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AV-based Intelligent Transportation System Solution for Canadian Cities

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Executive Summary

This study evaluates the impact of Autonomous Electric Vehicles (AEVs) on urban traffic flow for the Canadian cities of Winnipeg and Ottawa. AEVs are governed by software algorithms and, when equipped with Vehicle-to-Vehicle (V2V) communication, can adjust their driving behaviour to optimize traffic flow. This research utilizes mesoscopic simulations to investigate how AEV design parameters, within an Intelligent Transportation System (ITS), can influence traffic performance under varying penetration rates and different traffic demand levels. The results indicate that AEVs with aggressive driving behaviour offer the most significant reduction in travel times particularly at higher penetration rates. The results also show that AEV performance can vary with traffic characteristics and freeway usage. Finally, the ITS can have the additional environmental impact of reducing GHG emissions from internal combustion engine (ICE) vehicles in mixed fleets with AEVs due to improved traffic flow.

Keywords: Intelligent Transportation System for EVs, Autonomous xEV, V2V Communication, Modelling and Simulation, Environmental impact

1 Introduction

Autonomous Electric Vehicles (AEVs) have the potential to significantly improve urban traffic flow through the optimization of their driving behaviour. One of the distinctions between conventional driver-operated vehicles (DOVs) with internal combustion engines (ICE) and AEVs is in their driving behaviour. Whereas DOV operation is influenced by human behaviour, AVs are governed by design software algorithms, presenting a unique opportunity to optimize their driving behaviour. Additionally, AEVs can be equipped with Vehicle-to-Vehicle (V2V) communication technology which allows autonomous vehicles to be aware of each other and their traffic operations. By leveraging these design parameters along with the V2V technology, fleets of AEVs can be used as part of an Intelligent Transportation System (ITS) designed to improve urban traffic flow and reduce congestion.

This study evaluates how adjusting the driving behaviour parameters of AEVs can optimize city traffic flow. The impact of 100% AEV penetration and of mixed DOV/AEV fleet scenarios is analyzed using mesoscale traffic simulations for two Canadian cities: Ottawa and Winnipeg. Additionally, this study investigates whether a minimum threshold of AEV penetration is required for measurable benefits in traffic flow and which driving behaviour produces the most optimal results in terms of improving traffic flow. Beyond optimizing traffic flow, this study also explores if improved traffic conditions in mixed fleets can lead to reductions in emissions from ICE vehicles that remain in the fleet.

2 Literature Review

Autonomous Vehicles (AVs) 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 behaviour and the adoption rate of AVs required to achieve such benefits. The realization of these benefits is also dependent on other variables such as traffic demand and road types. Despite the abundance of microsimulation-based studies [1] – [9] on AV impact on traffic performance, understanding their effects on traffic performance in city-wide networks remains limited particularly where AV driving behaviour is optimized.

2.1 AV Impact on Road Capacity

Several studies have concluded that AVs have the potential to increase road capacity, especially at higher penetration rates. For example, a microsimulation study [1] revealed a quasi-linear increase in capacity with higher AV penetration rates. The road capacity increases by 16% at full AV penetration using a single predefined AV driving behaviour [1]. Another study [2] similarly revealed that AVs can increase highway capacity when AVs are a significant proportion of the vehicle fleet.

2.2 Driving Behaviour of AVs as a Key Parameter

The driving behaviour of AVs is a significant parameter that influences the impact on traffic performance as multiple studies confirmed [3]-[5]. Several studies highlighted the varying impacts between aggressive and conservative driving behaviours of AVs.

One study demonstrated that AVs have the potential to improve single-lane road service levels by reducing speed deviations and delays [3], particularly when operating with high levels of connectivity and automation.

A German study explored both aggressive and conservative AV driving behaviours on freeway segments revealing that AVs with conservative driving behaviour reduce the capacity of freeways while AVs with aggressive driving behaviour increase the capacity of freeways by 30% and reduce traffic delays significantly [4].

A sensitivity analysis study [5] modelled AVs using the microsimulation tool Vissim to investigate the impact of AV driving parameters on a 5 km section of a freeway and on a 1.1 km part of an urban arterial road. The results of the study indicated that AVs with aggressive driving behaviour, i.e. driving with smaller headway distances, could decrease delay and increase average speed while AVs with larger headway distances, on the other hand, had the opposite effect. The study also highlighted that the benefits of AVs were more pronounced in freeways (uninterrupted traffic) when compared to urban arterials (interrupted traffic). However, this study was constrained to relatively short corridors [5].

