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Environmental Impacts of Connected and Automated Vehicles Considering Traffic Flow and Road Characteristics

Saad Roustom[1], Adam Weiss, Yasser Hassan

Department of Civil and Environmental Engineering, Carleton University, Ottawa, Ontario, Canada, K1S 5B6, saad.roustom@carleton.ca

Department of Civil and Environmental Engineering, Carleton University, Ottawa, Ontario, Canada, K1S 5B6, adam.weiss3@carleton.ca

Department of Civil and Environmental Engineering, Carleton University, Ottawa, Ontario, Canada, K1S 5B6, yasser.hassan@carleton.ca

Abstract

Connected and automated vehicles (CAVs) have the potential to revolutionize the transportation system by improving traffic conditions, increasing road capacities and reducing congestions and crash risks. This study aims to investigate the implications of this technology on greenhouse gas (GHG) emissions levels through traffic micro-simulations of different driving behaviors and emissions modelling. Three different driving behaviors (cautious, normal and aggressive) of CAVs are simulated along with a base driving behavior of driver-operated vehicle (DOV) with different traffic demands and under different network configurations to evaluate CAVs' implications. The driving behavior of CAVs vary in parameters of longitudinal spacing thresholds, acceleration and deceleration behavior and lateral gap acceptance thresholds. Results of this study show that aggressive CAVs can reduce large percentages of GHG emissions compared to regular DOVs at urban signalized intersection networks and freeways but can also increase GHG emissions at situations of increased traffic demand and high congestion due to their higher acceleration rates which can cause irregular driving cycles. Cautious CAVs seem to increase GHG emissions on all road types and traffic conditions and degrade traffic flow conditions when compared to DOVs. Analysis of the findings suggest there are optimal traffic demand levels of aggressive CAVs that can maximize the reduction of GHG emissions relative to DOVs.

Keywords: Connected and automated vehicles, Greenhouse gas emissions, Traffic micro-simulations, Emissions modeling.

[1] * Corresponding author. Tel.: +1 819-743-2562;
E-mail address: saad.roustom@carelton.ca

1. Introduction

The transportation sector is the second-largest source of greenhouse gas (GHG) emissions in Canada, accounting for more than 25% of the total national emissions. GHG emissions from the transport sector have steadily increased with a net growth of 21% between 1990 and 2018 (1). Connected and automated vehicle (CAV) technologies have the potential to increase road capacity and cost savings by reducing congestion and reduce crash risks (2). In addition to these mobility and safety benefits, CAV technologies have the potential to reduce fuel consumption and transport GHG emissions. At a micro-level, these reductions may result from the CAV's ability to travel in platoons with consistent speeds and smaller gaps, lower rates of acceleration/deceleration compared to driver-operated vehicles (DOVs), and the connectivity which should reduce sudden traffic disturbance and allow for more harmonized flow. Research on automation is extremely critical since it will completely alter the transportation system as we know it. With optimistic predictions indicating that AVs will be affordable and common to displace DOVs by 2030 (2), policymakers are interested in quantitatively assessing the mobility, safety, and environmental impacts of AV/CAV impacts. However, the impact of CAVs on the environment and GHG emissions is still an under-researched area. Multiple studies find that implementing CAV technology on roads would reduce GHG emissions and fuel consumption. A recent study integrating Vissim and EPA's MOVES emission model, by Stogios et. al (3), finds that aggressive AVs may reduce GHG emission in an uninterrupted flow network (expressway) by 26% under high traffic demand but do not cause any major changes under low traffic demand. Under interrupted flow conditions, the study found out that aggressive AVs reduce emissions by 3.44% under high traffic demand while causing minimal changes under low traffic demand. A similar study, by Olia et al., shows that connected vehicles (CVs), not to be confused with autonomous vehicles, reduce GHG emissions by 30% at a 50% CV penetration rate (4). The study uses PARAMICS microsimulation software along with CMEM emission model. Another study, by Conlon and Lin, quantifies CO2 emissions for a congested urban network with different AV penetration rates using SUMO traffic micro-simulation software in conjunction to a Newton-based greenhouse gas model (NGM). The study concludes that a maximum reduction in CO2 emissions of 4.08% occurred at a 100% AV penetration rate. A similar study, by Liu et. al, find that AVs are able to reduce emissions by 14% in driving conditions that require frequent hard acceleration and braking events for drivers with aggressive styles (5). However, some studies indicate that the reduction in emissions can be overturned with reduced travel time and cost (6, 7). Brown et al. estimate that AVs have the potential range from more than 90% in fuel savings to 150% increase in energy consumption when compared to DOVs (6). Greenblatt and Shaheen (8) estimate that AVs can reduce GHG emissions by 80% or greater through efficient traffic flow and parking, platooning and automated ridesharing but these emissions can also increase threefold due to other factors such as induced demand, increased number of trips, shifts away from public transport and longer commutes. Another study, by Choi and Bae (9), evaluates the lane changing behavior of AVs impact on CO2 emissions when compared to DOVs. The study finds that CO2 emissions can reduce in case of lane changing from a fast to a slow lane by a range of 0.8% to 7.1% depending on the road level of service. In case of lane changing from a slow to a fast lane, the CO2 emission reduction ranges from 6.3% to 11.8% depending on the road level of service. This study aims to evaluate the impact of CAV technologies on GHG emissions under different driving behaviors and traffic demand levels by micro-simulating specific road sections in Ottawa, Ontario.

