Improving Urban Mobility: Analyzing Impacts of Connected and Automated Vehicles on Traffic and Emissions

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***Abstract*—**In most cities in the world, traffic has increased strongly over the last decades, causing high levels of congestion and deteriorating inner-city air quality. This study analyzes the impact of connected and automated vehicles (CAVs) on traffic performance and greenhouse gas (GHG) emissions under different CAV penetration rates in mixed fleet environments of CAVs and driver-operated vehicles (DOVs) and under three different traffic demand levels. Utilizing meso-scale traffic simulations of the City of Ottawa, Canada, the research evaluates the traffic performance of three distinct CAV driving behaviors—Cautious, Normal, and Aggressive—at penetration rates of 25%, 50%, 75%, and 100%, across three different traffic demand levels. The study employs advanced correlation models to estimate GHG emissions. The results reveal that Aggressive and Normal CAVs generally reduce traffic congestion and GHG emissions, with their benefits being more pronounced at higher penetration rates (50% to 100%) and elevated traffic demand levels. On the other hand, Cautious CAVs exhibit an increase in both traffic congestion and GHG emissions. However, results also show deteriorated traffic flow conditions when introducing 25% penetration rates of any type of CAVs. Aggressive CAVs outperform all other driving at improving traffic flow conditions and reducing GHG emissions. The findings of this study highlight the crucial role CAVs can play in enhancing urban traffic performance and mitigating the adverse impact of transportation on the environment. This research advocates for the adoption of effective CAV-related policies by regulatory bodies to optimize traffic flow and reduce GHG emissions. By providing insights into the impact of CAVs, this study aims to inform strategic decision-making and stimulate the development of sustainable urban mobility solutions.

***Keywords*—**Connected and automated vehicles, congestion, GHG emissions, mixed fleet environment, traffic performance, traffic simulations.

I. Introduction

TRAFFIC congestion has significantly increased in urban environments for the past decades leading to higher levels of emissions and worsen air quality. Connected and automated vehicles (CAVs) are self-driven vehicles capable of communicating with surrounding vehicles, infrastructure, and other internet-based devices. CAVs have the potential of significantly reducing the number of collisions, greenhouse gas (GHG) emissions, congestion, and improving mobility.

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

The main objective of this study is to evaluate the impact that CAV applications have on GHG emissions, as well as from the transition to higher levels of automated mobility, using meso-scope simulation methods. The impact of CAV penetration level and of traffic volume on the travel time, vehicle kilometers travelled (VKT), and GHG emission is investigated.

II. Literature Review

CAVs have a significant potential to improve traffic performance by allowing close car-following distances and facilitating smoother traffic flow. However, there are many uncertainties regarding the optimal driving behavior and the adoption rate of CAVs required to achieve such benefits. Despite the abundance of micro-simulation-based studies [1]-[8] on AV driving behaviors' impact on traffic performance and GHG emissions, understanding their effects on congestion and emissions in larger road networks, such as city-wide models, remains limited. This study addresses this gap by assessing various CAV driving behaviors under different penetration rates on a city-wide scale, using meso-simulations to explore scenarios with varying traffic demand levels. Such evaluation is crucial for gaining deeper insights into CAVs' potential to enhance traffic performance and reduce emissions on a broader scale, considering the diverse road network dynamics of large cities, which may influence route choices and traffic performance differently than microsimulation studies suggest.

It is important to note that this study builds upon previous research [9] that evaluated the impact of homogenous CAV vehicle fleets on traffic performance and GHG emissions. This study extends the evaluation to consider the impact of varying CAV penetration rates on traffic flow and emissions.