2.3 AVs in Mixed Fleet Environments

Studies also suggest that the penetration rate of AVs within a mixed fleet of conventional vehicles plays a crucial role in determining their effect on traffic performance.

A study utilized the microsimulation tool Aimsun to evaluate the impact of AVs in a mixed fleet environment with conventional driver-operated vehicles in an urban environment. The study reveals that AVs can improve traffic conditions when AV penetration rates exceed 60%, though it assumed a single predefined AV driving behaviour [6].

A similar study compared the impact of automation and connectivity on traffic flow for a ring network consisting of 119 km of roads and 117 intersections with no traffic signals. The study analyzed three different driving models including human-driven, automated, and connected and automated vehicles (DOVs, AVs and CAVs). The results of this study indicate that AVs perform the worst in terms of traffic performance due to the conservative driving behaviour they were given, leading to lower throughput and more saturated networks. CAVs, on the other hand, perform the best in terms of traffic performance due to their improved road capacity [7].

2.4 AVs Impact with Variable Traffic Demand

Traffic demand is another variable that may affect the performance of AVs. The benefits of AVs are not uniform across all traffic conditions as one study suggested [8]. AVs can enhance traffic performance under high-volume conditions, but they may have adverse effects at lower traffic volumes [8]. A similar study [9] modelled AVs on a segment of the autobahn in Germany using Vissim. The study also concluded that the benefits of AVs are more pronounced in congested networks, reducing average travel time by 9% compared to the scenario of conventional vehicles [9].

2.5 Gaps in the literature

While these microsimulation studies provide valuable insights into the impact of AVs, they tend to analyze isolated variables such as AV driving behaviour, AV penetration rate, traffic demand or road type. No study has comprehensively modelled all these factors in a city-wide meso-simulation where AV driving behaviour is adjusted to optimize traffic performance.

3 Method

The method employed in this study focuses on investigating the impact of adjusting AEV behaviour on traffic performance under different AEV penetration rates and traffic demand levels for the road network of full cities. This involved simulating various scenarios encompassing a wide spectrum of driving behaviours using the Dynameq traffic simulation software. The simulations account for three AEV driving behaviours—Cautious, Normal, and Aggressive—alongside conventional DOVs.

In addition to traffic performance analysis, this study also employs emissions correlations models [10] to estimate GHG emissions output from ICE vehicles. This enables an assessment of how AEV-induced traffic improvements in the network affect emissions produced by the remaining ICE vehicle fleet.

3.1 Areas of Study

This study considers two Canadian cities with varying urban densities: Ottawa and Winnipeg. Ottawa is a relatively large city with more complex traffic dynamics and offers a comparative perspective against Winnipeg, a smaller city with simpler traffic dynamics. These cities provide different urban traffic environments for assessing the effectiveness of AEV-driven ITS solutions.

It is important to note that for the city of Winnipeg an older model from around 1990 is used. While the city of Winnipeg has undergone significant changes since then, this model is used to provide a conceptual understanding of potential traffic impacts in a smaller Canadian city rather than a current up-to-date representation of Winnipeg itself.

3.2 Model Parameters and Scenarios

Mesoscopic traffic simulations were conducted to model traffic improvements brought by adjusting AEV driving behaviours. For each city, a total of 39 simulations were conducted in the Dynameq traffic simulation software. The simulations included a base DOV vehicle fleet, homogenous AEV fleets and mixed DOV/AEV fleets with 25%, 50%, and 75% AEVs, all under low, medium and high traffic demands. The simulations of AEVs included three different driving behaviours: Cautious, Normal and Aggressive.

The specifications for the three AEV driving behaviours can be found in Table 1. AEVs can use V2V communication with each other but not with DOVs. Therefore, AEVs are modelled with both the Connected Response Time parameter and a regular Response Time parameter. The Connected Response Time defines the minimum following distance between AEVs. However, if an AEV is following a non-AEV, the minimum following distance reverts to the Regular Response Time.

Table 1: Response times for different driving behaviours used in the simulations.

