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

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Introduction

- Transportation sector is the second-largest source of greenhouse gas (GHG) emissions in Canada.
- Accounts for more than 25% of the total national emissions.
- In driver-operated (DOV) vehicle traffic environment, traffic flow efficiency and capacity are dependent on human driving behaviour.
- Connected and automated vehicle (CAV) technologies have the potential to:
  - increase road capacity and cost savings
  - reduce congestion and reduce crash risks
  - reduce fuel consumption and transport GHG emissions

Problem Definition & Study Objectives

- Optimistic predictions indicate that automated vehicles (AVs) will be affordable and common to displace DOVs by 2030.
- Policymakers are interested in quantitatively assessing the mobility, safety, and environmental impacts of CAV.
- This study investigates how different CAV driving behaviours can impact vehicular GHG emission and how different traffic flow characteristics can influence change in emission levels.
- Developing regression models as means of understanding the relationship between traffic parameters and emissions.

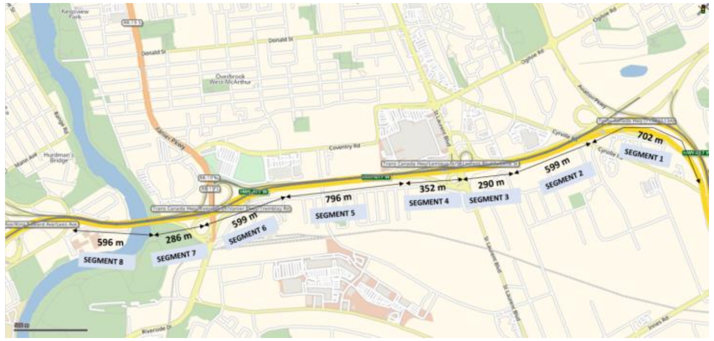
Literature Review

- CAVs are anticipated to reduce GHG emissions and improve traffic conditions
- Studies might exaggerate the benefits of CAVs when excluding:
  - variability of traffic demand,
  - network complexity, and
  - impact of road characteristics.
- Literature studies do not incorporate such variables within large microstimulated networks

Methods

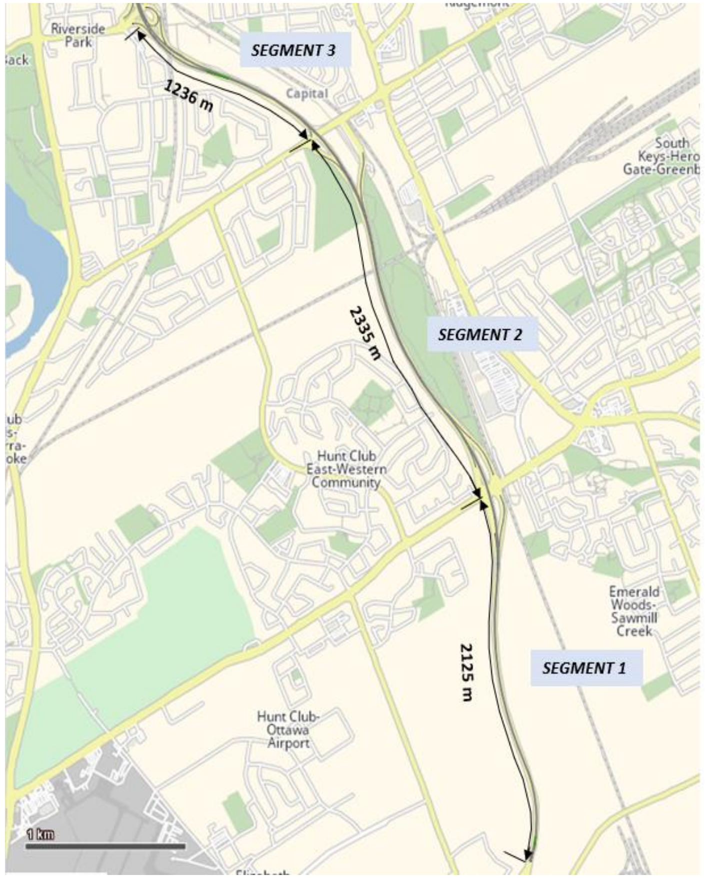
- Evaluate the impact of CAV technologies on GHG emissions under different driving behaviors and traffic demand levels by micro-simulating specific road sections in Ottawa, Ontario
- Microsimulation of four different routes within the City:
  - Highway 417
  - Hunt Club Rd
  - Baseline Rd
  - Airport Pkwy/Bronson Ave
- Four different driving behaviors:
  - Driver-operated vehicles (Base condition)
  - All Cautious CAVs
  - All Normal CAVs
  - All Aggressive CAVs
- Normal peak-hour demand and a 20% increased traffic demand

