion and GHG Emissions

Saad Roustom[a] and Hajo Ribberink

Natural Resources Canada, CanmetEnergy, 1 Haanel Dr, Ottawa, ON, Canada

Keywords: Connected and Automated Vehicles, Driving Behaviour, Traffic Performance, GHG Emissions.

Abstract: This study was conducted to identify an optimal driving behaviour of connected and automated vehicles (CAV) that can reduce traffic congestion and GHG emissions under different traffic demand levels. The study employed traffic simulations at the meso scale for the City of Ottawa, Canada, to assess traffic performance and used correlation models to estimate GHG emissions. Aggressive CAVs showed the greatest potential to enhance traffic performance and reduce GHG emissions under all traffic demand levels. The results show that Aggressive CAVs can increase highway capacity and lower vehicle travel time in comparison to Driver Operated Vehicles (DOVs) or CAVs with a less aggressive driving style. The findings of the study indicate that CAVs with aggressive driving behavior can play a crucial role in enhancing traffic performance and in helping to mitigate the adverse impact of transportation on the environment. The results of this study aim to encourage regulatory bodies to adopt effective CAV-related policies that can enhance traffic performance and reduce GHG emissions.

1 INTRODUCTION

1.1 Background

Automated Vehicles (AVs) use a combination of sensors and control algorithms to perform driving functions normally carried out by the driver. Some modern vehicles are equipped with low-level automated features such as adaptive cruise control (ACC), lane-keep assist (LKA), and automatic emergency braking (AEB). Connected vehicles (CVs) are vehicles with on-board radios capable of exchanging information through wireless communications with other vehicles, infrastructure, and internet-based devices. Information generally exchanged includes position, direction, speed, and intent which gets presented to other road users as either safety or mobility advisories. The combination of these technologies, a connected and automated vehicle (CAV), has the potential of significantly reducing the number of collisions, reducing congestion, reducing greenhouse gas (GHG) emissions, and improving mobility. However, the shift towards new transportation behaviours due to automation may also increase greenhouse gas emissions due to potentially higher vehicle-kilometers travelled (VKT) and a shift towards new models of transportation, such as Mobility-as-a-Service (MAAS), and self-parking capabilities.

Due to the novel and cooperative nature of CAV technologies, it becomes difficult to assess its impact in real-world scenario, as some CAV applications work most effectively at high penetration rates and are affected by a multitude of environmental variables. Assessing the impacts of CAVs in a simulated environment presents itself as a viable precursor to real-world testing, and results may provide insight to help guide policy development.

1.2 Objectives

This objective of this study was to assess whether the specific driving behaviour of CAVs can actively be utilized to reduce congestion and GHG emissions from transportation. This was done by investigating the impact of homogenous CAV vehicle fleets on the traffic performance and associated GHG emissions for the City of Ottawa, Canada, through a

[a] https://orcid.org/0000-0001-7648-5436

Roustom, S. and Ribberink, H.
Optimizing CAV Driving Behaviour to Reduce Traffic Congestion and GHG Emissions.
DOI: 10.5220/0011792500003479
In *Proceedings of the 9th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2023)*, pages 198-205
ISBN: 978-989-758-652-1; ISSN: 2184-495X

combination of traffic simulations at the meso scale and an emissions calculation method based on emissions correlations developed from micro simulations results. The study evaluated scenarios characterized by different CAV driving behaviours and different traffic demand levels. The results of this study aim to inform regulatory bodies to support the development of effective CAV- related policies to promote the environmentally efficient implementation of CAV technologies.