Driving behaviour	Regular Response Time (s)	Connected Response Time (s)
DOV	1.00	N/A
Cautious AEV	1.50	1.50
Normal AEV	1.00	0.90
Aggressive AEV	1.00	0.60

The simulation runs for both cities are conducted for the period of 6:30 AM to 11:00 AM. Vehicles are added to the road 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 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.

4 Results

4.1 Traffic Performance

The traffic performance of the different scenarios is analyzed to understand how AEVs can optimize traffic flow in different urban traffic settings. Tables 2 through 7 present total Vehicle Hours Travelled (VHT) and Vehicle Kilometers Travelled (VKT) metrics for the morning commute period for Winnipeg and Ottawa, respectively at 80%, 100% and 120% network demand (i.e. traffic volume) levels.

There are consistent patterns in the VHT results for both cities. Cautious AEVs consistently result in higher VHT in comparison to a DOV fleet across all penetration levels. As the penetration rate of AEVs increase, the network experiences an increase in VHT, indicating an increase in congestion. Normal AEVs generally result in slightly reduced VHT values when compared to DOV scenarios, especially at higher penetration rates (75% and 100%). Aggressive AEVs perform the best at reducing VHT values across all traffic demand levels for both cities. For Normal and Aggressive AEVs, the effects are more pronounced at higher AEV penetration rates. This is because the benefit of their lower connected response times, which effectively increases road capacity and thus reduces congestion, only materializes if enough AEVs are on the road. Moreover, the influence of AEV driving behaviour appears to be pronounced under higher traffic demand, as illustrated in Tables 2 through 7. Under such scenarios, traffic flow deteriorates significantly with Cautious AEVs, while both Normal and Aggressive AEVs contribute to lower VHT values and improved traffic flow.

In comparing the two cities, the benefits of Normal and Aggressive AEVs can be noticed at slightly lower penetration rates for Winnipeg, while Ottawa needed intermediate penetration rates of AEVs before seeing traffic flow improvements. The results are influenced by each city's urban environment and network structure, and the fact that the main freeway in Ottawa runs through the city, while Winnipeg has a peripheral freeway.

Table 2: VHT and VKT values for different AEV driving behaviours for the city of Winnipeg at 80% network demand

80% Network Demand		Total VHT (veh-hr)		Total VKT (veh-km)	
DOV		**8,914**	Compared to DOV	**382,105**	Compared to DOV
Cautious	**25%**	9,113	2.23%	383,991	0.49%
	50%	9,371	5.13%	386,285	1.09%
	75%	9,691	8.72%	389,034	1.81%
	100%	10,055	12.80%	391,321	2.41%
Normal	**25%**	8,915	0.01%	382,016	-0.02%
	50%	8,855	-0.66%	381,663	-0.12%
	75%	8,820	-1.05%	381,009	-0.29%
	100%	8,729	-2.07%	380,168	-0.51%
Aggressive	**25%**	8,853	-0.68%	381,706	-0.10%
	50%	8,777	-1.54%	380,338	-0.46%
	75%	8,608	-3.43%	379,486	-0.69%
	100%	8,393	-5.85%	378,008	-1.07%

Table 3: VHT and VKT values for different AEV driving behaviours for the city of Ottawa at 80% network demand

80% Network Demand		Total VHT (veh-hr)		Total VKT (veh-km)	
DOV		**69,668**	Compared to DOV	**4,150,203**	Compared to DOV
Cautious	**25%**	69,709	0.06%	4,147,527	-0.06%
	50%	69,918	0.36%	4,146,070	-0.10%
	75%	75,055	7.73%	4,123,966	-0.63%
	100%	72,889	4.62%	4,143,008	-0.17%
Normal	**25%**	69,928	0.37%	4,149,861	-0.01%
	50%	69,135	-0.77%	4,151,092	0.02%
	75%	69,194	-0.68%	4,160,039	0.24%
	100%	69,403	-0.38%	4,163,891	0.33%
Aggressive	**25%**	70,468	1.15%	4,150,858	0.02%
	50%	69,395	-0.39%	4,153,227	0.07%
	75%	68,263	-2.02%	4,174,170	0.58%
	100%	68,236	-2.06%	4,176,793	0.64%

Table 4: VHT and VKT values for different AEV driving behaviours for the city of Winnipeg at 100% network demand