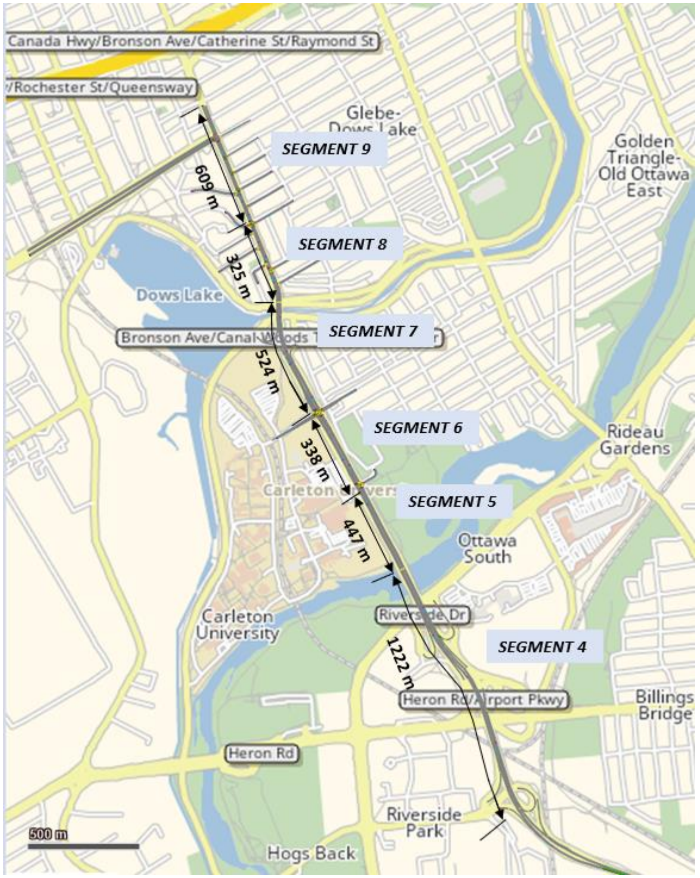
Highway 417



- East of the Aviation Parkway Interchange to west of the Bronson Avenue Interchange (Westbound)
- Approximately 7.5 km , 15 segments

Airport Parkway/Bronson Avenue



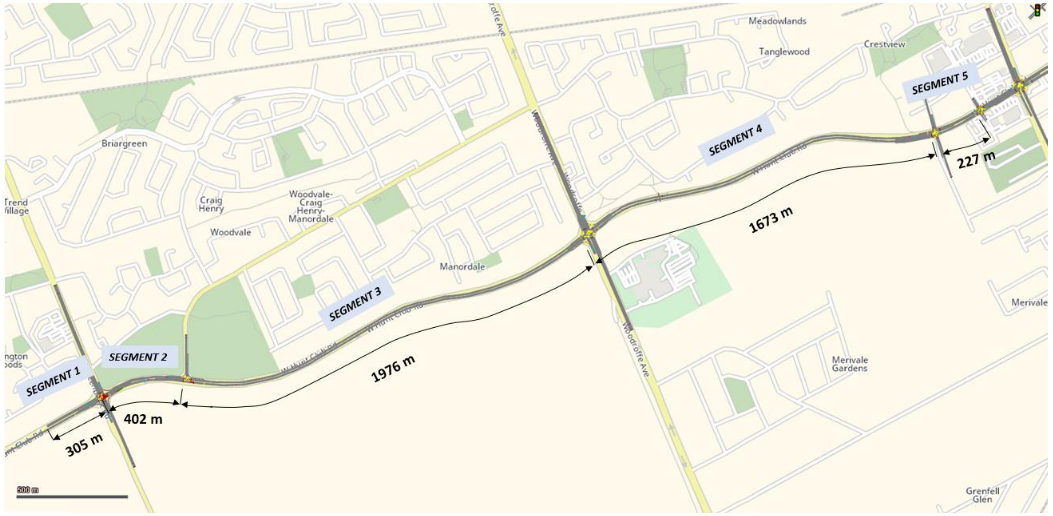


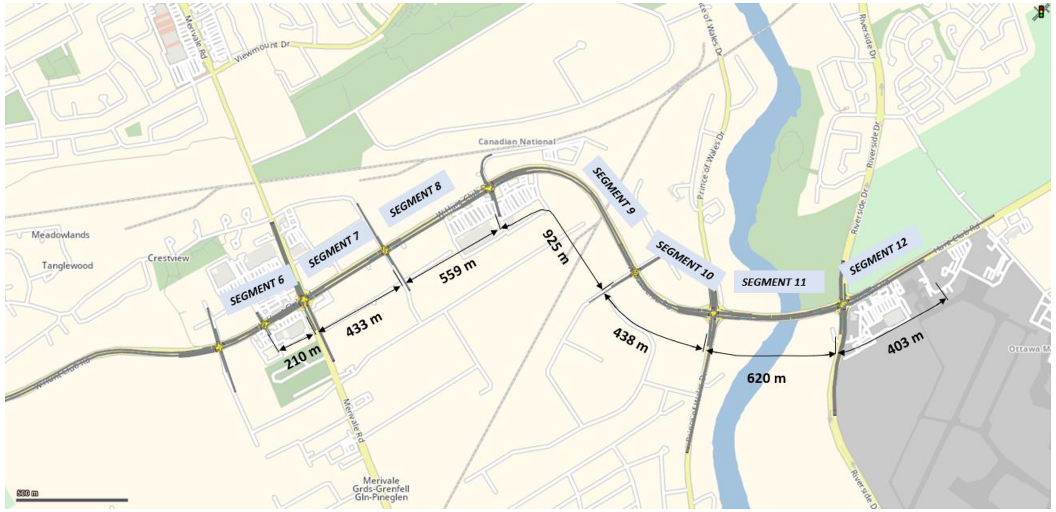
- Ottawa MacDonald-Cartier International Airport to the intersection of Bronson Avenue with Carling Road, 9 segments
- Low development density and 80 km/h speed limit at Airport Pkwy
- Six at-grade signalized and a number of unsignalized intersections on Bronson Ave