2 LITERATURE REVIEW

CAVs have a great potential to improve traffic performance due to their ability to travel with small headways and smoother traffic flow. Most studies confirm that such technology can enhance traffic characteristics and reduce congestion. However, there is some uncertainty on optimal driving behaviour parameters that can increase its efficiency. It is possible that at initial stages of CAV deployment, CAVs will have a more cautious driving behaviour to take into consideration user preference, safety and comfort (Atkins Ltd, 2016). Cautious CAVs may potentially decrease effective capacity and deteriorate traffic performance especially in a high demand and high-speed traffic environment according to a micro simulation study (Atkins Ltd, 2016). A micro simulation study evaluated the impact of AVs on network capacity with different AV driving parameters. The study found that capacity increases quasi-linearly with higher AV penetration rates and that at full AV penetration rate, road capacity increases by 16% (Lu et al., 2020). Another micro simulation study reports that AVs at full penetration rates and under high volumes can improve traffic performance, but also decrease it at lower traffic volumes (Bohm & Häger, 2015). AVs can also result in a better level of service on single-lane roads by reducing speed deviations and delays according to a micro simulation study (Wang & Wang, 2017). The study concludes that benefits of CAVs are achieved under high levels of connectivity and automation (i.e., an aggressive drive style). Another micro-simulation based study simulated AVs on a network of 13 intersections and total distance of 4.5 km. The study found out that at increased AV penetration rates, the traffic flow is improved with a reduction of average delay up to 31%. An agent-based approach study found that a full AV traffic environment can increase the capacity of a multi-lane highway by 250% compared to regular driver-operated vehicles (Abdulsattar et al., 2020).

Studies also show that CAVs employment could potentially reduce GHG emissions or increase it. A modelling study utilized the SUMO microsimulation package to examine the impact of different degrees of vehicle automation on emissions in an urban network. The results show that acceleration is high highly correlated with emissions. Although automated vehicles can achieve higher acceleration values causing higher emissions, this was compensated by giving them lower rates of acceleration for higher automation levels. The results of this study concluded that automated vehicles could reduce carbon monoxide (CO) emissions by 38.5%, carbon dioxide (CO_2) emissions by 17.0% and hydrocarbons (HC) emissions by 36.3% for the best scenario in which the penetration rate of automated vehicles is 100% (Biramo & Mekonnen, 2022). A similar study explored the environmental impacts of AVs along an urban freeway corridor using Vissim and EPA’s MOVES. The study considered AV penetration rates of 10%, 20% and 30%. The study found out that only a 5% decrease in emissions can be expected with AV technology at a 30% penetration rate. However, this comes at cost of penalizing travel time by up to 13% for both AVs and conventional vehicles when compared to existing conditions (Tomás et al., 2020). A micro simulation-based study found that Aggressive AVs can reduce GHG emissions by 26% in an uninterrupted flow network and by 3% in an interrupted flow network under high traffic demand levels (Stogios et al., 2019). A similar study concluded that in a congested urban network, a maximum reduction of CO_2 emissions is achieved by 4% at a full AV penetration rate (Conlon & Lin, 2019). Other studies show that the reduction in emissions due to enhanced traffic performance can be overturned by an increase in traffic demand causing more GHG emissions (Brown et al., 2014; Wadud et al., 2016).

While many studies have been conducted to investigate the impact of CAV driving behaviours on traffic performance and GHG emissions using micro simulations, there is a lack of understanding on how CAVs will impact congestion and emissions in a larger road network such as a city-wide model. The study presented in this article assesses different CAV driving behaviours at the scale of a city with over one million inhabitants using meso simulation of scenarios with different CAV driving styles and under different traffic demand levels. The evaluation of CAV driving behaviour at the scale of a large city is critical to creating a deeper understanding of the potential of CAVs to improve traffic performance and reduce emissions, because the larger road network in the city will allow CAVs to choose different routes, for instance to avoid congestion, and their impact on traffic performance will differ from results obtained through micro simulation studies.

3 METHODOLOGIES

The approach followed to investigate whether the level of congestion in a city can be reduced by actively adjusting the driving behaviour of CAVs was to simulate a comprehensive set of scenarios covering a wide range of driving behaviours and traffic volumes. For each of these scenarios, the evaluation of the impact of CAVs on traffic performance and GHG emissions involved meso simulation of the traffic using the Ottawa Regional Model (MMM Group Limited, 2014) using the Dynameq traffic simulation software (INRO, n.d.-a), and applying emission correlation models to the simulation results in a post-processing step. The study took into consideration the regular driver-operated vehicle behaviour along with three CAV driving behaviours: Cautious, Normal and Aggressive. The emission correlations were developed in a different project by Carleton University (Roustom, 2022), and were based on micro simulation studies for four main routes in the City of Ottawa utilizing the same driving behaviours as used in this study. Carleton University developed emission regression models that can be used to estimate the emissions of CAVs for the total City of Ottawa. The meso simulation tool Dynameq does not have the capability to calculate emissions for vehicles in its simulations. Therefore, the models provided by Carleton University were used in a post-processing step for GHG emission estimation.