This study aims to evaluate the impact of CAV technologies on GHG emissions under different driving behaviors and traffic demand levels by micro-simulating specific large road sections in Ottawa, Ontario. The study incorporates second-by-second traffic microsimulation and emissions modelling to accurately compare vehicular GHG emissions between Driver-Operated Vehicles (DOVs) and CAVs on different road types with uninterrupted traffic flow and interrupted traffic flow at different traffic demand levels.

2. Methodology

The approach followed to assess the impact of CAVs on GHG emissions and fuel consumption involves traffic microsimulation of four different routes within the City of Ottawa. First, base scenarios are simulated with the vehicle fleet made entirely of conventional DOVs calibrated to local driving behavior found in literature (10, 11). Then, different scenarios of all-CAV vehicle fleets are simulated to correspond to a range of possible behavior parameters. The simulation scenarios consider three different CAV behaviors, which are cautious, normal, and aggressive as provided in Vissim (12). Each driving behavior is modelled with a normal peak-hour traffic demand and a 20% increased traffic demand to account for potential traffic growth and expected increase in demand due to increased road capacity with CAV adoption. Each simulation scenario is run with three different seed numbers, thus producing a total of eight simulation scenarios and 24 simulation runs for each of the four routes. The simulations involved two main software packages: PTV Vissim 2021 for traffic microsimulation and the

Environmental Protection Agency's MOtor Vehicle Emission Simulator (MOVES3) for estimating GHG emissions and fuel consumption. The output of Vissim simulations includes second-by-second speed and acceleration values for each vehicle in the simulation along with link volumes. These trajectories are used to create a vehicle operating mode distribution for each vehicle type for use in MOVES3.

Vissim (12) can simulate DOVs and CAVs though it still has limited capabilities in directly simulating some CAV features such as connectivity. Vissim does allow user-defined algorithms incorporating CAV features in the simulations. As mentioned earlier, four major routes (or networks) in Ottawa, Ontario were considered in the microsimulation covering different route characteristics including road classification, road geometry, surrounding land use, traffic control, and traffic volumes, as follows:

- **Highway 417:** urban freeway, heavy peak traffic volumes, uninterrupted flow, short interchange spacings (approximately 7.5 km).
- **Hunt Club Road:** four-lane major arterial, divided, low development density, low volumes of non-motorized vehicle transportation modes, signalized intersections mostly at large spacings (approximately 7.5 km).
- **Baseline Road**: four-lane major arterial, divided, higher development density, higher volumes of non-motorized vehicle transportation modes, signalized intersections mostly at shorter spacings (approximately 8.2 km).
- **Airport Parkway/Bronson Avenue:** major arterial changing from two-lane to divided multilane to undivided four-lane. Development density, signal spacings, and volumes of non-motorized vehicle transportation modes change along the route (approximately 9.1 km).

Each of the road sections are divided into multiple segments with varying road characteristics and uninterrupted lengths to analyze the impact of such variables on GHG emission estimates with different driving behaviors. Because of the full control of access and complete separation between the two directions of Highway 417, only one direction of this road is considered in the simulation. The other three roads do not have full control of access, resulting in interaction between the two directions of traffic at least at every intersection. Therefore, the two directions of traffic on the three arterial roads are considered in the simulations. Each simulated network is divided into segments varying in length and characteristics to evaluate CAV impact on GHG emissions on a micro-level.

2.1 Traffic Data

Morning peak hour traffic volumes were acquired from the City of Ottawa and simulated for each road network. The provided volumes were traffic volume forecasts for 2031 based on the transportation demand modeling and forecasting for the National Capital Region (TRANS Regional Model) (13). Although the City of Ottawa's Transportation Master Plan (13) provides different configurations of the planned road and transportation network in 2031, many of the planned improvements and changes in the network have not been implemented and the plan is currently under revision. Therefore, the current configuration of road network is used in the simulations with the forecasted traffic volumes except for Airport Parkway which is modeled according to the City's preliminary plan for partial widening of the parkway as the current configuration cannot carry the forecasted volume. These traffic volumes are directional volumes with no information on most turning movements. Therefore, Miovision DataLink (14), a traffic data platform used by the City of Ottawa, is used to estimate percentages of the through volume at each intersection that correspond to the different turning movements. Traffic composition percentages are also extracted from studies in Miovision DataLink. Heavy-duty vehicles are considered as single unit short-haul trucks on the arterial networks and as single unit long-haul trucks for the freeway. Traffic signal information provided by the City of Ottawa are used to setup the intersections' signal control using the ring barrier controller module within Vissim. The data included existing timing plans with phasing sequences. The morning peak plans are used for the simulations to correspond to the morning peak volumes used in the simulations.