Baseline Road

Greenbank Road to the intersection with Prince of Wales Drive, 8.15 km in each direction, 8 segments

Hunt Club Rd





Greenbank Road to the intersection with Riverside Drive,12 intersections,7.5 km in each direction.

Traffic Data

- Morning peak hour traffic volumes forecasts for 2031
- Current configuration of road network is used in the simulations with the forecasted traffic volumes
- Miovision DataLink is used to estimate percentages of the through and turning volume at each intersection
- Traffic signal information provided by the City of Ottawa

Driving Behaviours

- The driving behavior model and parameters are established for regular DOVs and CAVs based on a review of the literature.
- The parameters used in this study for Wiedemann's 99 were calibrated for local traffic on Highway 417 (*Pakzadnia*)
- The parameters for Wiedemann's 74 are based on a calibration performed in Waterloo, Ontario (same province) for an urban arterial (*Lu*)

TABLE 1: Car Following Parameters for the Wiedemann's 99 Model and the Wiedemann's 74 Model

	Parameters (units)	DOVs		CAVs		
		Default	Calibrated	Cautious	Normal	Aggressive
Wiedemann's 99	CC0 (m)	1.50	1.00	1.50	1.50	1.00
	CC1 (s)	0.90	0.75	1.50	0.90	0.60
	CC2 (m)	4.00	3.00	0.00	0.00	0.00
	CC3 (s)	-8.00	-8.00	-10.0	-8.0	-6.00
	CC4 (m/s)	-0.35	-0.30	-0.10	-0.10	-0.10
	CC5 (m/s)	0.35	0.30	0.10	0.10	0.10
	CC6 (1/(m.s))	11.44	11.44	0.00	0.00	0.00
	CC7 (m/s^2)	0.25	0.25	0.10	0.10	0.10
	CC8 (m/s^2)	3.50	3.50	3.00	3.50	4.00
	CC9 (m/s^2)	1.50	1.50	1.20	1.50	2.00
Wiedemann's 74	**Parameters (units)**			**Default**		**Calibrated**
	Average standstill distance (m)			2.00		2.00
	Additive part of safety distance (m)			2.00		1.993
	Multiplicative part of safety distance (m)			3.00		3.00

Parameters	Unit	Description
CC0	m	Standstill distance between two vehicles.
CC1	s	Gap time between vehicles.
CC2	m	The following distance: additional distance beyond the desired safety distance.
CC3	s	The threshold for the following vehicle to reach the safety distance to the slower leading vehicle at the start of the deceleration process in seconds.
CC4	m/s	Negative speed difference: The lower threshold for the following vehicle relative speed compared to the leading vehicle.
CC5	m/s	Positive speed difference: The upper threshold for the following vehicle relative speed compared to the leading vehicle.
CC6	1/(m • s)	Distance dependency of oscillation: The influence of distance on speed oscillation during the following process.
CC7	m/s^2	Oscillation Acceleration during the following process.
CC8	m/s^2	Standstill Acceleration
CC9	m/s^2	Acceleration at 80 km/h

Traffic Microsimulation Output

- The output of the traffic simulation includes detailed vehicle trajectories on a second-by-second basis including:
  - speed (km/h)
  - Acceleration (m/s^2)
  - vehicle weight (metric tonnes)
  - vehicle type
  - link number

Emissions Modelling

- MOVES3 is an emission modeling system that can estimate mobile source emissions at national, county and project levels
- OPMODE intensive second-by-second emission modeling

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			

Operating Mode Distributions (VSP)

- Allows the user to define vehicle activity on a second-by-second basis as a function of Vehicle Specific Power (VSP):

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

where
VSP = Vehicle Specific Power (kw/Mg);
vt = speed at time t (m/s);
at = acceleration at time t (m/s^2);
m = vehicle mass (Mg);
A = rolling resistance term (kW – s/m);
B = rotational resistance term (kW – s^2/m^2);

- There are 23 different operating modes defined for the running-exhaust process. These operating modes are categorized based on VSP, speed, and acceleration.