A combination of micro and meso simulation was needed for this research. The micro simulation conducted earlier by Carleton University was required for the detailed evaluation of the driving behaviour of CAVs. CAVs behave differently on the road than Driver Operated Vehicles (DOVs), for instance because their connectivity allows them to drive closer together. Meso simulation was necessary to understand how the different driving behaviour of CAVs would impact the overall traffic flow and congestion in a large city.

3.1 Meso Simulations

The Ottawa Regional Traffic model (MMM Group Limited, 2014) was obtained from the City of Ottawa together with a forecast of expected travel volumes for the year 2031. The model covers the total road network of the Ottawa-Gatineau region, consisting of over 700 traffic zones, over 5,000 intersections and close to 25,000 road segments. The Ottawa Regional Traffic Model is implemented in the macro simulation tool Emme (INRO, n.d.-b) and was calibrated using data from Ottawa's Origin-Destination Survey (MMM Group Limited, 2014). After receiving the calibrated Ottawa Regional Traffic Model from the City of Ottawa, it was exported from Emme into Dynameq and adjusted for functionality in the meso simulation tool. This involved adjusting the number of lanes and the layout of intersections and roads on all major through routes where needed. Traffic lights were added to all major intersections, and intersections in the downtown area were given appropriate stop/yield characteristics. Signal controls were generated using Dynameq's signal control optimizer routine and may not necessarily reflect the actual signal controls in Ottawa.

A total of 12 scenarios were evaluated to find the optimal driving characteristics of CAVs under different traffic conditions. DOV, Cautious, Normal and Aggressive driving behaviours were simulated with homogenous CAV fleets and traffic flows of 80%, 100% and 120% of the forecasted morning peak hour volumes for the year 2031. Simulations were optimized to result in minimum overall travel time for the total fleet. The parameters of each driving behaviour are shown in Table 1. The values were taken from the Carleton University study (Roustom, 2022). The simulation runs for the City of Ottawa were conducted for the period of 6:30 AM to 11:00 AM. Vehicles were added to the network during the first two and a half hours of the simulation (6:30 AM to 9:00 AM), and the simulations continued for another two hours to allow all vehicles to reach their destinations. General traffic characteristics such as vehicle-hours travelled (VHT) and vehicle-kilometers travelled (VKT) were aggregated over the full 4.5-hour simulation period. The meso-simulation outputs included road volumes, average speeds, density, and other road characteristics such as the number of lanes and link length.

A diverse fleet of passenger and commercial vehicles was used in the simulations, reflecting differences in vehicle size experienced in normal traffic. In all simulations, the vehicle fleet consisted of either 100% DOVs or 100% CAVs of a certain type. The rates of deployment and adoption of CAV technology are dependent on several factors such as technological advancement, consumer acceptance and policy regulations. This study assesses the scenarios using 100% CAV fleets to investigate the

Table 1: Traffic behaviour parameters.

Driving Behaviour	Effective length (m)	Response Time (seconds)
DOV	Car length + 2	**1**
Cautious CAV	Car length + 1.5	**1.5**
Normal CAV	Car length + 1.5	**0.9**
Aggressive CAV	Car length + 1	**0.6**

full potential of this technology. Future work can be done to study transition phases which will include a mixed fleet vehicle environment.