100% Network Demand		Total VHT (veh-hr)		Total VKT (veh-km)	
DOV		**12,080**	Compared to DOV	**480,755**	Compared to DOV
Cautious	**25%**	12,423	2.84%	483,612	0.59%
	50%	12,930	7.04%	487,116	1.32%
	75%	13,636	12.88%	491,422	2.22%
	100%	14,409	19.28%	499,436	3.89%
Normal	**25%**	12,059	-0.17%	480,088	-0.14%
	50%	11,963	-0.97%	480,024	-0.15%
	75%	11,874	-1.71%	479,326	-0.30%
	100%	11,693	-3.20%	477,409	-0.70%
Aggressive	**25%**	11,918	-1.34%	480,113	-0.13%
	50%	11,745	-2.77%	478,516	-0.47%
	75%	11,372	-5.86%	474,077	-1.39%
	100%	10,862	-10.08%	469,496	-2.34%

Table 5: VHT and VKT values for different AEV driving behaviours for the city of Ottawa at 100% network demand

100% Network Demand		Total VHT (veh-hr)		Total VKT (veh-km)	
DOV		**90,898**	Compared to DOV	**5,144,242**	Compared to DOV
Cautious	**25%**	92,142	1.37%	5,146,190	0.04%
	50%	92,033	1.25%	5,147,381	0.06%
	75%	106,594	17.27%	5,179,205	0.68%
	100%	100,710	10.79%	5,174,475	0.59%
Normal	**25%**	91,659	0.84%	5,147,312	0.06%
	50%	89,862	-1.14%	5,147,312	0.06%
	75%	89,515	-1.52%	5,152,672	0.16%
	100%	90,438	-0.51%	5,159,261	0.29%
Aggressive	**25%**	91,237	0.37%	5,144,856	0.01%
	50%	90,270	-0.69%	5,144,231	0.00%
	75%	86,136	-5.24%	5,186,557	0.82%
	100%	85,708	-5.71%	5,198,242	1.05%

Table 6: VHT and VKT values for different AEV driving behaviours for the city of Winnipeg at 120% network demand

120% Network Demand		Total VHT (veh-hr)		Total VKT (veh-km)	
DOV		**16,152**	Compared to DOV	**585,888**	Compared to DOV
Cautious	**25%**	16,939	4.87%	587,913	0.35%
	50%	17,937	11.05%	598,367	2.13%
	75%	19,000	17.63%	610,472	4.20%
	100%	20,409	26.36%	627,358	7.08%
Normal	**25%**	15,614	-3.33%	581,237	-0.79%
	50%	15,756	-2.45%	582,254	-0.62%
	75%	16,022	-0.80%	583,491	-0.41%
	100%	15,286	-5.36%	580,530	-0.91%
Aggressive	**25%**	15,775	-2.33%	582,491	-0.58%
	50%	15,312	-5.20%	579,452	-1.10%
	75%	14,618	-9.50%	574,376	-1.96%
	100%	13,673	-15.35%	566,777	-3.26%

Table 7: VHT and VKT values for different AEV driving behaviours for the city of Ottawa at 120% network demand

120% Network Demand		Total VHT (veh-hr)		Total VKT (veh-km)	
DOV		**124,106**	Compared to DOV	**6,239,120**	Compared to DOV
Cautious	**25%**	127,898	3.06%	6,297,190	0.93%
	50%	124,533	0.34%	6,208,612	-0.49%
	75%	161,888	30.44%	6,473,660	3.76%
	100%	141,981	14.40%	6,390,020	2.42%
Normal	**25%**	126,195	1.68%	6,321,414	1.32%
	50%	120,909	-2.58%	6,207,841	-0.50%
	75%	121,003	-2.50%	6,228,569	-0.17%
	100%	119,311	-3.86%	6,214,828	-0.39%
Aggressive	**25%**	126,355	1.81%	6,316,375	1.24%
	50%	120,123	-3.21%	6,214,421	-0.40%
	75%	109,037	-12.14%	6,204,804	-0.55%
	100%	107,691	-13.23%	6,225,518	-0.22%

Furthermore, in the Ottawa model, there is little noticeable difference in results when AEV penetration rates increase from 75% to 100% for Normal and Aggressive AEVs as shown, for example, in Table 7. The VHT and VKT results are nearly identical, with the results for the 75% penetration rates being only slightly lower. In contrast, for the Winnipeg model, the 100% AEV penetration rate is significantly more effective than the 75% rate for both Normal and Aggressive AEV, as seen in Table 6. The performance gap between these two penetration levels is much more pronounced in the Winnipeg model, with 100% penetration leading to a more substantial improvement in traffic flow.

