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Evaluating the Impacts of Connected Vehicles on GHG Emissions: How to Transfer the Results from the Literature

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Abstract. Transportation in North America is responsible alone for 40 % of Greenhouse Gas (GHG) emissions, of which half is produced by private vehicles. Connected vehicles (CV) are presented as a solution to reduce several adverse impacts of transportation, including air pollution and GHG emissions. The objectives of this paper are twofold: the first is to review and synthesize the main studies in the literature on the impacts of CVs on GHG emissions and the second is to propose a method to transfer these results to contexts that are different from the ones in which the original studies were conducted. As a case study, this transfer methodology is applied to the Island of Montréal in Canada. The main CV applications for traffic lights and eco-driving in urban environments show small GHG reductions. The largest impact is produced on highways by cooperative adaptive cruise control, which involves some level of automation.

Keywords: Connected vehicles, greenhouse gas emissions, transfer.

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Introduction

Transportation is considered in North America as the primary source of climate change, responsible alone for 40 % of Greenhouse Gas (GHG) emissions, of which half is produced by private vehicles. Given the observed and anticipated environmental impacts of climate change (IPCC 2014), there are considerable efforts for reducing the GHG emissions by the transportation sector. While the ideal, longer term, solution is a shift to more sustainable modes of transportation, the simplest solution is to replace current vehicles running on fossil fuels and emitting GHG. But adoption is slow, and vehicles running on fossil fuels are still the priority in the battle against the climate change.

Among the vehicle technologies under development that are part of intelligent transportation systems (ITS), vehicle communications or connected vehicles are presented as a solution to reduce several adverse impacts of transportation, including air pollution and GHG emissions. Vehicle-to-everything (V2X) communication is defined as “the passing of information from a vehicle to any entity that may affect the vehicle, and vice versa” (Vehicle-to-everything 2017). “Vehicle communications use on-board dedicated short-range radio communication devices to transmit messages about the vehicle’s speed, heading, brake status, and other information” to other vehicles (Vehicle-to-Vehicle, V2V), to the infrastructure (Vehicle-to-Infrastructure, V2I), other users (Vehicle-to-Pedestrian, V2P) and devices (Vehicle-to-device, V2D) (Harding, et al. 2014). Vehicles equipped with such communication technology are commonly called connected vehicles (CV). Vehicle communication provide data that enable several applications that may improve safety, traffic flow and decrease environmental impacts (Shladover 2017, Harding, et al. 2014). CVs are referred to as collaborative or cooperative ITS in Europe to emphasize the collaborative or cooperative nature of these applications. Despite the long history of research in this area, dating back more than two decades to "Intelligent Highway/Vehicle Systems", there are few reviews of the impacts of CVs that consider the limitation of available studies. To the best of the authors' knowledge, there is no method to adapt or extrapolate the results of transportation impact studies to different contexts, for example to a region different from the one used in the initial study. In North America, the vast majority of published studies has been done in the context of the US and their results must therefore be assessed in terms of applicability to other contexts.

The objectives of this paper are twofold: the first is to review and synthesize the main studies regarding the impacts of CVs on GHG emissions and the second is to propose a method to transfer the available results to contexts that are different from the ones in which the original studies were done. As a case study, this transfer methodology is applied to the context of the Island of Montréal in Canada.

The literature review is presented in the next section. It is followed by a description of the proposed transfer methodology using the Island of Montréal as a case study. Finally the paper is concluded and future work is discussed.

Literature Review

Connected Vehicle Applications

In one the main research programs on the impacts of CVs on the environment, "Applications for the Environment: Real-Time Information Synthesis" (AERIS), carried out in the US from 2009 to 2014, five categories of applications are identified (AERIS Research Program 2016):