3.2 GHG Emission Estimation

Using the results of the micro simulations, Carleton University calculated detailed second-by-second GHG emissions for four example roads in the City of Ottawa. The example roads each had different traffic characteristics, representing typical congested traffic conditions in the downtown area (Bronson Avenue), arterial roads with short distances between intersections (Baseline Avenue), arterial roads with large distances between intersections, and highway traffic. Additionally, a regression analysis was performed on the GHG emission results to develop correlations between the GHG emission intensity (kg CO_2 eq.) and parameters displaying vehicle movement characteristics (average speed and average vehicle density) and road information (road segment length and number of lanes). The correlations were used in this study in a post-processing step to calculate overall GHG emissions for the vehicle fleet in Ottawa based upon traffic information per road segment from the Dynameq simulations. Since an emission correlation was developed for each of the four example routes, in the calculation of the emissions for the total city the appropriate correlation was selected per road segment according to the posted speed limit of the segment:

4 RESULTS

4.1 Traffic Performance

For each scenario, the total amount of vehicle-hours travelled and vehicle-kilometers travelled were determined by aggregating the travel times of all vehicles in the meso simulation. Table 2 and Table 3 present the results for the evaluated scenarios. The results in Table 2 show that Aggressive CAVs were able to reduce total vehicle-hours travelled by 14.2%. CAVs with normal driving behaviour also reduce travel time compared to DOVs, but the effect is much smaller than for Aggressive CAVs. CAVs with a cautious driving style increase travel time for all traffic flow levels and cause higher levels of congestion. The small differences in VKT between

Table 2: Vehicle-hours travelled (VHT) results for the Ottawa Regional Model under different scenarios.

Case		Vehicle-hour Travelled	
Traffic Flow	**Driving Behaviour**		
80%	**DOV**	**69,668**	**Compare to DOV 80%**
	Cautious	74,951	7.6%
	Normal	68,864	-1.2%
	Aggressive	67,463	-3.2%
100%	**DOV**	**90,898**	**Compare to DOV 100%**
	Cautious	106,867	17.6%
	Normal	89,024	-2.1%
	Aggressive	85,134	-6.3%
120%	**DOV**	**124,106**	**Compare to DOV 120%**
	Cautious	163,603	31.8%
	Normal	118,597	-4.4%
	Aggressive	106,507	-14.2%

Table 3: Vehicle-kilometers travelled (VKT) results for the Ottawa Regional Model under different scenarios.

Case		Vehicle-kilometers Travelled	
Traffic Flow	**Driving Behaviour**		
80%	**DOV**	**4,150,204**	**Compare to DOV 80%**
	Cautious	4,115,115	-0.8%
	Normal	4,160,152	1.1%
	Aggressive	4,173,698	0.3%
100%	**DOV**	**5,144,241**	**Compare to DOV100%**
	Cautious	5,179,543	0.7%
	Normal	5,154,417	-0.5%
	Aggressive	5,193,811	0.8%
120%	**DOV**	**6,239,120**	**Compare to DOV 120%**
	Cautious	6,434,729	3.1%
	Normal	6,221,226	-3.4%
	Aggressive	6,217,404	-0.1%

CAV and DOV scenarios indicate that differences in VHT are mostly due to differences in traffic conditions, i.e., the level of congestion.

It is clear from Table 2 that CAVs with aggressive driving behaviour can obtain the largest reduction in average travel time compared to DOVs for all traffic flow levels. To better demonstrate the impact of CAV driving behaviour and traffic volume on travel time, the average travel time per vehicle was calculated for each scenario. The results are displayed in Figure together with the average travel time for uncongested conditions (at 10% traffic flow). The different lines in the figure illustrate the increase in average travel time with an increase in traffic volume for a certain driving behaviour. The DOV scenarios showed a 19% increase in average travel time when traffic volume increased from 80% to 120% of the morning commute volume. Cautious CAVs experienced a 46% increase in average travel time, while the increase in average travel time for CAVs with aggressive driving behaviour was only 5%, which corresponds to less than 30% of the increase in travel time experienced by DOVs.

The results of Figure 1 indicate that the introduction of CAVs with aggressive driving behaviour has the potential to lead to a drastic reduction in congestion and similarly limit the corresponding increase in average travel time, thanks to their ability to travel with shorter inter-vehicle distances and creating a more harmonized traffic flow.