Operating Mode Distributions

opModeID	Description	Speed (mi/h)	VSP (kW/Mg)	Acceleration (mi/h-s)
0	Deceleration/Braking	N/A	N/A	$a_t \leq -2.0\ OR$ $(a_t < -1.0\ \&$ $a_{t-1} < -1.0\ \&$ $a_{t-2} < -1.0)$
1	Idle	$-1.0 \leq v_t < 1.0$		N/A
11	Coast	$1.0 \leq v_t < 25.0$	$VSP < 0$	
12	Cruise/Acceleration		$0 \leq VSP < 3$	
13			$3 \leq VSP < 6$	
14			$6 \leq VSP < 9$	
15			$9 \leq VSP < 12$	
16			$VSP < 12$	
21	Coast	$25.0 \leq v_t < 50.0$	$VSP < 0$	
22	Cruise/Acceleration		$0 \leq VSP < 3$	
23			$3 \leq VSP < 6$	
24			$6 \leq VSP < 9$	
25			$9 \leq VSP < 12$	
27			$12 \leq VSP < 18$	
28			$18 \leq VSP < 24$	
29			$24 \leq VSP < 30$	
30			$VSP \geq 30$	
33	Coast/ Cruise/ Acceleration	$v_t \geq 50.0$	$VSP < 6$	
35	Cruise/Acceleration		$6 \leq VSP < 12$	
37			$12 \leq VSP < 18$	
38			$8 \leq VSP < 24$	
39			$24 \leq VSP < 30$	
40			$VSP \geq 30$	

MOVES3 Outputs

- SQL Database
  - Pollutant emissions' quantity per each link (CO2 Eq kg)
  - Vehicle Kilometers Travelled (VKT)

Road Networks Results Summary

Road Network	HWY417	Baseline Road	Airport Parkway/ Bronson Avenue	Hunt Club Road
2031 AM Peak Hour Volume	• Aggressive CAVs significantly improve traffic conditions. • Aggressive CAVs reduce emissions per VKT by 8.5%.	• Aggressive CAVs perform the best in terms of both traffic flow and emissions. • Aggressive and normal CAVs perform better at segments with longer uninterrupted lengths and less side traffic penetration volumes.	• Aggressive CAVs reduce per VKT emissions. • Relative delay values are relatively much smaller segments which have low development density and low traffic interruptions.	• Normal and aggressive CAVs reduce emissions per VKT.
120% of 2031 AM Peak Hour Volume	• CAVs generally do not perform well in terms of traffic flow and GHG emissions. • CAVs increase per VKT emissions.	• Reduction in emissions and congestion increases with the increase of traffic volume up to a specific volume.	• Reduction in emissions and congestion increases with the increase of traffic volume up to a specific volume.	• Normal and aggressive CAVs seem to increase emissions per VKT due to their higher acceleration and deceleration threshold rates.

Regression Models

- The dependent variable is the equivalent CO_2 emissions per VKT (kg/VKT) for all models
- A linear regression model is created for each road classification for segments and intersections.
- Variables considered before elimination:
  - average speed (km/h),
  - density (veh/km),
  - average relative delay (%),
  - number of lanes,
  - segment length (km), and
  - dummy variables for the three driving behaviours

Table 5-11: GHG emission segment-based model summary per road classification

Road Classification	R	R^2	Adjusted R^2	SSE
Freeway	0.819	0.671	0.668	0.034
Arterial	0.771	0.594	0.591	0.112
Rural	0.851	0.725	0.717	0.008
Arterial with short-spaced Intersections	0.828	0.685	0.678	0.046

Table 5-15: GHG emission intersections-based model summary per road classification

Road Classification	R	R^2	Adjusted R^2	SSE
Arterial	0.686	0.471	0.470	0.306
Short-spaced Intersections	0.883	0.779	0.778	0.086

Summary

- Exploring effects of variability in traffic demand levels and road characteristics in more extensive scale networks for different CAV behaviours.
- Helping vehicle manufacturers better understand how to program optimal CAV driving behaviour to produce fewer emissions
- Aiding roadway designers in providing an understanding of how some roadway characteristics may be unwarranted with the expected deployment of CAV technology.
- The regression models provided in this study can be used to compare GHG emissions on much larger scale models to have a broader understanding of the impact of CAVs
- Generally, CAVs can have a solid potential to reduce GHG emissions, especially with optimal traffic demand levels and road characteristics.