1. Eco-Signal operations aim to reduce fuel consumption and emissions at signalized intersections. Applications include: Eco-Approach and Departure at Signalized Intersections, Eco-Traffic Signal Timing, Eco-Traffic Signal Priority and Connected Eco-Driving.
2. Eco-Lanes are dedicated freeway lanes, similar to managed lanes, which encourage use from vehicles operating in eco-friendly ways. Drivers would be able to opt-in to these dedicated eco-lanes to take advantage of eco-friendly applications such as Eco-Cooperative Adaptive Cruise Control (Eco-CACC), Eco-Speed Harmonization and (again) Connected Eco-Driving.
3. Low Emissions Zones are geographically defined areas that seek to promote environmentally-friendly transportation choices or restrict high-polluting vehicles from entering the zone based on real-time traffic and environmental conditions.
4. Eco-Traveller Information aims to provide traveller information regarding available modes, optimal routes, and departure times in real-time either pre-trip or en-route that can impact fuel consumption and vehicular emissions.
5. Eco-Integrated Corridor Management (Eco-ICM) treats travel corridors as an integrated asset with a focus on decreasing fuel consumption and emissions.

While the names may differ from one study to another, from the US to the EU, these categories cover the main applications of CVs. Their effects are illustrated in Figure 1. Effect on GHG emissions are typically through the control of the vehicle, whether manually by the driver, or automatically. Manual driving techniques are called energy-efficient or eco driving. The only application that involves a level of automation and is usually included in connected vehicle applications is cooperative adaptive cruise control, which relies on longitudinal automated vehicle control. The purpose of these techniques is to reduce accelerations (their number and magnitude), the number of stops, idling time and promote the adoption of optimal speed that minimizes emissions.

The second mechanism is through information and incentives affecting the user travel behaviours, namely the choice of transportation mode and vehicle type. This mechanism is in play in low-emission zone applications and will not be further discussed as the effect on GHG emissions is indirect, through a transportation mode shift.

Review of the Experiments Measuring the Impacts on GHG Emissions

This subsection focuses on the experimental studies that have measured or estimated the impacts of connected vehicle applications on GHG emissions. Experiments have been done for eco-signal operations and eco-lanes and rely on either field tests or traffic simulations.

Eco-Signal operations

The main CV applications in urban environments are related to traffic signals:

- green light optimal speed advisory (GLOSA)
- signal timing optimization
- signal priority for transit and commercial vehicles

The last application to be considered in this category is connected eco-driving and it has been studied on both arterials and highways. While these applications have been evaluated in several projects (FOT-Net WIKI n.d.), it may be difficult to find detailed information about the results and the method used to generate them.

GLOSA is called Eco-Approach and Departure at Signalized Intersections in the AERIS project, where it has mostly been tested in a previously calibrated traffic simulation of a 6.5-mile section of the El Camino Real in the bay area arterial including 27-intersections (Yelchuru, Fitzgerel, et al. 2014). Emissions are estimated using the MOtor Vehicle Emissions Simulator (MOVES) developed by the US Environmental Protection Agency (EPA) (U.S. Environnemental Protection Agency 2014). Using V2I communication, the application has access to information about signal timing and advises drivers on the optimal speed to minimize emissions, without stopping at the traffic light if possible. The results are presented for different scenarios, by changing the connected vehicle penetration rate for a given demand (set to a volume to capacity v/c ratio of 0.77) or by changing the demand for a connected vehicle penetration rate of 100 %. The reduction in GHG emissions ranges from -1.1 % to 2.0 % for the maximum penetration rate, with negative numbers indicating an increase in emissions. This increase occurs in congested traffic conditions. These impacts also depend on the types of vehicles, with larger gains for trucks than for passenger vehicles. The gains are the largest (5.0 %) for trucks at the lowest CV penetration rate (20 %), decreasing as penetration rate increases. This is the opposite for passenger vehicles: there are emission increases at the lowest penetration rate, which become smaller as penetration rate increases and turn to gains at 65 % penetration rate. It should be noted that the application's performance depends on the range of the communication equipment.

GLOSA has also been tested in a small field experiment in the AERIS project involving one CV and one isolated signalized intersection in a closed circuit without any other vehicle. This limited test showed a decrease in fuel consumption of 13.59 %. Similarly, in the Canadian CV testbed at the University of Alberta in Edmonton called ACTIVE-AURORA, an experiment with one CV and one connected signalized intersection has shown reductions of 14.0 % in GHG emissions (Ke 2015).