2.2 Simulation Scenarios

Different compositions of the vehicle fleet are considered in the simulations to assess the impacts of CAVs and their driving mode on GHG emissions. These scenarios include three different settings of CAV driving parameters in addition to DOV driver behavior as a base case for comparison. In addition, the improved mobility and increase of road capacity produced by CAVs will likely induce additional traffic demands in terms of increased traffic volumes (15). Therefore, as explained earlier, the simulation scenarios consider the projected 2031 traffic volumes as the base volumes and increased volumes which are the projected 2031 volumes plus 20% increase. Thus, eight different scenarios are used in the traffic micro-simulations as follows:

- Scenario 1A: Base traffic volumes with 100% DOVs (base scenario).
- Scenario 1B: Increased traffic volumes with 100% DOVs.
- Scenario 2A: Base traffic volumes with 100% cautious CAVs.
- Scenario 2B: Increased traffic volumes with 100% cautious CAVs.
- Scenario 3A: Base traffic volumes with 100% normal CAVs.
- Scenario 3B: Increased traffic volumes with 100% normal CAVs.
- Scenario 4A: Base traffic volumes with 100% aggressive CAVs.
- Scenario 4B: Increased traffic volumes with 100% aggressive CAVs.

2.3 Driving Behavior Parameters

Vissim requires setting values for different driver behavior parameters that reflect how drivers control their vehicles. While Vissim has a set of default parameters, it is recommended to calibrate these parameters based on the local traffic conditions. There are different parameters that can be adjusted for Wiedemann's 99 (suitable for freeway traffic) and Wiedemann's 74 (suitable for urban traffic and merging areas) car following models, respectively, that are used in Vissim (12). Ideally, the parameters for the car following models would be established based on a field data collection process and calibration of these parameters to match observed data. Unfortunately, the COVID-19 pandemic has resulted in considerable changes in the composition of driver population and considerable reduction in peak traffic volumes. Subsequently, it was not possible to collect field data to calibrate the traffic microsimulation under conditions like those considered in the simulation during the course of this study. Therefore, the driving behavior model and parameters are established for regular DOVs and CAVs based on a review of the literature. CAV behavior parameters can be estimated based on the vehicles' response time and the kinematics governing the relationship between speed, acceleration/deceleration, distance, and friction. However, some CAV users may not be comfortable with some of these parameters set near their safe limits. Tesla, for example, uses a seven-point scale that allows drivers to set their comfortable separation distance (16). Accordingly, Vissim provides different default sets of CAV behavior parameters which follow the Wiedemann's 99 Model for all types of networks. As mentioned earlier, three different sets of driving behavior parameters are used to correspond to cautious, normal, and aggressive CAV settings to cover the whole spectrum of possible CAV settings. For DOVs, the parameters used in this study for Wiedemann's 99 were calibrated for local traffic on Highway 417 in a previous study (10). No previous calibration studies are found in the literature for major arterials within the same City Therefore, the parameters for Wiedemann's 74 are based on a calibration performed in Waterloo, Ontario (same province) for an urban arterial (11).

2.4 Traffic Microsimulation Output

The output of the traffic simulation includes detailed vehicle trajectories on a second-by-second basis for each individual vehicle speed, vehicle acceleration, vehicle weight, vehicle type, and link number. This output is processed to create the input for MOVES3 to estimate fuel consumption and GHG emissions. MOVES3 is an emission modeling system that can estimate mobile source emissions at national, county and project levels (17). It can provide accurate emission estimates from cars, trucks, and other mobile sources with a wide range of user-defined characteristics. Users can define vehicle types, pollutants, time periods, geographical areas, vehicle operating characteristics and road types. The model performs a series of calculations to provide estimates of total emissions or emission rates per vehicle. For project-level analysis, which is the scope of this project, MOVES3 provides three approaches for modeling emissions. For the purposes of this study, detailed accurate estimates of GHG emissions are needed, and therefore the OPMODE intensive second-by-second emission modeling approach is used. (18). The approach takes into consideration the variations in the driving behavior for each link. To link Vissim and MOVES3, an external script is developed to convert the trajectory output files from Vissim into an operating mode distribution to be inputted into MOVES3 (19).

2.5 MOVES3 Inputs

MOVES3 requires different sets of inputs to model emissions accurately (20). (Table 1) summarizes the inputs specified for the networks simulated in this project. It should be noted that among the input data is the specification of a county for which a database of vehicle distributions and meteorological characteristics is used in the emissions modeling. However, it only has databases for US counties, and no Canadian regions are available in the database. Therefore, a close US County, Erie County, is selected. It should be noted however that the datasets and distributions relevant to the selected county such as vehicle age distributions and temperature levels can be overwritten. Available data based for local context can be imported to overwrite these default datasets.