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Paired sample t-tests

Driving behaviours with statistically different mean values for GHG emissions per VKT within each road classification

Freeway				
Driving Behaviour	Base	Cautious	Normal	Aggressive
Base	x			
Cautious	Yes	x		
Normal	Yes	No	x	
Aggressive	No	Yes	No	x

Arterial				
Driving Behaviour	Base	Cautious	Normal	Aggressive
Base	x			
Cautious	Yes	x		
Normal	Yes	Yes	x	
Aggressive	Yes	Yes	Yes	x

Rural				
Driving Behaviour	Base	Cautious	Normal	Aggressive
Base	x			
Cautious	Yes	x		
Normal	Yes	Yes	x	
Aggressive	Yes	No	Yes	x

Arterial with Short-Spaced Intersection				
Driving Behaviour	Base	Cautious	Normal	Aggressive
Base	x			
Cautious	Yes	x		
Normal	Yes	Yes	x	
Aggressive	Yes	Yes	Yes	x

Data Processing

- Results from Vissim (link-by-link) processed into results per segment.
- Links making up main intersections are better separated from the main segment between two major intersections.

Network	**Highway 417**	**Airport Pkwy/Bronson Ave.**	**Baseline Rd**	**Hunt Club Rd**
Number of total links	94	279	655	376
Number of intersection links	N/A	29	117	88
Number of segments	12	18	16	24
Number of runs	24	24	24	24

Regression Models Continued

- The significance level set for removing an independent variable is 10%.
- Independent variables with Variance Inflation Factor (VIF)>5 were examined and removed if their inclusion did not improve the model fit.

Table 5-11: GHG emission segment-based model summary per road classification

Road Classification	R	R^2	Adjusted R^2	SSE
Freeway	0.819	0.671	0.668	0.034
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Table 5-15: GHG emission intersections-based model summary per road classification

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Arterial	0.686	0.471	0.470	0.306
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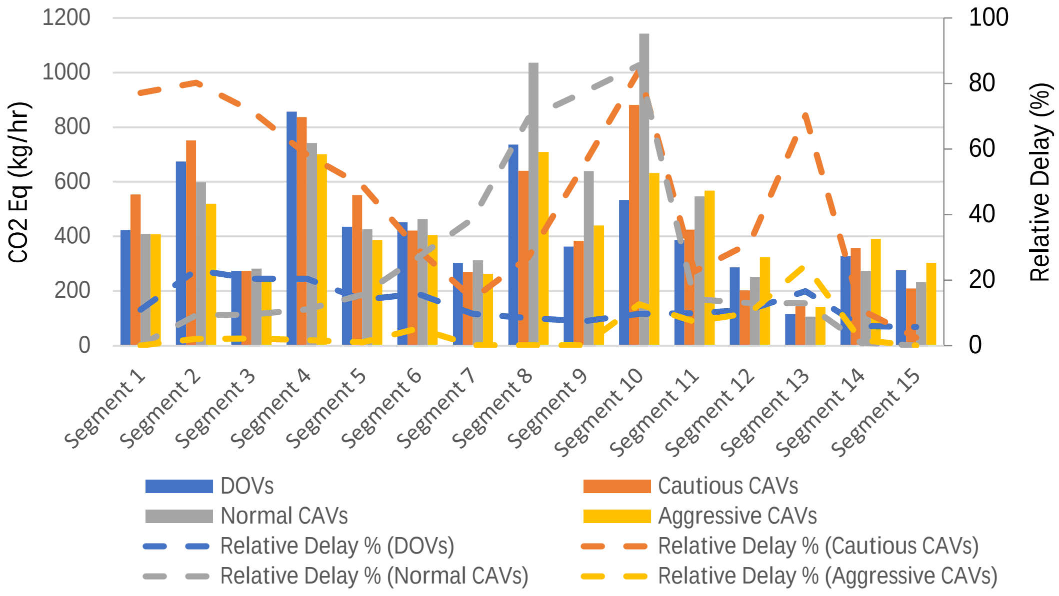
Highway 417 Results

- Aggressive CAVs reduce GHG emissions per VKT by 8.5%
- Cautious and Normal CAVs increase GHG emissions