The total of all vehicle-hours travelled (VHT) by the vehicle fleet on different road types and the corresponding total of all vehicle-kilometres travelled (VKT) driven on these roads during the morning commute period was compared for the simulated scenarios. Table 4 displays the VHT values for all scenarios and the difference between the VHT for the CAV scenarios and their respective DOV scenarios. In a similar way, Table displays the VKT values for all scenarios and the difference between the VKT for the CAV scenarios and their corresponding DOV scenarios. In general, the overall number of kilometers driven in the city is similar for each of the driving behaviours, as was shown in Table 3.

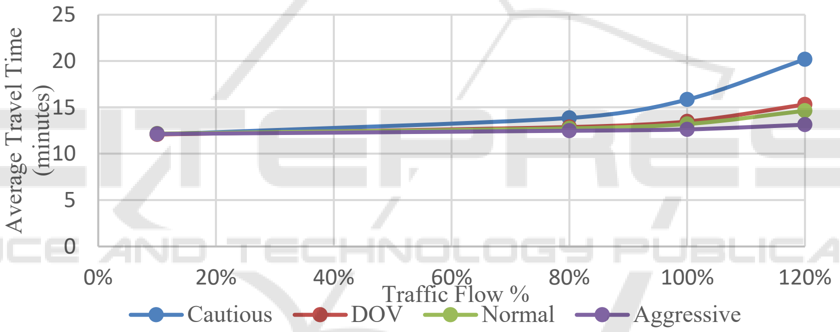

Figure 1: Comparison of average travel time for each driving behaviour under different traffic flow conditions.

Table 4: Vehicle-hours travelled (VHT) for different road classifications for all scenarios, and the difference in VHT of CAV scenarios compared to the corresponding DOV scenario.

Scenario		Highway		Arterial and Other Roads					
Traffic Flow	Driving Behaviour			0 - 50 km/h		50 - 65 km/h		65 - 100 km/h	
80%	**DOV**	**21,210**		**19,419**		**8,372**		**20,667**	
	Cautious	21,357	1%	21,619	11%	9,640	15%	22,335	8%
	Normal	21,091	-1%	19,176	-1%	8,200	-2%	20,398	-1%
	Aggressive	20,771	-2%	18,680	-4%	7,926	-5%	20,086	-3%
100%	**DOV**	**26,220**		**26,205**		**11,690**		**26,784**	
	Cautious	28,018	7%	32,918	26%	14,163	21%	31,769	19%
	Normal	26,088	-1%	25,339	-3%	11,221	-4%	26,376	-2%
	Aggressive	25,923	-1%	23,913	-9%	10,165	-13%	25,133	-6%
120%	**DOV**	**33,285**		**37,783**		**15,841**		**37,198**	
	Cautious	38,202	15%	54,423	44%	20,749	31%	50,228	35%
	Normal	32,962	-1%	35,292	-7%	15,201	-4%	35,143	-6%
	Aggressive	31,201	-6%	30,726	-19%	13,184	-17%	31,396	-16%

Table 5: Vehicle-kilometers travelled (VKT) for different road classifications for all scenarios, and the difference in VKT of CAV scenarios compared to the corresponding DOV scenario.

Scenario		**Highway**		**Arterial and Other Roads**					
Traffic Flow	Driving Behaviour			**0 - 50 km/h**		**50 - 65 km/h**		**65 - 100 km/h**	
80%	**DOV**	**1,772,901**		**726,219**		**311,835**		**1,339,249**	
	Cautious	1,605,509	-9%	776,531	7%	346,243	11%	1,386,832	4%
	Normal	1,801,163	2%	720,948	-1%	307,091	-2%	1,330,950	-1%
	Aggressive	1,841,164	4%	710,527	-2%	299,875	-4%	1,322,132	-1%
100%	**DOV**	**2,080,292**		**948,865**		**418,597**		**1,696,487**	
	Cautious	1,865,808	-10%	1,065,292	12%	459,008	10%	1,789,435	5%
	Normal	2,135,973	3%	929,953	-2%	405,665	-3%	1,682,826	-1%
	Aggressive	2,272,802	9%	897,972	-5%	381,455	-9%	1,641,582	-3%
120%	**DOV**	**2,344,502**		**1,239,439**		**531,695**		**2,123,484**	
	Cautious	2,073,624	-12%	1,468,212	18%	569,485	7%	2,323,408	9%
	Normal	2,400,831	2%	1,200,553	-3%	522,348	-2%	2,097,494	-1%
	Aggressive	2,614,169	12%	1,115,977	-10%	475,643	-11%	2,011,615	-5%