Table 1: Summary of MOVES3 Inputs for each Network

Input Parameters	Highway 417	Airport Pkwy./Bronson Ave.	Baseline Rd.	Hunt Club Rd.
Scale	Project scale			
Year	2020			
Month	March			
Time	8:00 AM to 9:00 AM			
Geographic Bound (County)	Erie County, New York			
Road Type	Urban Restricted Access	Urban Restricted Access/Urban Unrestricted Access	Urban Unrestricted Access	Urban Unrestricted Access
Temperature	12.2 °F			
Humidity	67 %			
Pollutants	GHG Emission Equivalent			
Processes	Running Exhaust Emissions			
Input Database Import	Operating Mode Distributions Vehicle Age Distributions Links' Lengths and Densities Fuel Types, Fuel Formulation and Fuel Fraction			

MOVES3 allows the user to define vehicle activity on a second-by-second basis as a function of Vehicle Specific Power (VSP), which represents the tractive power exerted by the vehicle to move itself and its cargo or passengers. It can be computed in terms of vehicle speed, acceleration, and mass as follows:

$$VSP = \frac{Av_t + Bv_t^2 + Cv_t^3 + mv_t\left(a_t + gsin(\theta_t)\right)}{m} \tag{1}$$

Where
VSP = Vehicle Specific Power (kw/Mg); v_t = speed at time t (m/s); a_t = acceleration at time t (m/s2); m = vehicle mass (Mg); A = rolling resistance term (kW – s/m); B = rotational resistance term (kW – s2/m2); C = aerodynamic drag (kW – s3/m3); and Resistance terms were taken from EPA's Database (21–23).

There are 23 different operating modes defined for the running-exhaust process. These operating modes are categorized based on VSP, speed, and acceleration. As mentioned earlier, a MATLAB script is developed to convert the trajectory output files from each simulation run to operating mode distributions for each vehicle type on every link in the simulation model based on the operating mode bin values. The vehicle age distribution assumed in this study is based on Ontario's vehicle registration data in the latest Canadian Vehicle Survey, which was conducted for the calendar year 2009 (24). The data in the survey include vehicle registration numbers by age up to 20 years old for both light-duty vehicles and heavy vehicles. MOVES3 requires proportion distributions by age up to 30 years old. Therefore, the proportions for the first 19 years are calculated directly based on these registration numbers while the proportions for years 20-30 are extrapolated based on the last 10 years values (10-19 years old) similar to the approach followed in previous studies (5). No local data is available for fuel type or fuel mix. The default datasets for fuel supply, fuel usage fraction, and fuel formulation for Erie County, New York are used in the emissions estimation. This selection assumes that the fuel formulation is very similar regionally (5).

2.6 MOVES3 Outputs

MOVES3 calculates pollutant emissions and fuel energy consumption quantity per each link inputted in the model. All results from outputs are stored in a database that can be managed through Structured Query Language (SQL). Once the database is extracted, an external script is developed to sum up each pollutant emission for every link in the network simulated.

3. Results and Discussion

This section summarizes the results of traffic performance, measured in terms of relative delay per segment. Relative delay is defined as the total delay divided by the total travel time of all vehicles in the segment. A smaller percentage of relative delay indicates smoother traffic flow conditions while higher relative delay percentages indicate worse traffic flow conditions. Total GHG emissions, measured in terms of the total CO2 Eq (kg/h), are also presented. Because a network may not be able to accommodate all the assigned traffic, some vehicles may not get into the data collection section during the simulation time. Therefore, CO2 Eq results are also presented per vehicle-kilometer traveled (VKT). Unless stated otherwise, comparison of CAV impacts on traffic performance and GHG emissions in this discussion are all relative to the DOV scenario on the same network and traffic volume. All figures in this section demonstrate results for normal peak hour traffic volumes.

3.1 Highway 417 Network

On Highway 417, aggressive CAVs have the potential to slightly reduce total GHG emissions by 0.12% over the entire network length. Aggressive CAVs also perform better in terms of traffic condition with lower delay values compared to all other driving behaviors. The aggressive CAVs perform much better in terms of GHG emissions at segments with longer interchange spacings (segments 1 to 8) since there are less disturbance of the uniform flow achieved by the CAVs as shown in (Figure 1). This can be noticed with increased delay values at short interchange lengths where on-ramp vehicles disturb the flow. Cautious and normal CAVs did not perform well in terms of GHG emissions as they increase GHG emissions (kg/h) by 7.3% and 15.8%, respectively. Both cautious and normal CAVs had longer delay values as seen in (Figure 1) indicating higher congestion levels and GHG emissions. When assessing GHG emissions per VKT demonstrated with (Figure 2), aggressive CAVs reduced GHG emissions (kg/VKT) by 8.47% on the Highway 417 network. The results show higher VKT values for aggressive CAVs indicating better traffic flow conditions that allowed the network's demand to be accommodated. Cautious and normal CAVs, on the other hand, seem to have lower VKT values indicating poorer traffic flow conditions and higher GHG emissions.