The traffic signal timing application developed in the AERIS project relies on a genetic algorithm to optimize a series of fixed signal timing plans off line in order to minimize fuel consumption (Yelchuru, Fitzgerel, et al. 2014). The best signal timing is then chosen depending on traffic conditions. Using the same simulation as for GLOSA, the reduction in fuel consumption ranges from 0.8 % to 5.3 %, increasing with the CV penetration rate; still, it has been tested only for unsaturated conditions (v/c=0.77).

Although signal priority is already used for transit vehicles (buses), V2I communications would make the application available to more vehicle categories to maximize environmental benefits, e.g. commercial vehicles, and be reactive to more parameters such as the vehicle type, including fuel type, the number of passengers in transit vehicles or whether the vehicle approaches as part of a platoon (Yelchuru, Fitzgerel, et al. 2014). Two applications were tested separately for transit vehicles and trucks on the same simulation as the two previous AERIS applications. The truck signal priority application provides gains from 1.0 % to 4.7 % for passenger vehicles and trucks. While the transit priority application provides gains for transit vehicles (0.2 % to 1.5 %), it causes increases in GHG emissions overall (taking into account passenger vehicles). As can be expected, impacts on vehicles without priority increases as green extensions for priority vehicles increase.

In the other major recent CV project carried out in Europe, COMPASS4D (Hill, Edwards and Goodman 2016), applications for signalized arterials were evaluated in field experiments in seven European cities combined with traffic simulations. Complicating things, several applications were simultaneously tested in a general concept of energy efficient intersection: GLOSA, signal priority, vehicle idling reduction and a countdown to green to help drivers react quickly. The effects were evaluated on different types of vehicles in the different cities, including passenger vehicles, buses, trucks, taxis and emergency vehicles. “Network performance of the COMPASS4D services was assessed by extrapolating findings from the data analysis and simulation activities” and yield overall reductions in GHG emissions, estimated using the model described in (Panis, Broekx and Liu 2006). Reductions are larger for heavy vehicles (5 to 10 %) than for passenger vehicles. Results are mixed for buses, with reductions (up to 7.33 %) and increases (-0.60 %) depending on the city and the location of stops (upstream or downstream from the intersection). Finally, it is noted that the gains are larger for signal priority than for GLOSA, although signal priority can cause delays on vehicles without priority (with overall reductions in GHG emissions).

Eco-driving has also been evaluated in AERIS using the same traffic simulation of the El Camino Real signalized arterial. The application provides advice on speed, acceleration, gear change and driving behaviour. The magnitude of reductions decreases as demand increases and CV penetration rate decreases, going from a maximum of 3.5 % for the lowest demand (v/c=0.38) and 100 % penetration rate to a minimum of -1.4 % (emission increases) for saturated conditions (v/c=1) and 100 % penetration rate. Reductions in GHG emissions are observed along increases in travel time.

Eco-Lanes

The main CV applications on highways are cooperative adaptive cruise control (CACC) and speed harmonization. They have been both evaluated in the AERIS project using a different, previously calibrated, traffic simulation model of a five-lane 13-mile stretch of SR-91 E east of Los Angeles (Yelchuru, Fitzgerel, et al. 2014), with MOVES for emission estimation. The principle of speed harmonization is to recommend harmonized speeds for each 500-m segment through V2I communications. With 100 % CV penetration, emissions reductions can go up to 4.36 % in the scenario with the lowest demand at 25 000 veh/h, but decrease as demand increases. Actually, for demand of 31 000 veh/h and 34 000 veh/h, GHG emissions increase 2.03 % and 1.52 % respectively. And yet, they decrease by 2.16 % for 37 000 veh/h. Such non-linear effects are surprising. As one can expect however, the magnitude of reductions increases as penetration rate increases for a given demand. It should be noted that the most important gains were measured upstream from a recurrent bottleneck.

In CACC, CV can assemble into platoons with a leader controlling the speed of following vehicles through V2V communications accounting for factors such as weather, road grade and geometry. Based on the same simulation as the speed harmonization application, gains increase with the demand and decrease for larger inter-vehicular distances (IVD), from 0.1 % at 25 000 veh/h with IVD of 15 m to 19.2 % at 37 000 veh/h with IVD of 5 m. CACC has also been tested in the SARTRE European projects in the field, with two trucks and three passenger vehicles over about 200 km (Chan, et al. 2012). Vehicles were separated by about only 4 m at 90 km/h, which yielded maximum fuel consumption decrease of 16 % for the first following vehicle. Lower gains were measured for larger inter-vehicular distances. The leader had modest gains, between 1 to 6 %.