Initial CAV deployment may prioritize cautious driving behavior to address concerns related to user safety, comfort, and preference [1]. Traffic simulation studies suggest that cautious CAV behavior could worsen traffic performance, particularly in high-demand, high-speed traffic environments [1]. A micro-simulation study evaluating the impact of AVs on network capacity reveals a quasi-linear increase in capacity with higher

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AV penetration rates. At full AV penetration, road capacity can increase by up to 16% [2]. However, other studies suggest that while AVs can enhance traffic performance under high-volume conditions, they may have adverse effects at lower traffic volumes [3]. AVs also demonstrate the potential to improve single-lane road service levels by reducing speed deviations and delays [4], particularly when operating with high levels of connectivity and automation.

Studies also show that CAV technology adoption could potentially reduce GHG emissions or increase it. A micro-simulation modeling study utilized the SUMO package to investigate the impact of different degrees of vehicle automation on emissions in an urban network environment. Results of the study show that acceleration is highly correlated with emissions. Although automated vehicles can achieve higher acceleration values swiftly causing higher emissions, it can be compensated by their lower frequency of accelerations which decreases with higher automation levels. The results of this study concluded that automated vehicles can reduce carbon monoxide (CO) emissions by 38.5%, carbon dioxide (CO_2) emissions by 17.0% and hydrocarbons (HC) emissions by 36.3% at full AV penetration rate [5]. A similar utilized Vissim and EPA's MOVES to investigate the impact of AVs on an urban freeway corridor. The study considered AV penetration rates of 10%, 20% and 30%. The results show a potential 5% decrease in emissions at a 30% AV penetration rate. However, this is coupled with an increase in travel time by up to 13% when compared to existing conditions [6]. Similarly, micro-simulation-based studies demonstrate varied outcomes, with aggressive AVs potentially reducing GHG emissions by 26% in uninterrupted flow networks [7], while others suggest a maximum 4% reduction in CO_2 emissions at full AV penetration in congested urban networks [8]. Notably, some studies caution that improvements in traffic performance may be offset by increased traffic demand, leading to higher GHG emissions [10], [11].

III. Methodologies

The approach employed in this study focuses on investigating the impact of CAVs on traffic performance and GHG emissions under different CAV penetration rates and traffic demand levels within the urban context of the City of Ottawa, Canada using the Ottawa Regional Model [12].

This involved simulating various scenarios encompassing a wide spectrum of driving behaviors using Dynameq traffic simulation software [13]. Post-simulations, emission correlation models developed by Carleton University [14] are applied. These models, derived from microsimulation studies on key routes in Ottawa, account for three CAV driving behaviors—Cautious, Normal, and Aggressive—alongside conventional driver-operated vehicles. Carleton University's emission regression models facilitate GHG emission estimation for the entire city, supplementing Dynameq's inability to directly calculate vehicle emissions. Integrating micro and meso-simulation is crucial for this research. While microsimulation provides detailed insights into CAV behavior, meso-simulation is indispensable for understanding their broader impact on traffic flow and congestion in urban environments.

A. Meso-Scale Simulations

The Ottawa Regional Traffic model [12] 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 was implemented in the macro simulation tool Emme [15] and was calibrated using data from Ottawa's Origin-Destination Survey. After receiving the calibrated Ottawa Regional Traffic Model from the City of Ottawa, it is 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 are added to all major intersections, and intersections in the downtown area are given appropriate stop/yield characteristics. Signal controls are generated using Dynameq's signal control optimizer routine and may not necessarily reflect the actual signal controls in Ottawa.

The study uses Dynameq, a meso-scale traffic simulation tool, to simulate three different CAV driving behavior along with the baseline DOV behavior for 80%, 100% and 120% of Ottawa's morning period peak demand. The CAV driving behaviors in the study include Cautions, Normal and Aggressive. Further, the study evaluates the impact of CAV penetration rates of 25%, 50% 75%, and 100% for each of the CAV driving behavior.