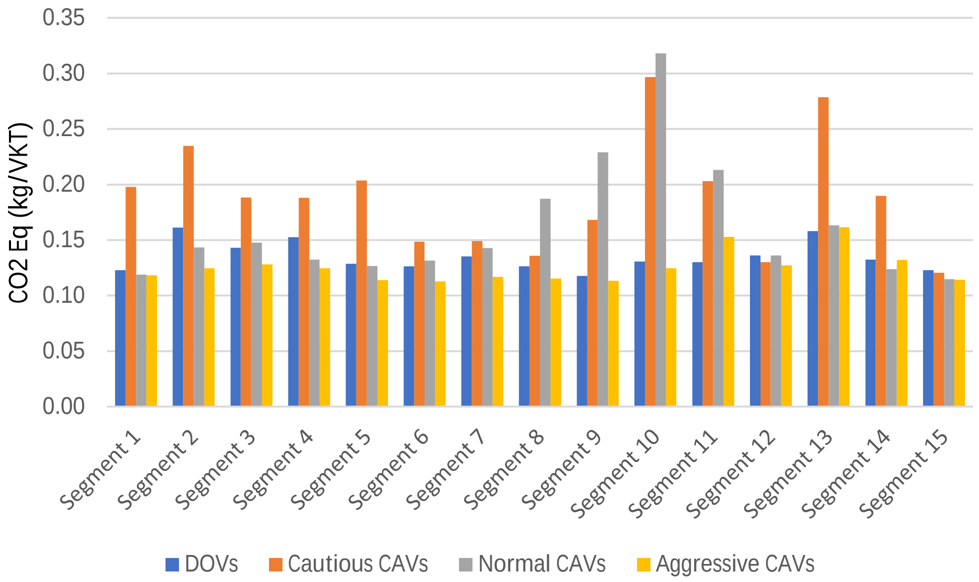


Table 5-3: ANOVA Table for GHG emissions per VKT based on different road classification

		Sum of Squares	Mean Square	*F*	Sig.
CO2 Eq. per VKT (kg/veh.km) * Road Classification	Between Groups (Combined)	14.168	4.723	255.198	2.45×10^{-137}
	Within Groups	32.349	0.019		
	Total	46.518			

Table 5-2: GHG Emission per VKT output mean comparison for different road classification

Road Classification	Mean	N	Std. Deviation
Freeway	0.169	360	0.059
Arterial	0.338	960	0.175
Rural	0.111	192	0.015
Short-spaced Intersections	0.192	240	0.081
Total	0.259	1752	0.163

Table 5-4: Paired Samples t-tests for GHG emissions per VKT for different road classification group pairs

	Pair	Paired Differences: Mean	Paired Differences: Std. Deviation	Paired Differences: Std. Error Mean	*t*	Sig. (2-tailed)
1	Freeway Vs Arterial	-0.025	0.108	0.006	-4.378	1.572×10^{-05}
2	Freeway vs Rural	0.057	0.052	0.004	15.372	2.733×10^{-35}
3	Freeway vs Arterial with short-spaced intersections	-0.020	0.103	0.007	-2.992	3.059×10^{-03}
4	Arteria vs Rural	0.111	0.107	0.008	14.321	4.027×10^{-32}
5	Arterial vs Arterial with short-spaced intersections	0.020	0.123	0.008	2.504	1.296×10^{-02}
6	Rural vs Arterial with short-spaced intersections	-0.090	0.090	0.006	-13.964	4.839×10^{-31}

Table 5-12: GHG emission segment-based model coefficients per road classification

Road Classification	Variables	Unstandardized Coefficients		t	Sig. (p-value)	Collinearity Statistics	
		B	Std. Error			Tolerance	VIF
Freeway	(Constant)	0.1813	0.0149	12.14	1.27×10^{-28}		
	Average speed (km/h)	-0.0010	0.0001	-7.71	1.30×10^{-13}	0.21	4.70
	Density (veh/km)	0.0002	4.42×10^{-5}	4.90	1.44×10^{-6}	0.21	4.75
	No of Lanes	0.0110	0.0031	3.51	4.98×10^{-4}	0.92	1.09
Arterial	(Constant)	-0.2698	0.0415	-6.51	1.23×10^{-10}		
	Average speed (km/h)	0.0064	0.0005	14.05	6.99×10^{-41}	0.26	3.86
	Density (veh/km)	0.0026	0.0001	17.97	2.26×10^{-62}	0.35	2.85
	Relative delay (%)	0.0035	0.0004	8.73	1.12×10^{-17}	0.19	5.24
	No of Lanes	0.0657	0.0118	5.58	3.09×10^{-8}	0.86	1.16
	Segment Length (m)	-0.0691	7.33×10^{-6}	-9.43	2.95×10^{-20}	0.80	1.25
	Base	0.0195	0.0094	2.07	3.83×10^{-02}	0.62	1.62
	Cautious	0.0418	0.0105	3.99	7.02×10^{-05}	0.64	1.56
	Aggressive	-0.0652	0.0142	-4.60	4.90×10^{-06}	0.72	1.38
Rural	(Constant)	0.1257	0.0029	43.26	5.20×10^{-99}		
	Density (veh/km)	-0.0007	0.0001	-8.48	6.94×10^{-15}	0.63	1.58
	Segment Length (km)	-0.0045	1.14×10^{-6}	-3.94	1.16×10^{-4}	0.95	1.05
	Base	0.0040	0.0014	2.81	5.42×10^{-03}	0.84	1.19
	Relative delay (%)	0.2401	0.0123	19.45	1.09×10^{-46}	0.53	1.87
	Cautious	-0.0053	0.0016	-3.39	8.63×10^{-04}	0.69	1.44
Arterial with short-spaced Intersections	(Constant)	0.1774	0.0315	5.64	4.93×10^{-8}		
	Average speed (km/h)	-0.0018	0.0006	-3.08	2.29×10^{-3}	0.20	5.08
	Density (veh/km)	0.0009	0.0001	6.36	1.02×10^{-9}	0.21	4.85
	Cautious	0.0222	0.0084	2.65	8.53×10^{-3}	0.68	1.47
	Base	0.0175	0.0076	2.29	2.29×10^{-2}	0.81	1.23