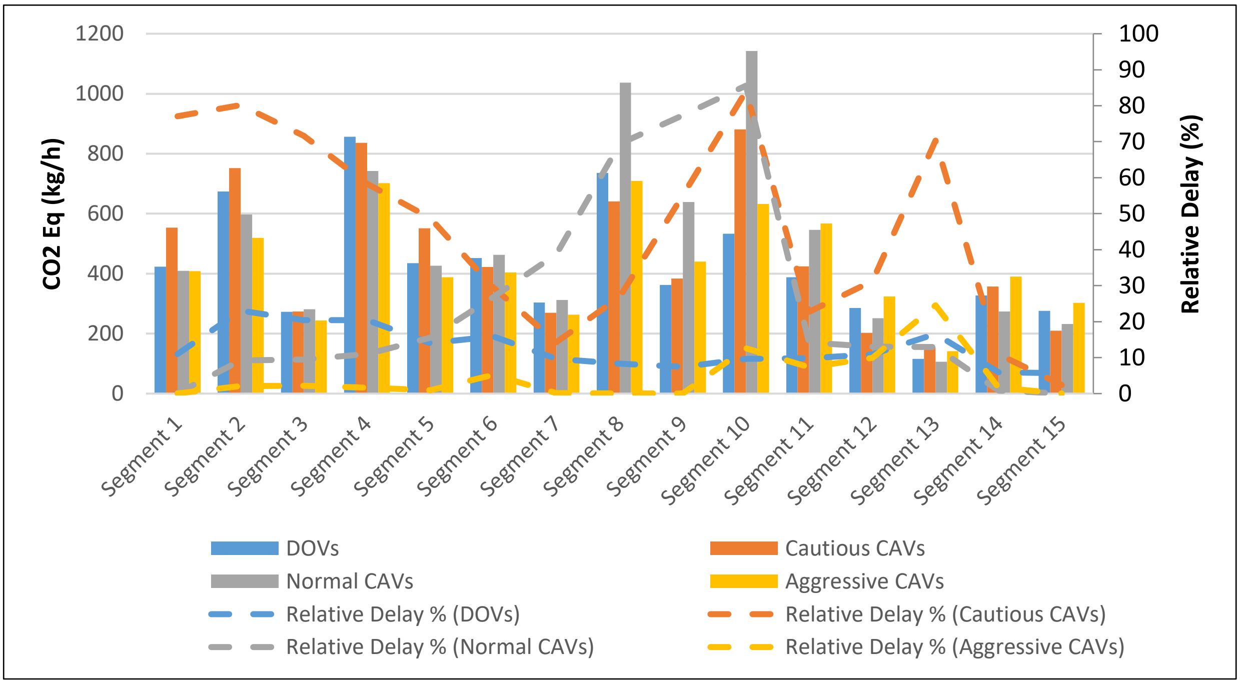


Figure 1: Average total hourly GHG emissions and relative delay for Highway 417 segments with normal traffic demand.