A total of 39 scenarios are evaluated to understand the impact of CAVs given different penetration rate and traffic demand levels. The simulations are optimized to result in minimum overall travel time for the total fleet. The parameters of each CAV driving behavior are shown in Table I. The values are identical to the ones from the Carleton University study [14]. The CAV model in Dynameq has an attribute known as the "Connected Response Time" for CAV vehicle types. This attribute is specifically designed to define the minimum following distance between a CAV and the vehicle in front of it when that leading vehicle is also a CAV. However, in the event that the CAV is following a non-CAV vehicle, the minimum following distance reverts to the standard response time pre-defined for the CAV vehicle type in Dynameq.

The simulation runs for the City of Ottawa are conducted for the period of 6:30 AM to 11:00 AM. Vehicles are 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 continue 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) are aggregated over the full 4.5-hour simulation period. The meso-simulation outputs include road volumes, average speeds, density, and other road characteristics such as the number of lanes and link length.

The simulations involve a varied fleet comprising both passenger and commercial vehicles, mirroring the diversity in vehicle sizes commonly encountered in real-world traffic.

TABLE I
DRIVING BEHAVIOR PARAMETERS

Driving Behavior	Effective length	Response Time
DOV	Car length + 2	**1.0**
Cautious CAV	Car length + 1.5	**1.5**
Normal CAV	Car length + 1.5	**0.9**
Aggressive CAV	Car length + 1	**0.6**

B. GHG Emissions Estimation

Using the results of the micro simulations, Carleton University calculated second-by-second GHG emissions for four example roads within the City of Ottawa [14]. These roads were selected to represent various traffic conditions prevalent in different areas of the city, including highway traffic, downtown congestion (Bronson Avenue), arterial roads with short inter-intersection distances (Baseline Avenue), and arterial roads with longer inter-intersection distances. Additionally, a regression analysis was conducted on the GHG emission results to develop correlation models between emission intensity (kg CO_2 eq.) and parameters displaying vehicle traffic characteristics (average speed and average vehicle density) and road geometry (number of lanes and road segment). These correlation models consider CAV driving behavior and penetration rate. The correlations are subsequently employed in a post-processing phase of the study to estimate total GHG emissions for Ottawa's vehicle fleet based on traffic information obtained from Dynameq simulations. Given that a unique emission correlation was derived for each of the four example routes, the appropriate correlation is selected for each road segment in the citywide emission calculation, based on the segment's posted speed limit.

IV. RESULTS

A. Traffic Performance

Traffic performance is evaluated in terms of VHT, VKT and average travel time for all scenarios across varying CAV penetration rates. Tables II-IV present the VHT and VKT results for the different scenarios for traffic demand levels of 80%, 100% and 120%, respectively.

The analysis of VHT and VKT results present a consistent trend across various traffic demand levels. As the penetration rate of Normal and Aggressive CAVs increases, a notable reduction in total VHT is observed. At lower to medium traffic demand levels (80% and 100%), Normal CAVs seem to perform best at the 50% to 75% penetration rate range in terms of VHT reduction compared to DOVs. However, this is also coupled with a slight increase in VKT.

At higher traffic demand (120%), Normal CAVs exhibit better performance at 100% penetration level in terms of reducing VHT. Aggressive CAVs consistently perform better as penetration rate increases in terms of VHT reduction across all traffic demand levels. Generally, the benefits of Normal and Aggressive CAVs become apparent at a 50% penetration rate, contributing to improved overall traffic conditions. CAVs appear to have a negative impact on traffic conditions at a 25% penetration rate. This trend implies that increased Normal and Aggressive CAV penetration rates generally contribute to an enhancement in overall traffic flow conditions.