Summary

The ranges of the reductions and increases in GHG emissions are summarized for the main CV applications in Table 1. It also includes whether the application is effective in congested traffic conditions. It can be first seen that the effects are most important for CACC, then followed by GLOSA and signal priority. Second, it is noteworthy that most applications may result in GHG emission increases, as high as 2 %.

Limitations

There are several important limitations in the reported studies, related to the methods used and the missing information in their description. AERIS used mostly traffic simulations to evaluate the impacts of CVs. It is impossible to know how the models are implemented in the commercial traffic simulation software (PARAMICS) that was used. More importantly, there is little information on the calibration and validation steps necessary to use traffic simulation: such complex models are prone to overfitting, which limits their ability to make correct predictions in conditions differing from the conditions of the calibration (Hollander and Liu 2008). This is particularly important for CVs, which will behave differently from existing vehicles. Furthermore, the chosen parameters of the simulation, notably for the car-following, lane-change models as well as the vehicle fleet, are not provided. The two models represent only isolated corridors, an arterial and a highway, without the adjacent network; the effect on the larger networks therefore cannot be evaluated. The sensitivity analysis for the main variables, traffic condition measured by v/c and CV penetration rate for the arterial model, demand and CV penetration rate for the highway model, was done separately for these parameters. The observed non-linear effects between the impacts on GHG emissions and these parameters imply there must be unobserved variables to explain these complex relationships. It must also be noted that all models assume complete and perfect driver compliance to the recommendations by the CV applications. Except for CACC where vehicle longitudinal control is automated, the reported numbers represent best case scenarios that ignore human physical and cognitive limits as well as willingness, or the lack thereof, to follow advices.

Regarding specific applications, GLOSA and connected traffic signal optimization have been tested only with fixed signal timing and not with single intersection adaptive traffic control or even network-wide adaptive traffic control. It should also be noted that the effects of GLOSA only apply to an area of influence of the signalized intersection, although this is not clearly reported. In AERIS, it seems conflated with the communication distance of the V2I communication from the traffic controller (300 m), while for COMPASS4D, "all performance indicators are calculated from a 250 m radius circle centred on the intersections".

Experiments in the field have several advantages over models and simulations, but their cost and resource requirements limit their size and duration. For example, the SARTRE project involved only five vehicles and the following factors were fixed: platoon configuration, traffic conditions. The impacts of manoeuvres to enter and exit the platoons, as well as the interactions with non-connected vehicles are also not evaluated. If the number of tested vehicles was larger in the COMPASS4D project, the range of results is also wider, in particular among the different configurations and implementations in the seven cities involved in the project. There is no information on the intersection geometries, the type of traffic control, the location of bus stops at intersections, the speed limits, the characteristics of the involved vehicles or the traffic conditions (congestion or not). Besides, the individual effects of some applications is unknown, as several applications like GLOSA and signal priority were implemented simultaneously in the energy efficient intersections. Finally, there is no detail on the methods used, in particular about the way the experiments were combined with or fed the network wide simulations that yielded the reported results.

Transfer Methodology

The second objective of this paper is to propose a simple method to transfer or extrapolate the impacts measured in the literature to a different context. In the absence of existing tests of CVs in that context, there are two broad categories of methods to transfer results from the literature: a simulation, as done in the AERIS project, or the extrapolation of the results by taking into account the main differences between the contexts. In this paper, we propose to transfer the results to the case study of Montréal, in Canada, where no CV application has been tested except for GLOSA in the ACTIVE-AURORA Testbed in Edmonton. Given the lack of crucial information in the literature, this paper focuses on a simple and general transfer method to evaluate the magnitude of the effects for the whole road network and the whole fleet. The aim is that such a method can be applied in any region with easily available data on the supply side (road network data) and demand side (distance travelled, congestion estimations).