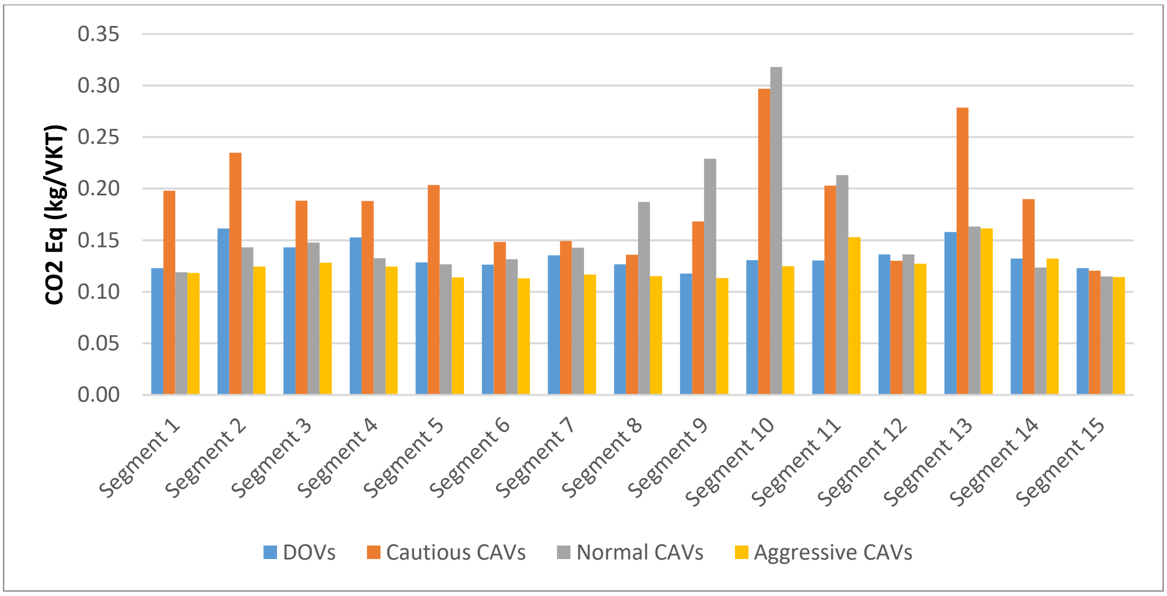
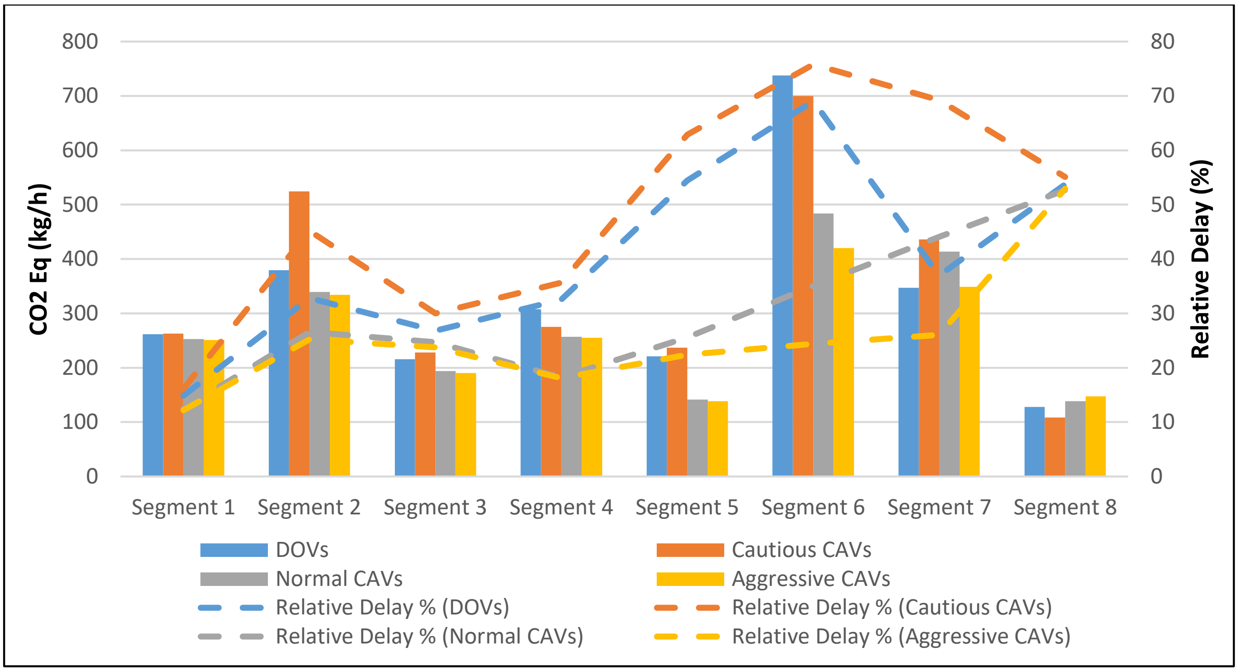


Figure 2: Average GHG emissions per VKT for Highway 417's segments with normal traffic demand.