Table 5-13: GHG Emission per VKT output mean comparison for intersection road classifications

Road Classification	Mean	N	Std. Deviation
Arterial Intersections	0.536	4920	0.421
Short-spaced Intersections	0.312	696	0.182
Total	0.508	5616	0.406

Table 5-14: ANOVA Table for GHG emissions per VKT based on different intersection road classifications

		Sum of Squares	Mean Square	*F*	Sig.
CO2 Eq. per VKT (kg/veh.km) * Intersection Road Classification	Between Groups (Combined)	30.498	30.498	191.677	6.89×10^{-43}
	Within Groups	893.252	0.159		
	Total	923.750			

Table 5-15: GHG emission intersections-based model summary per road classification

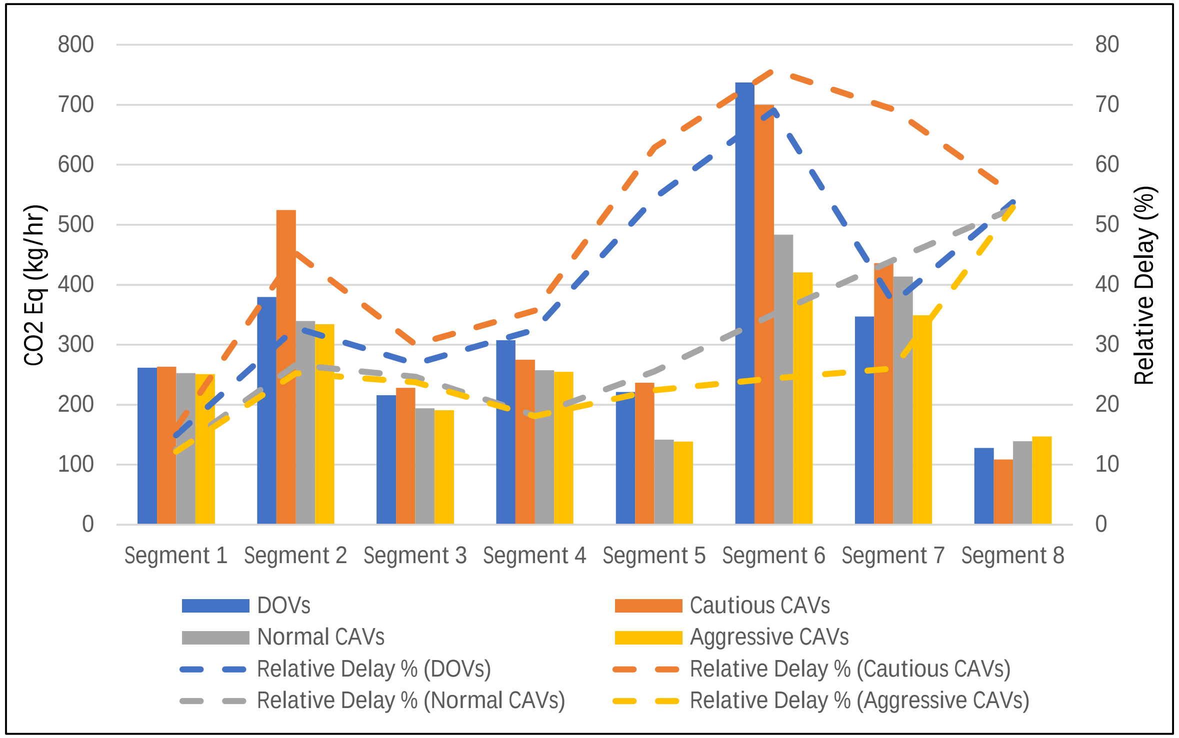
Road Classification	R	R^2	Adjusted R^2	SSE
Arterial	0.686	0.471	0.470	0.306
Short-spaced Intersections	0.883	0.779	0.778	0.086