The VKT results exhibit different trends between the two cities. For Winnipeg, the VKT results follow a pattern similar to the VHT results, though at a lower scale. In contrast for Ottawa, The VKT results seem more irregular across driving behaviour scenarios, with fluctuations that appear more random and less correlated with penetration levels. The variation in VKT among different driving behaviour scenarios of the same traffic demand is due to some vehicles taking different routes influenced by the varying traffic performance (i.e. level of congestion) associated with each driving behaviour.

Figure 1 below illustrates the average travel time per vehicle across the three traffic demand levels for both cities, offering additional insights into the traffic flow conditions under different AEV scenarios. In general, the average travel time increases with network demand, indicating higher levels of congestion for the scenarios with 120% network demand.

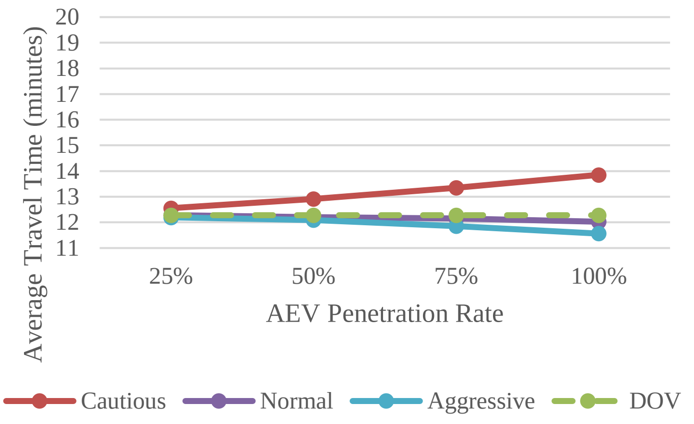
One notable distinction is the behaviour of Cautious AEVs when comparing both cities. In the Ottawa model, at a 75% AEV penetration rate, traffic performance is at its worst, with the highest average travel times, as shown in Figure 1. However, this is not the case in the Winnipeg model, where the worst traffic conditions are observed at a 100% penetration rate of Cautious AEVs. This contrast highlights how AEV behaviour and penetration levels affect each city's traffic performance differently, depending on the urban environment and network structure.

In general, the impact of AEVs on travel characteristics in both cities follows the same overall trend and shows that an AEV-based ITS system can improve traffic performance if an aggressive driving style is employed. However, traffic performance of mixed DOV/AEV fleets is highly complex and is not yet sufficiently understood. For instance, it’s not clear why the Ottawa scenario of 75% Cautious AEVs consistently has more much higher VHT than fleets having 100% Cautious AEVs while this not the case in the Winnipeg model. Additional research will be needed for this. However, the following factors could be part of the explanation why the Ottawa model behaves differently than Winnipeg:

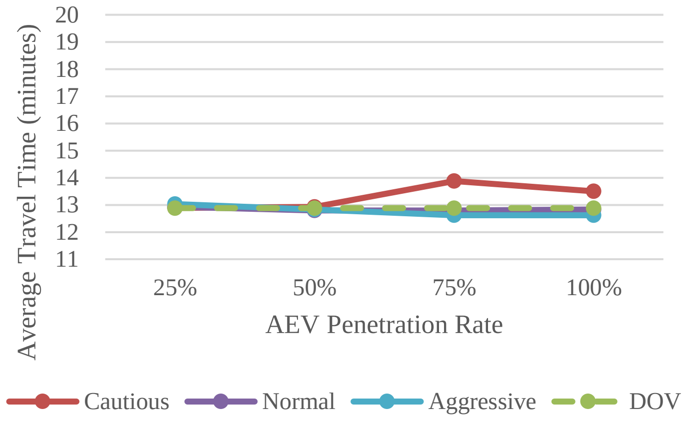
- **Network Characteristics and Traffic Demand:** Ottawa's traffic demand is significantly higher than Winnipeg's, which intensifies congestion in ways that are not as prominent in lower-demand environments like Winnipeg.