However, this does not mean that each scenario had the same traffic characteristics. This can be seen from analyzing the VKT results aggregated for different road classifications according to their type and posted speed limit, as presented in Table. These more detailed results show different aspects of vehicle movements under the various scenarios. Compared to DOVs, Aggressive CAVs drive fewer kilometers on arterial roads and on other roads but have higher VKT values for highways in combination with lower VHT values for this road type. This indicates that Aggressive driving behaviour increases highway capacity allowing for more vehicle-kilometers travelled with lower VHT. Cautious CAVs on the other hand, have significantly increased VHT values and higher VKT values on arterial and other roads in comparison to DOV. This reflects the situation that vehicles are avoiding the more congested highways, which is also demonstrated by the relatively higher VHT values but lower VKT values for highways under this scenario.

4.2 GHG Emissions

The GHG emissions of the total vehicle fleet in Ottawa were calculated and expressed as total equivalent CO_2 emissions produced throughout the total morning commute simulation period. The GHG emission results are shown in Table 6.

Table 6: GHG emissions for the total vehicle fleet from the Ottawa Regional Model under different scenarios.

Case		**CO2 eq kg**	
Traffic Flow	**Driving Behaviour**		
80%	**DOV**	**809,147**	**Compare to DOV 80%**
	Cautious	887,518	9.7%
	Normal	769,484	-4.9%
	Aggressive	763,048	-5.7%
100%	**DOV**	**1,036,577**	**Compare to DOV 100%**
	Cautious	1,158,066	11.7%
	Normal	984,645	-5.0%
	Aggressive	975,155	-5.9%
120%	**DOV**	**1,302,093**	**Compare to DOV 120%**
	Cautious	1,493,366	14.7%
	Normal	1,230,897	-5.5%
	Aggressive	1,195,355	-8.2%

The trends in total GHG emissions for the different scenarios are consistent with the results for the travel time as shown. CAVs with CAVs with an aggressive driving behaviour having the largest reduction in GHG emissions in comparison to DOVs.

The relative reduction in GHG emissions increases at higher traffic volumes, indicating a larger benefit of an aggressive driving style for higher levels of congestion as shown in figure 2 which displays the average amount of GHG emissions per vehicle for each scenario under different traffic demand conditions. GHG emission results for CAVs with a normal driving behaviour follow similar emissions trends as for the aggressive driving style, but with lower reduction percentages. Cautious CAVs cause an increase in GHG emissions for all traffic flow levels.

5 CONCLUSIONS

This study employed meso simulations and emission estimation to investigate whether equipping CAVs with a specific driving style could result in a reduction in congestion, in average travel time and in GHG emissions. This was done by assessing the impact of CAV vehicle fleets on traffic performance and GHG emissions for the City of Ottawa in Canada. The study evaluated four different driving behaviours: DOVs, Cautious CAVs, Normal CAVs, and Aggressive CAVs. The city-wide model was simulated with traffic volumes equal to 80%, 100% and 120% of peak-hour traffic forecasted for the year 2031.The results of the simulations show that an aggressive driving style is the most optimal driving behaviour for CAVs in all scenarios, and that equipping CAVs with this driving style can lead to significant reductions in travel time and in GHG emissions compared to DOVs, especially at higher traffic volumes. The detailed results of the meso simulations showed that equipping CAVs with an aggressive driving style will increase road capacity, allowing more vehicles to use the highway and effectively reduce congestion on arterial and other roads.

The results of the study presented in this article clearly indicate that the driving behaviour of CAVs can be utilized to reduce travel time and congestion in an urban environment when employing a homogenous fleet of 100% CAVs. However, it is unclear what level of penetration of Aggressive CAVs in a mixed CAV/DOV fleet will be necessary to start seeing the benefits of enhanced traffic movement. Similarly, it is unknown how fleets of CAVs with different driving behaviours (Cautious, Normal, and Aggressive) will impact congestion and transportation emissions. These subjects will be part of ongoing research on this topic.