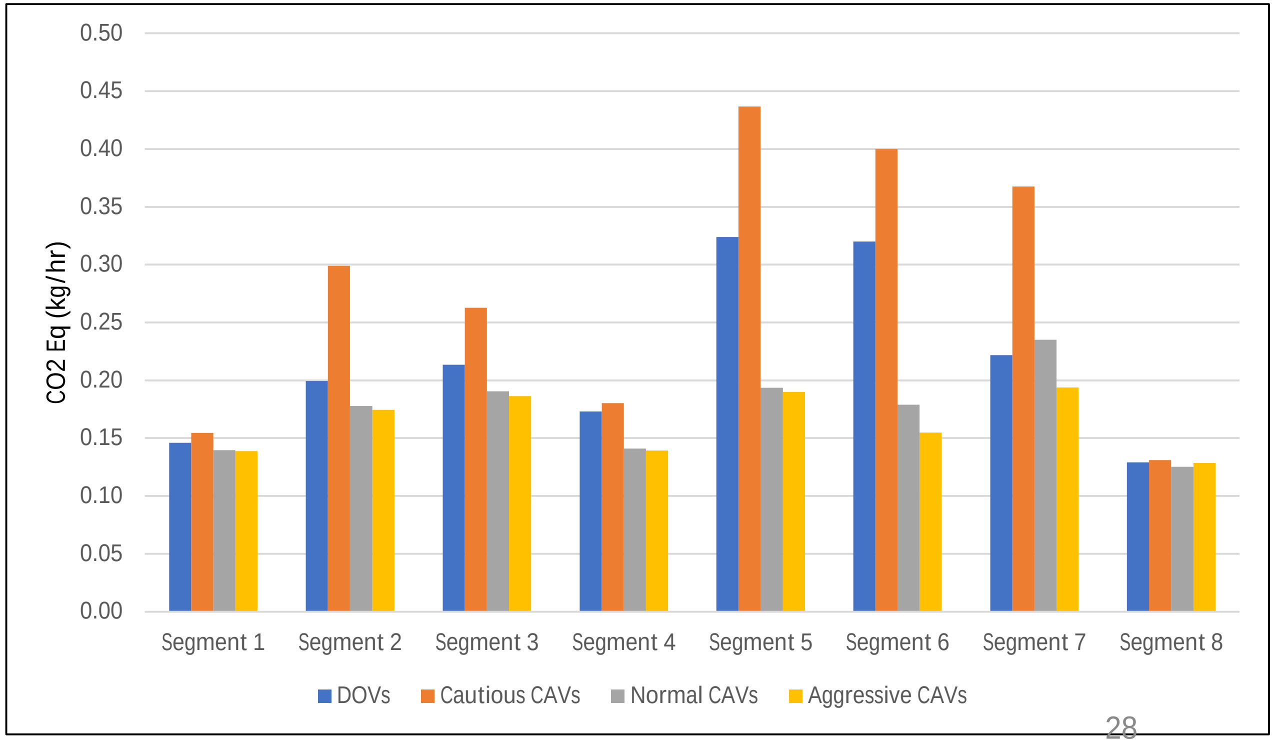
Table 5-16: GHG emission intersections-based model coefficients per road classification

Road Classification	Variables	Unstandardized Coefficients		t	Sig. (p-value)	Collinearity Statistics	
		B	Std. Error			Tolerance	VIF
Arterial	(Constant)	-0.1485	0.0329	-4.52	6.34×10^{-6}		
	Average speed (km/h)	0.0052	0.0005	9.67	6.40×10^{-22}	0.19	5.32
	Density (veh/km)	-0.0002	0.0001	-1.66	9.75×10^{-2}	0.40	2.49
	Relative delay (%)	1.0659	0.0305	34.98	1.56×10^{-239}	0.20	5.06
	Segment Length (m)	-0.0022	0.0002	-11.70	3.29×10^{-31}	0.91	1.10
	Base	-0.0314	0.0107	-2.92	3.51×10^{-3}	0.88	1.13
	Cautious	0.0376	0.0108	3.50	4.76×10^{-4}	0.88	1.14
	RightTurn	0.0709	0.0126	5.62	2.03×10^{-8}	0.62	1.60
	LeftTurn	0.3023	0.0131	23.01	2.33×10^{-111}	0.53	1.87
Short-spaced Intersections	(Constant)	0.4445	0.0171	25.99	2.65×10^{-104}		
	Average speed (km/h)	-0.0051	0.0003	-16.44	1.72×10^{-51}	0.40	2.50
	Density (veh/km)	0.0008	0.0001	9.90	1.08×10^{-21}	0.31	3.23
	No of Lanes	-0.0183	0.0052	-3.54	4.25×10^{-4}	0.43	2.31
	Base	-0.0456	0.0076	-5.98	3.65×10^{-9}	0.98	1.03
	RightTurn	-0.0161	0.0089	-1.81	7.05×10^{-2}	0.63	1.58
	LeftTurn	0.1589	0.0111	14.37	3.67×10^{-41}	0.47	2.11

Baseline Road Results

- Aggressive CAVs reduce GHG emissions per VKT by 25.5% and 4.7% in the eastbound direction and westbound direction, respectively.
- Cautious CAVs, on the other hand, increased totally hourly GHG emissions by 6.7% and 4.5% on the eastbound and westbound direction, respectively.





Airport Pkwy/ Bronson Ave Results

- Aggressive CAVs reduce GHG emissions per VKT by 9.3% and 8.4% in the northbound and southbound directions, respectively.
- Optimal level of traffic demand where the benefits of CAVs will be maximum.

Hunt Club Results

- Emissions per VKT decrease with normal and aggressive CAVs
- All types of CAVs achieve little to no improvements in traffic flow conditions for most of the segments in the westbound direction

Simulation Scenarios

- **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.