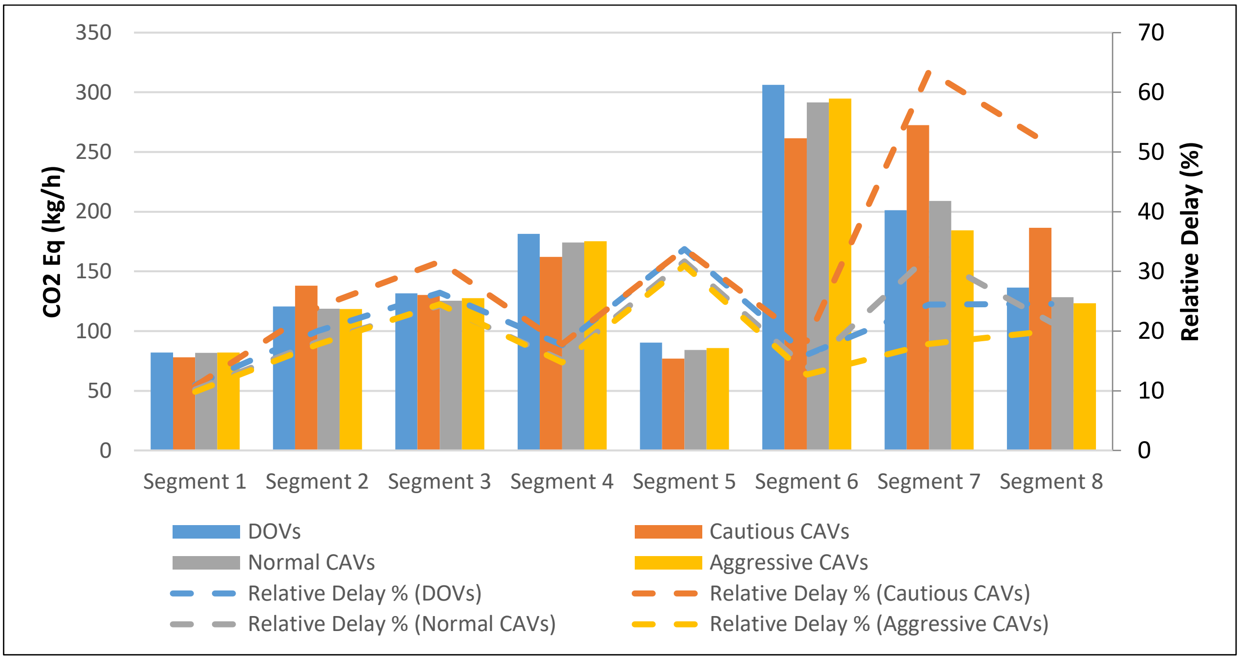
When traffic demand is increased by 20% above the peak hour volumes, CAVs in general do not perform well in terms of both traffic flow conditions and GHG emissions. Although cautious CAVs do reduce total hourly GHG emissions (kg/h) over the whole network by 3.37%, GHG emissions per VKT (kg/VKT) increases by 26.7% indicating a deteriorated network traffic condition. This is evident from the low VKT values that cautious CAVs have as less vehicles are able to get into the network due to the congestions. Normal and aggressive CAVs, on the other hand, increase total GHG emissions (kg/h) by 21.2% and 35.2%, respectively. With increased on-ramp volumes interrupting the mainline flow, CAVs are not able to travel as smoothly with lower acceleration and deceleration rates as with the lower traffic demand preventing them from decreasing their GHG emissions and aggravating traffic conditions. When assessing the GHG emissions per VKT, cautious, normal and aggressive CAVs all increase GHG emissions (kg/VKT) by 26.7%, 31.5% and 33.9%, respectively.

3.2 Baseline Road Network

Similar to Highway 417, aggressive CAVs perform the best on Baseline Road in terms of both traffic flow conditions and GHG emissions compared to all other driving behaviors as shown in (Figure 3). Aggressive CAVs are able to reduce total hourly GHG emissions (kg/h) by 19.7% and 4.7% in the eastbound and westbound direction, respectively, normal CAVs are also able to reduce total hourly GHG emissions by 14.5% and 2.9 % in the eastbound and westbound direction, respectively. The higher reduction in total emissions in the westbound direction can be attributed to the higher traffic demand in the westbound direction in which the CAV driving behavior can adequately improve the traffic flow conditions. Generally, aggressive and normal CAVs perform better at segments with longer uninterrupted lengths and less side traffic penetration volumes. Cautious CAVs, on the other hand, increased totally hourly GHG emissions (kg/h) by 6.7% and 4.5% on the eastbound and westbound direction, respectively as demonstrated in (Figure 3). In terms of results per VKT, the results are not significantly different than the total hourly GHG emissions due to the close values of VKT but it is important to highlight that aggressive CAVs reduce GHG emissions per VKT (kg/VKT) by 25.5% in the eastbound direction when compared to DOVs while cautious CAVs increases GHG emissions per VKT (kg/VKT) by 23.5% in the westbound direction when compared to DOVs indicating poorer traffic flow conditions with cautious CAVs. This demonstrates that aggressive CAVs improve the traffic flow conditions allowing for higher VKT values and lower GHG emissions.



(a) Eastbound direction.



(b) Westbound direction.

Figure 3: Average total hourly GHG emissions and relative delay for the Baseline Road Network's segments with normal traffic demand.

When the simulated traffic volume is increased by 20%, aggressive CAVs still outperform DOVs in terms of GHG emissions and relative delay, with a 0.2% reduction in total hourly GHG emissions (kg/h) for the eastbound direction and a 7.9% reduction in the westbound direction. It is important to note that by increasing the traffic volumes, the percent reduction in the eastbound direction decreases while it increases in the westbound direction. This is due to the higher volumes travelling in the eastbound direction compared to the westbound direction. The results demonstrate that at low volume levels, aggressive CAVs can reduce total GHG emissions and congestion. However, increasing volumes to levels that cause congestion will limit their ability to reduce GHG emissions significantly and might even increase GHG emissions compared to DOVs. The network experiences frequent interruptions in traffic flow due to the frequent closed-spaced signalized intersections. These interruptions can prevent harmonized flow and uniform driving behavior since CAVs are consistently trying to maintain uniform gaps increasing the GHG emissions in return. This is shown in segments 7 and 8 in the eastbound direction where heavy traffic exists as aggressive CAVs increase total hourly GHG emissions (kg/h) in both segments by 50.7%