Scope and Limits of Existing Studies

As described previously, the lack of information has important consequences on the ability to transfer the available results to different contexts. There is no information on the model parameters such as the vehicle and driver characteristics used in the studies, which makes it difficult to adjust them for a different context. Besides, the impact of the following factors is unknown: how is the corridor under study integrated in the whole road network, how do signalized arterials that cross each other interact, are the applications effective in addition to existing real time adaptive traffic control, what are the type and density of weaving sections on highways as well as the platoon characteristics (for CACC). Also, the impact of some variables has been tested (CV penetration rate, demand) separately, and their interaction is unknown. No confidence intervals are provided for the GHG emission impacts, nor the detailed results of the runs of the traffic simulation or the field data collection.

Extrapolating Factors

Given the limitations of the studies, the transfer is done using the most important factors that have been reported to have an impact on GHG emissions:

- the number of signalized intersections, regardless of the type of signal timing plan (adaptive or not, coordinated or not);
- the number of signalized intersections with transit signal priority;
- the length of the highway and urban network;
- the congestion level per class of road;
- the travelled distance per class of road.

The idea to extrapolate, from the results, the general effect for the whole road network and all vehicles is to consider that the effects are proportional to the presence of the relevant factors in the general population of reference.

Traffic Lights

In the case of GLOSA and signal timing optimization, the effect is proportional to the length of the network that is under the influence of signalized intersections, e.g. considering the 300 m V2I communication distance used in AERIS. For a given zone, the application coefficient τ_{signal} is calculated using the following equation:

$$\tau_{signal} = \frac{NL_{signal}}{L_{urban\ network}} \qquad (1)$$

where N is the number of signalized intersection in the zone, L_{signal} is the length of road where GLOSA has an impact on GHG emissions and $L_{urban\ network}$ is the length of the road network excluding highways in the zone. Given an influence distance of 300 m and assuming four approaches with both directions of traffic, $L_{signal} = 4 \times 300\text{ m} = 1.2\text{ km}$. In the context of Montréal (considering the Island of Montréal), there are $N = 2298$ signalized intersection and $L_{urban\ network} = 4071$ km of roads excluding highways (obtained from the City of Montréal open data portal (City of Montréal 2017)), which yields a coefficient $\tau_{signal} = 67.75\ \%$.

Traffic Lights with Signal Priority

For CV applications related to traffic signal priority, one needs to know the signalized intersections equipped with the V2I enabling equipment. The hypothesis is that the effect is proportional to the number of priority vehicles crossing at these intersections. For the Island of Montreal, for transit signal priority, there are currently 273 signalized intersections equipped with bus signal priority. Using the open GTFS data of the Montréal transit agency (Société de transport de Montréal 2017) and assuming that these signalized intersections are on the most frequent bus routes (their location is unknown), we estimate that there are 166 641 crossings at signalized intersections with transit signal priority out of 530 072 crossings at signalized intersections. The resulting coefficient is $\tau_{signal\ priority} = {}^{166\,641}/_{530\,072} = 31.44\ \%$.

No information is available about the routes of trucks, which makes the transfer of the impact of truck signal priority on GHG emissions impossible to do.

Road Class and Traffic Conditions

Finally, since some CV applications apply only to some road classes (highway or not) and are only efficient in non-congested conditions, one needs to estimate the proportion of the distance travelled per road class under congested and non-congested conditions.

In Montréal, the required data is estimated using trips from a household travel survey. Observed trips are assigned to the road network to estimate the extent of congestion of the road network; results from simulations by Transport Québec are used (Les Conseillers ADEC inc. 2014). The results are presented in Table 2. Assuming that the travelled distances are evenly spread on the road network, the coefficients to apply depend on the road class and efficiency in congested conditions: for example, a coefficient of 47.12 % will be applied for the speed harmonization application since it is effective only highways in non-congested conditions.

Case Study for the Island of Montréal

The factors to be applied for each application are presented in Table 3. If two factors are checked for an application, their coefficients will be multiplied. The results of the AERIS project are used solely for this case study for consistency and because they are the only one that report the impact of factors such as CV penetration rate and demand. The results are presented in Table 4 and Table 5 below.