- **Non-Linearity in Mixed Traffic:** Mixed traffic environments, where AEVs and traditional vehicles coexist, can behave in non-linear ways, particularly when the penetration rate reaches intermediate levels.

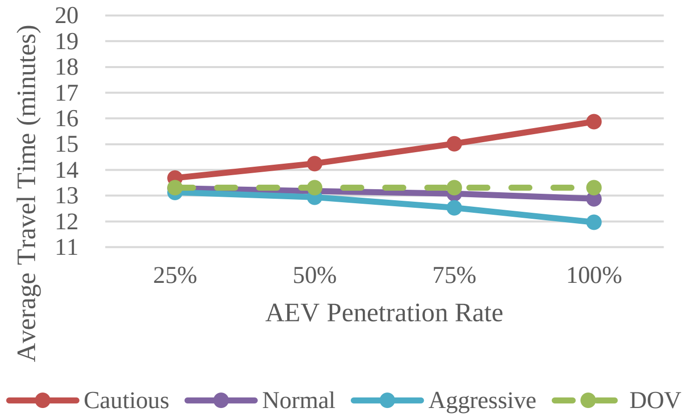
- **Highway System Configuration**: In Ottawa, the fact that the main freeway runs through the city introduces more interactions between through traffic and local traffic, creating different traffic dynamics than for a city with only arterial roads.



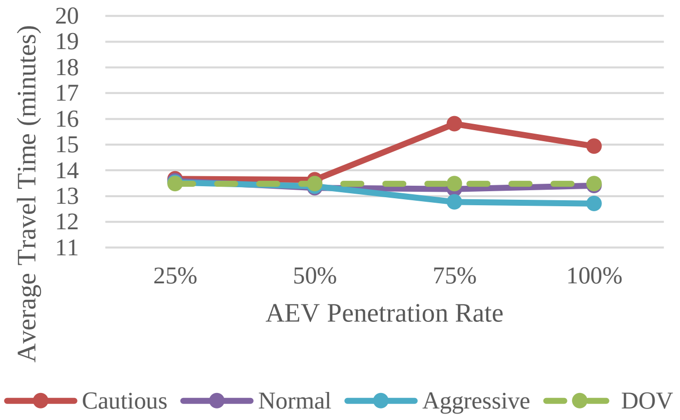
(a) Winnipeg at 80% network demand



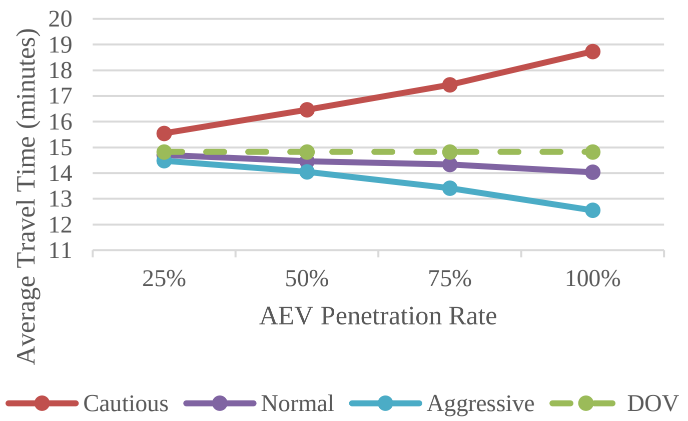
(b) Ottawa at 80% network demand



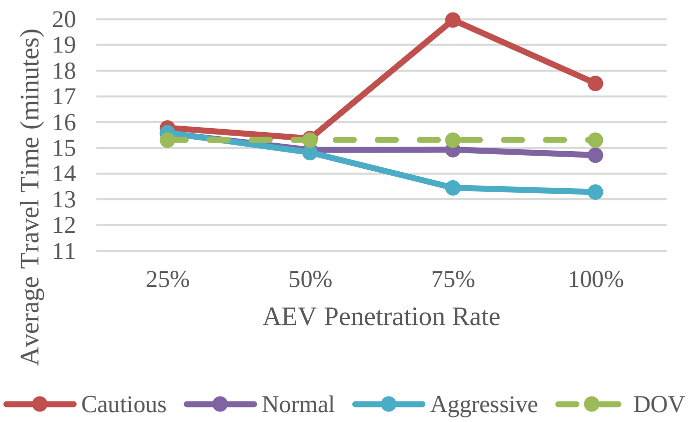
(c) Winnipeg at 100% network demand



(d) Ottawa at 100% network demand



(e) Winnipeg at 120% network demand



(f) Ottawa at 120% network demand

Figure 1: Comparison of Average Travel Time per vehicle between the different AEV driving behaviours at different penetration rates