TABLE II
VHT AND VKT RESULTS FOR DIFFERENT CAV DRIVING BEHAVIORS UNDER DIFFERENT PENETRATION RATES AT 80% TRAFFIC DEMAND

Case		Total VHT (veh-hr)	Total VKT (veh-km)
DOV		69,668	4,150,203
Cautious	25%	69,709	4,147,527
	50%	69,918	4,146,070
	75%	75,055	4,123,966
	100%	72,889	4,143,008
Normal	25%	69,928	4,149,861
	50%	69,135	4,151,092
	75%	69,194	4,160,039
	100%	69,403	4,163,891
Aggressive	25%	70,468	4,150,858
	50%	69,395	4,153,227
	75%	68,263	4,174,170
	100%	68,236	4,176,793

TABLE III
VHT AND VKT RESULTS FOR DIFFERENT CAV DRIVING BEHAVIORS UNDER DIFFERENT PENETRATION RATES AT 100% TRAFFIC DEMAND

Case		Total VHT (veh-hr)	Total VKT (veh-km)
DOV		90,898	5,144,242
Cautious	25%	92,142	5,146,190
	50%	92,033	5,147,381
	75%	106,594	5,179,205
	100%	100,710	5,174,475
Normal	25%	91,659	5,147,312
	50%	89,862	5,147,312
	75%	89,515	5,152,672
	100%	90,438	5,159,261
Aggressive	25%	91,237	5,144,856
	50%	90,270	5,144,231
	75%	86,136	5,186,557
	100%	85,708	5,198,242

TABLE IV
VHT AND VKT RESULTS FOR DIFFERENT CAV DRIVING BEHAVIORS UNDER DIFFERENT PENETRATION RATES AT 120% TRAFFIC DEMAND

Case		Total VHT (veh-hr)	Total VKT (veh-km)
DOV		124,106	6,239,120
Cautious	25%	127,898	6,297,190
	50%	124,533	6,208,612
	75%	161,888	6,473,660
	100%	141,981	6,390,020
Normal	25%	126,195	6,321,414
	50%	120,909	6,207,841
	75%	121,003	6,228,569
	100%	119,311	6,214,828
Aggressive	25%	126,355	6,316,375
	50%	120,123	6,214,421
	75%	109,037	6,204,804
	100%	107,691	6,225,518

Cautious CAVs display a tendency to worsen traffic conditions with increasing penetration rates, particularly reaching a peak deterioration at the 75% penetration rate. There is a noteworthy observation to be made on the results presented in Tables II-IV: All scenarios having a mixed fleet with a 25% penetration of CAVs report an increase in VHT when compared to a scenario with a full fleet of DOVs. This increase indicates a potential aggravation of traffic flow conditions when introducing a minority share of vehicles with different driving behavior. This phenomenon is not yet fully understood, as it contradicts the reduction in VHT observed at higher penetration rates for Normal and Aggressive CAVs where an improvement in traffic flow becomes evident. A similar, though opposite result is seen for Cautious CAVs, where a homogeneous fleet of 100% Cautious CAVs consistently has lower VHT values than a mixed fleet of 75% Cautious CAVs and 25% DOVs. Despite the general trend favoring Aggressive CAVs in reducing VHT, there are some instances at lower CAV penetration rates where Normal CAVs outperform Aggressive CAVs, achieving lower VHT values. This is another example of complex DOV/CAV interactions in traffic flow that are not yet understood and may need further investigation in the future.

To account for variations in VKT associated with different driving behaviors, a comparison of travel times normalized against total network demand is conducted. Figs. 1 to 3 illustrate the average travel time per vehicle across the three traffic demand levels, providing additional insights into the traffic flow conditions under various CAV scenarios.

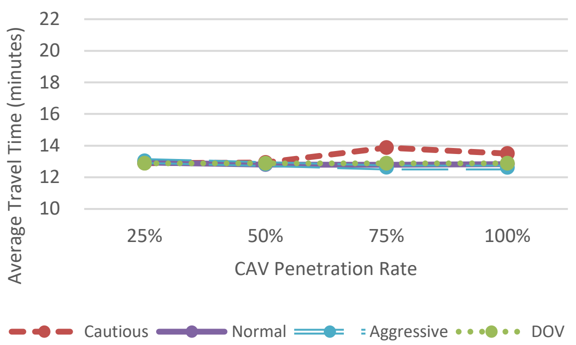

Fig. 1 Comparison of average travel time per vehicle for different CAV driving behaviors at various penetration rates and DOV scenario (80% traffic demand)