The reductions (or gains in case of negative numbers) presented are all smaller than the reported numbers in the AERIS reports since the effect was measured in the experiment only for parts of the network and other conditions (congestion or not) where the CV applications were effective. The results for the Island of Montréal extrapolate these number to the whole network and all conditions, including parts where there are no traffic lights or where traffic is congested and therefore GLOSA or eco-driving have no effect. The case of bus signal priority presented in Table 4 is extrapolated for all signalized intersections, assuming only the current traffic lights with bus signal priority would have the technology for connected bus signal priority. The only factor applying to CACC in Table 5 is that it would be implemented only on highways and thus applies only to the 55.4 % of distance travelled on highways.

In urban environments (non-highways), the transfer of the four CV applications, GLOSA, traffic signal timing, bus signal priority and eco-driving brings maximum GHG emission reductions of 0.11 %, 4.03 %, 0.47 % and 0.13 % respectively. These gains are small and represent the best case scenarios, with 100 % CV penetration rate and a hypothesis of perfect compliance of drivers in the traffic simulation models. These applications in urban environments show reductions in low traffic volume, when drivers can follow the application recommendations without hindrance by other drivers. Even in these ideal conditions, the gains are small. Many of these applications are ineffective in congested traffic conditions, which can be easily understood for traffic light applications where optimization is difficult in such conditions. In fact, such applications, in particular bus signal priority, show negative side effects on overall GHG emissions.

The extrapolated effects of CV applications on highways, speed harmonization and CACC, are respectively 2.22 % and 10.6 % reductions in GHG emissions. These gains are larger than the gains of applications in urban environments, with no measured negative side effects.

Conclusion

After reviewing the main researches on the impact of CVs on GHG emissions, this paper has proposed a simple method to transfer these results in a different context. This transfer is based on easily accessible data such as:

- the number of signalized intersections;
- the length of the highway and urban network;
- the distance travelled per class of road;
- the proportion of the network that is congested per class of road.

The method was applied to the Island of Montréal, using the results of the AERIS project as a base for the following applications: GLOSA, traffic signal timing, bus signal priority and eco-driving on arterials, speed harmonization and CACC on highways. The results of some applications like GLOSA, traffic signal timing or eco-driving, already small, get even smaller when extrapolated to the whole network. The case of bus signal priority is interesting as the gains are larger for buses, but the overall impact is negative, i.e. leads to increasing GHG emissions. CV applications on highways have larger effects, even after extrapolating to the whole network and all traffic conditions and provide therefore better opportunities.

But identifying the limitations in the current literature is another important outcome of this work. The two main projects rely either exclusively or to some extent on microscopic traffic simulation and they do not provide enough details on the process (calibration and validation, number of simulations, driving behaviour and vehicle parameters, etc.) to evaluate the quality of their results. All projects, especially in simulations, also assume perfect compliance and ability to follow the recommendations of the CV applications: it is impossible to know how drivers will react and how it would change the results. Several important explanatory variables for example related to the traffic lights (traffic signal timing parameters, traffic light distances, zone of influence, etc.) or traffic conditions (for field experiments) are not presented and they may explain some non-linear effects between the presented explanatory variables such as the CV penetration rate and the reductions in GHG emissions. Also, it is impossible to evaluate what would be the incremental effects of the CV applications in addition to existing ITS, for example what additional effect GLOSA or connected bus signal priority would have with adaptive traffic lights or existing bus signal priority.

The proposed transfer method and the presented results depends on hypotheses and the available data. The main hypothesis is related to the distribution of congested traffic conditions on the road network, assumed to be uniform, which is not realistic. Higher class roads, highways and arterials, are probably more congested over time than local roads. A more realistic estimation of the congested area would probably result in a higher share of distances being travelled in congested conditions, therefore further reducing the impact of applications that are ineffective in congestion (GLOSA, eco-driving and speed harmonization).

It should be clear from the reviewed studies and proposed transfer method that more work is needed in the area of the impacts of CV applications to GHG emissions, in particular in contexts and regions were no or few tests have been made so far. The available studies seem too broad and there is a lack of details with respect to the experiments as well as on the specific impacts of the various explanatory variables. The reference scenarios should be carefully defined, in particular in terms of existing traffic control systems, to study the impact of adding CV applications. The data should be collected as disaggregated as possible to evaluate the impacts of CV applications and understand the mechanisms behind the effects.