ACKNOWLEDGEMENTS

Funding for this study was received from Transport Canada under the ecoTECHNOLOGY for Vehicles program. The authors express great thanks to the City of Ottawa and the TRANS committee for sharing the Ottawa Regional Traffic Model for use in this study.

REFERENCES

Abdulsattar, H., Siam, M. R. K., & Wang, H. (2020). Characterisation of the impacts of autonomous driving on highway capacity in a mixed traffic environment: an agent-based approach. *IET Intelligent Transport Systems*, *14*, 1132 –1141. https://doi.org/10.1049/iet-its.2019.0285

Atkins Ltd. (2016). *Research on the Impacts of Connected and Autonomous Vehicles (CAVs) on Traffic Flow Summary Report Department for Transport*. https://trid.trb.org/view/1448450

Biramo, Z. B., & Mekonnen, A. A. (2022). *Modeling the potential impacts of automated vehicles on pollutant emissions under different scenarios of a test track. Environmental Systems Research, 11(1), 28.* https://doi.org/10.1186/s40068-022-00276-2

Bohm, F., & Häger, K. (2015). *Introduction of Autonomous Vehicles in the Swedish Traffic System : Effects and Changes Due to the New Self-Driving Car Technology*. https://www.semanticscholar.org/paper/Introduction-of-Autonomous-Vehicles-in-the-Swedish-Bohm-H%C3%A4ger/ea2be6805b2adaba043df516e132f128 9ce103cb#citing-papers

Brown, A., Gonder, J., & Repac, B. (2014). An Analysis of Possible Energy Impacts of Automated Vehicles. In G. Meyer & S. Beiker (Eds.), *Road Vehicle Automation* (pp. 137–153). Springer International Publishing. https://doi.org/10.1007/978-3-319-05990-7_13

Conlon, J., & Lin, J. (2019). Greenhouse Gas Emission Impact of Autonomous Vehicle Introduction in an Urban Network. *Transportation Research Record*, *2673*(5), 142–152. https://doi.org/10.1177/03611 98119839970

INRO. (n.d.-a). *Dynameq*.

INRO. (n.d.-b). *Emme*.

Lu, Q., Tettamanti, T., Hörcher, D., & Varga, I. (2020). The impact of autonomous vehicles on urban traffic network capacity: an experimental analysis by microscopic traffic simulation. *Transportation Letters*, *12*(8), 540–549. https://doi.org/10.1080/19427867.2019.1662561

MMM Group Limited. (2014). *TRANS Model – Evolution of the TRANS Regional Travel Forecasting Model.*

Roustom, S. G. (2022). *Environmental Impacts of Connected and Automated Vehicles Considering Traffic Flow and Road Characteristics.* Thesis (M.App.Sc.) - Carleton University, 2022.

Tomás, R. F., Fernandes, P., Macedo, E., Bandeira, J. M., & Coelho, M. C. (2020). *Assessing the emission* *impacts of autonomous vehicles on metropolitan freeways. Transportation Research Procedia, 47, 617–624.* https://doi.org/https://doi.org/10.1016/j.trpro.2020.03.139

Stogios, C., Kasraian, D., Roorda, M. J., & Hatzopoulou, M. (2019). Simulating impacts of automated driving behavior and traffic conditions on vehicle emissions. *Transportation Research Part D: Transport and Environment*, *76*, 176–192. https://doi.org/10.1016/j.trd.2019.09.020

Wadud, Z., MacKenzie, D., & Leiby, P. (2016). Help or hindrance? The travel, energy and carbon impacts of highly automated vehicles. *Transportation Research Part A: Policy and Practice*, *86*, 1–18. https://doi.org/10.1016/j.tra.2015.12.001

Wang, Y., & Wang, L. (2017). Autonomous vehicles' performance on single lane road: A simulation under VISSIM environment. *2017 10th International Congress on Image and Signal Processing, BioMedical Engineering and Informatics (CISP-BMEI)*, 1–5. https://doi.org/10.1109/CISP-BMEI.2017.8302162