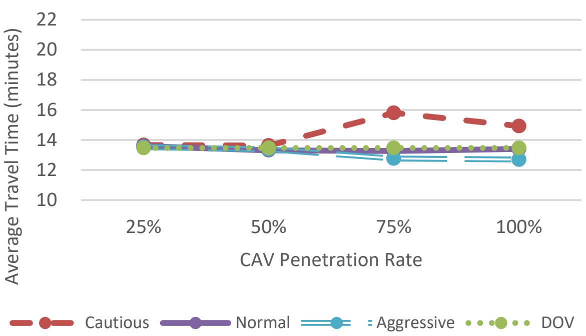

Fig. 2 Comparison of average travel time per vehicle for different CAV driving behaviors at various penetration rates and DOV scenario (100% traffic demand)

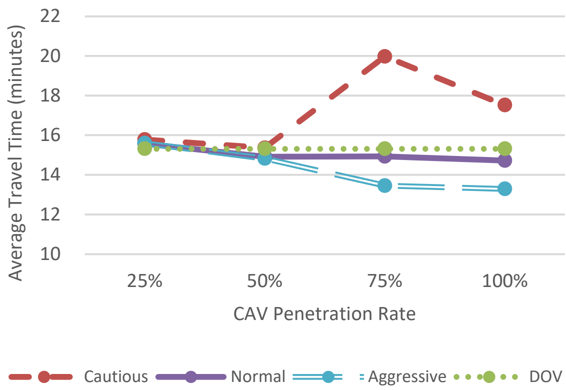

Fig. 3 Comparison of average travel time per vehicle for different CAV driving behaviors at various penetration rates and DOV scenario (120% traffic demand)

Figs. 1-3 illustrate that Aggressive CAVs perform best at reducing average travel time per vehicle, with their impact being more pronounced as traffic demand and penetration rates increase. Normal CAVs exhibit minimal effect on average travel time per vehicle compared to DOVs, only slightly reducing it with higher penetration rates. In contrast, Cautious CAVs significantly increase average travel time per vehicle, particularly at the 75% penetration rate.

B. GHG Emissions

This study compares GHG emissions of homogenous and mixed fleets for each CAV driving behavior at different penetration rates with the DOV scenario across the three different traffic demand levels as shown in Tables V-VII. The GHG emission trends are generally consistent with the traffic behavior trends in Tables II-IV.

Aggressive CAVs offer the largest reduction in GHG emissions at all penetration rates compared to DOVs and all other CAV driving behaviors with relative penetration rates. This effect becomes notably more pronounced at higher penetration rates and elevated traffic demand levels. It can also be noticed that there is no major change in emissions between the 75% and the 100% Aggressive CAV penetration rate.

Normal CAVs mirror the trends observed with Aggressive CAVs, although with a slightly lower reduction in GHG emissions. Cautious CAVs display a contrasting pattern, revealing an increase in GHG emissions with higher penetration rates. The most substantial spike in GHG emissions occurs at a 75% penetration rate of Cautious CAVs.

It is also important to note that at 25% CAV penetration rate, all CAV driving behaviors seem to reduce GHG emissions when compared to DOV although they perform worse in terms of traffic condition (see Tables II-IV). This observed disparity is likely attributed to the differences between the micro-simulations and meso-simulations. For the micro-simulations, Carleton's University's results show that 25% penetration rates of CAVs can improve traffic conditions. This contrasts the traffic results derived from the meso-simulations, where traffic conditions are deteriorated at CAV penetration rates of 25%. The employed GHG emission models are based on results derived from micro-simulations. Consequently, the depicted reduced emissions seen in Tables V-VII for the 25% CAV penetration rates are probably tied to the traffic dynamics captured within the micro-simulations.