and 22.7%, respectively. Normal CAVs increase total hourly GHG emissions by 12.85% in the eastbound while reducing emissions by 4.9% in the westbound direction. Again, the increase in total GHG emissions in the eastbound direction is attributed to the higher volumes traveling in that direction compared to the westbound direction. Assessing the GHG emissions per VKT at increased traffic volumes, normal and aggressive CAVs reduce GHG emissions (kg/VKT) by 3.8% and 20.3 % in the eastbound direction, respectively, and by 12.2 % and 15.3% in the westbound direction. This higher percentage reduction in terms of GHG emissions per VKT compared to total hourly GHG emissions indicates better traffic flow conditions with the aggressive driving behavior scenario as the values of VKT increase.

3.3 Airport Parkway/Bronson Avenue Network

The trends of change in GHG emissions and relative delay on the Airport Parkway/Bronson Avenue network are similar to those already observed on the Baseline Road network. Aggressive CAVs reduce total hourly GHG emissions (kg/h) by 9.3% and 6.5% in the northbound and southbound directions, respectively, while the corresponding reductions with normal CAVs are 8.2% and 6.6%. Cautious CAVs also reduce total GHG emissions (kg/h) in the southbound direction by 2.8% but they increase the emissions in the northbound direction by 8.7%. The trends also show that the relative delay values are relatively much smaller on the south segments, which have low development density and low traffic interruptions, compared to the north segments with high development density and frequent interruptions. Taking into consideration the VKT, aggressive CAVs reduce GHG emissions per VKT (kg/VKT) by 9.3% and 8.4% in the northbound and southbound directions, respectively. The percentage reduction of GHG emissions due to aggressive CAVs on the north segments is higher than the corresponding reduction on the south segments despite the higher frequency of traffic interruptions on the north segments. This can be explained by the relatively low traffic volumes where the benefits of CAVs are more pronounced. However, the south segments with low volumes and low traffic interruptions may have lowered the relative benefits of aggressive CAVs. This suggests that there is an optimal level of traffic demand where the benefits of CAVs will be maximum. The low traffic volumes on this network prompted higher reduction in GHG emissions due to CAVs on the same network with increased traffic demand. Aggressive CAVs reduce total hourly GHG emissions (kg/h) by 21.58% and 7.9% in the northbound and southbound directions, respectively. Similarly, normal CAVs reduce GHG emissions (kg/h) by 18.1% and 7.8% in the northbound and southbound directions, respectively. Cautious CAVs increase total GHG emissions (kg/h) by 3.0% in the northbound direction but decrease it in the southbound direction by 7.4%.

3.4 Hunt Club Road Network

Similar trends for the changes in GHG emissions with CAVs are observed on this network. Because of the high traffic volume on the eastbound of Hunt Club Road, the total GHG emissions (kg/h) increase with cautious, normal, and aggressive CAVs by 6.23%, 6.0% and 4.3%, respectively. On the other hand, emissions per VKT actually decrease with normal and aggressive CAVs indicating that these two settings accommodate more volumes of the hourly traffic demand. On the other hand, all types of CAVs achieve little to no improvements in traffic flow conditions for most of the segments in the westbound direction. The one exception to this is the last segment where cautious CAV delay percentages significantly increase due to higher traffic demand presence on that segment.

4. Conclusions

This study employed traffic microsimulation and emissions modeling to evaluate the environmental impact of CAV technologies on GHG emissions specifically, under various driving behaviors, road types and traffic demand levels in Ottawa, Ontario. The study focuses on investigating CAV implications on GHG emissions for both interrupted urban signalized road sections and uninterrupted freeway traffic flow conditions. The networks are simulated with forecasted peak hour traffic volumes. Additionally, to accommodate the expected induced future traffic demand of CAVs, a 20% increase to peak hour traffic demand is also considered. The study's results shows that aggressive CAVs perform the best in reducing GHG emissions compared to all other driving behaviors on both urban signalized intersection networks and freeways under most peak hour traffic volumes. This is due to their ability to improve traffic conditions as segments that experience higher reduction in delay values compared to DOVs and more cautious CAVs. As a result, aggressive CAVs show larger reductions in GHG emissions per VKT in most situations. Aggressive CAVs have the greatest performance in terms of reducing GHG emissions per VKT along segments with longer uninterrupted lengths and less side penetrating volumes. However, with increased volumes, aggressive CAVs also show that they can increase GHG emissions if high congestion levels are caused by the increase in traffic demand due their higher acceleration and deceleration rates causing irregular driving behavior. On the other hand, cautious CAVs performed the worst increasing GHG emissions on both urban signalized intersection networks and freeways and degrading traffic conditions. Future research should focus on modeling emissions with improved CAV traffic operation strategies to increase efficiency and managing travel demand levels to maximize the efficacy of aggressive CAVs at reducing GHG emissions.

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