4.2 GHG Emissions Reduction from ICE Vehicles

It will take time before the full vehicle fleet in a city will be part of an AEV-based ITS. However, during the build-up phase the ITS can have additional benefits for the portion of the fleet still composed of conventional ICE vehicles. The reduction of congestion and travel time from the ITS traffic optimization can lower emissions from the remaining ICE vehicles in the fleet.

This section evaluates how improved traffic conditions resulting from AEV introduction can lead to reductions in emissions from ICE vehicles. For example, when AEVs enhance traffic conditions, the ICE vehicles also benefit from the improved traffic conditions in the network. Tables 8 and 9 present the percent change in GHG emissions from ICE vehicles when introducing AEVs for the city of Winnipeg and the city of Ottawa, respectively. The results presented are not direct emission reduction from the electric AEVs replacing ICE vehicles, but rather the impact of traffic optimization from introducing AEVs on the emissions from the remaining fleet of ICE vehicles. The percentage change in GHG emissions relate to the emissions per ICE vehicle still on the road.

The results indicate that Normal and Aggressive AEVs induce an emissions reduction from ICE vehicles in the mixed vehicle fleet due to the improved traffic conditions. For many scenarios, the greatest reduction in emissions from ICE vehicles occurs at lower penetration rates (25%) of Normal and Aggressive AEVs. This suggests that an early AEV-based ITS adoption can yield an immediate environmental benefit.

Cautious AEVs, on the other hand, lead to an increase in emissions from ICE vehicles due to the deteriorated traffic conditions at higher penetration rates (50% and 75%). However, Cautious AEVs tend to reduce emissions from ICE vehicles at lower penetration rates (25%).

Table 8: Emissions reduction from ICE vehicles from introducing AEVs in Winnipeg

Traffic Demand	Case		ICE Emissions (CO2 Eq. kg)	
80%	DOV		**72,036**	**% change in emissions produced per ICE vehicle**
	Cautious	**25%**	53,702	-0.84%
		50%	37,461	1.61%
		75%	20,461	2.98%
	Normal	**25%**	50,627	-4.79%
		50%	33,687	-3.36%
		75%	16,798	-1.73%
	Aggressive	**25%**	50,648	-4.69%
		50%	33,607	-3.35%
		75%	16,574	-1.83%
100%	DOV		**72,036**	**% change in emissions produced per ICE vehicle**
	Cautious	**25%**	53,702	-0.45%
		50%	37,461	2.00%
		75%	20,461	3.40%
	Normal	**25%**	50,627	-4.72%
		50%	33,687	-3.24%
		75%	16,798	-1.68%
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		75%	16,574	-1.99%
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	Normal	**25%**	50,627	-5.28%
		50%	33,687	-1.06%
		75%	16,798	-1.59%
	Aggressive	**25%**	50,648	-4.89%
		50%	33,607	-3.81%
		75%	16,574	-2.27%

Table 9: Emissions reduction from ICE vehicles from introducing AEVs in Ottawa

Traffic Demand	Case		ICE Emissions (CO2 Eq. kg)	
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		50%	33,687	-2.92%
		75%	16,798	-1.42%
	Aggressive	**25%**	50,648	-3.12%
		50%	33,607	-3.18%
		75%	16,574	-2.02%

5 Conclusions

The findings of this study demonstrate that introducing an ITS based on AEVs with aggressive driving design parameters can improve traffic flow conditions particularly at higher AEV penetration rates. Aggressive AEVs are the most effective in reducing travel times within the simulated urban networks of Winnipeg and Ottawa.

Study results also showed varying results for different AEV penetration rates and between the two cities. Additional research is needed to understand the highly complex vehicle interaction in mixed DOV/AEV fleets.

While the AEV-based ITS systems is expanded over time to cover a large part of the total vehicle fleet, it can have the additional benefit of reducing GHG emissions from conventional ICE vehicles in a mixed fleet environment due to the improved overall traffic conditions of the network even at initial stages of deployment.

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Presenter Biography

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