TABLE V
COMPARISON OF GHG EMISSIONS BETWEEN THE DIFFERENT CAV DRIVING BEHAVIORS AT DIFFERENT PENETRATION RATES AND THE DOV SCENARIO AT 80% TRAFFIC DEMAND

Case		Emissions (CO_2 eq. kg)	
DOV		596,071	Compared to DOV
Cautious	25%	573,808	-3.74%
	50%	619,290	3.90%
	75%	692,371	16.16%
	100%	695,611	16.70%
Normal	25%	569,312	-4.49%
	50%	562,237	-5.68%
	75%	563,611	-5.45%
	100%	564,512	-5.29%
Aggressive	25%	567,598	-4.78%
	50%	558,871	-6.24%
	75%	558,515	-6.30%
	100%	558,695	-6.27%

TABLE VI
COMPARISON OF GHG EMISSIONS BETWEEN THE DIFFERENT CAV DRIVING BEHAVIORS AT DIFFERENT PENETRATION RATES AND THE DOV SCENARIO AT 100% TRAFFIC DEMAND

Case		Emissions (CO_2 eq. kg)	
DOV		767,687	Compared to DOV
Cautious	25%	743,711	-3.12%
	50%	797,742	3.91%
	75%	897,243	16.88%
	100%	895,083	16.59%
Normal	25%	735,448	-4.20%
	50%	728,098	-5.16%
	75%	724,997	-5.56%
	100%	724,932	-5.57%
Aggressive	25%	730,035	-4.90%
	50%	721,552	-6.01%
	75%	717,279	-6.57%
	100%	717,201	-6.58%

TABLE VII
COMPARISON OF GHG EMISSIONS BETWEEN THE DIFFERENT CAV DRIVING BEHAVIORS AT DIFFERENT PENETRATION RATES AND THE DOV SCENARIO AT 120% TRAFFIC DEMAND

Case		Emissions (CO_2 eq. kg)	
DOV		968,999	Compared to DOV
Cautious	25%	946,456	-2.33%
	50%	998,862	3.08%
	75%	1,149,368	18.61%
	100%	1,130,414	16.66%
Normal	25%	935,740	-3.43%
	50%	912,461	-5.83%
	75%	914,083	-5.67%
	100%	911,216	-5.96%
Aggressive	25%	928,625	-4.17%
	50%	907,405	-6.36%
	75%	890,647	-8.09%
	100%	892,393	-7.91%

V. CONCLUSIONS

This study investigates the impact of CAVs on traffic performance and GHG emissions within scenarios with varying CAV penetration rates and under different traffic demand levels for the city of Ottawa, Canada. This is evaluated through meso-scope traffic simulations and GHG emission correlation models and for different CAV driving behaviors.

Findings of this study indicate that Aggressive and Normal CAVs generally contribute to reduced traffic congestion and GHG emissions with their benefits being more pronounced at higher penetration rates and higher traffic demand levels. However, Cautious CAVs exhibit a tendency to worsen traffic conditions and increase GHG emissions particularly at higher penetration rates.

Introducing a 25% penetration rate of any CAV behavior results in deteriorated traffic flow conditions as opposed to the improvements observed at higher penetration rates. This highlights the complexity of interactions between DOVs and CAVs and indicates that further investigation of this phenomenon is required.

Aggressive CAVs outperform all other driving behaviors in terms of reducing both traffic congestion and GHG emission. However, there are instances observed in which Normal CAVs demonstrate better performance than Aggressive CAVs at lower penetration rates. Again, this vehicular interaction is not yet understood and may need further investigation in the future.

This study highlights the potential of CAVs to enhance urban traffic performance and reduce adverse environmental impacts, advocating for making robust CAV-related policies to improve traffic flow conditions and reduce GHG emissions. This research aims to inform strategic decision-making and advance the development of sustainable urban mobility solutions by offering insights into CAV impacts.

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