And of course, traffic simulation should be calibrated and validated (Hollander and Liu 2008), and the corresponding data described in detail in the report.

To conclude, the most interesting CV applications for GHG reductions are on highways, and tellingly, the most effective by a large margin, CACC, involves automating part of the driving task. This supports the wave of interest for automated vehicles of various levels which may have a greater effect than CVs on negative transportation impacts, including accidents and emissions.

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Table 1. Range of GHG emission reductions for different applications based on the literature (negative numbers represent increases in emissions)

Applications		**Effective in congestion**	**Min**	**Max**
Eco-Signal Operations				
GLOSA			-1.1 %	14.0 %
Traffic Signal Timing		✓	0.8 %	5.3 %
Transit Signal Priority	Transit	✓	1.5 %	2.8 %
	All vehicles	✓	-1.0 %	-0.5 %
Eco-Driving			-1.4 %	6.8 %
Eco-Lanes				
Speed Harmonization			-2.0 %	4.4 %
Collaborative Adaptive Cruise Control		✓	5.0 %	19.2 %

Table 2. Congestion per road class on the Island of Montréal (top) and distribution of the distance travelled per period of the day, road class and traffic condition (congested or not) (bottom)

	Proportion of road length under congestion* (% of lane-km)	
Period	Highway	Arterials
Off Peak	0 %	0 %
Morning Peak	28 %	34 %
Evening Peak	27 %	36 %

*The definition of congestion is that mean speed is below 60 % of free-flow speed.

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Road Class	Period	Non-Congested	Congested	Total
Arterials (non-highway)	Off Peak	20.21 %	0.00 %	20.21 %
	Morning Peak	7.44 %	3.83 %	11.27 %
	Evening Peak	8.40 %	4.73 %	13.13 %
	Total	36.05 %	8.56 %	44.61 %
Highway	Off Peak	25.28 %	0.00 %	25.28 %
	Morning Peak	10.34 %	4.02 %	14.36 %
	Evening Peak	11.50 %	4.25 %	15.75 %
	Total	47.12 %	8.27 %	55.39 %
Total		83.17 %	16.83 %	100.00 %

Table 3. CV Applications and the factors considered for transfer to a different context

Applications \ Transfer Factors	**Traffic Lights**	**Traffic Lights with Priority**	**Non-Congested Conditions**	**Highways**
GLOSA	✓		✓	
Traffic Signal Timing	✓			
Signal Priority for Transit		✓		
Eco-Driving			✓	
Speed Harmonization			✓	✓
Collaborative Adaptive Cruise Control				✓

Table 4. Extrapolation of the impact of GLOSA, traffic signal timing, bus signal priority for the Island of Montréal as function of CV penetration rate or v/c (in percent of GHG emission reductions)

CV Penetration Rate (v/c=0.77)	GLOSA (AERIS)	Traffic Light Factor	Non-Congestion Factor for Arterials
		Coefficient : 67.7%	Coefficient : 36.1%
20 %	-0.04 %	-0.03 %	-0.01 %
35 %	0.04 %	0.03 %	0.01 %
50 %	0.10 %	0.07 %	0.02 %
65 %	0.30 %	0.20 %	0.07 %
80 %	0.40 %	0.27 %	0.10 %
100 %	0.40 %	0.27 %	0.10 %

CV Penetration Rate (v/c=0.77)	Traffic Signal Timing (AERIS)	Traffic Light Factor
		Coefficient : 67.7 %
20 %	0.80 %	0.54 %
35 %	1.80 %	1.22 %
50 %	4.40 %	2.98 %
65 %	4.50 %	3.05 %
80 %	5.10 %	3.45 %
100 %	5.30 %	3.59 %

Ratio v/c (CV Penetration Rate=100 %)	Bus Signal Priority (AERIS)		Traffic Lights with Priority Factor*	
	Bus	All	Bus	All
			Coefficient : 31.4 %	
0.38	0.20 %	-1.00 %	0.06 %	-0.31 %
0.77	1.50 %	-0.50 %	0.47 %	-0.16 %
1.00	1.00 %	-0.60 %	0.31 %	-0.19 %

*Assuming that the current traffic lights with bus signal priority are equipped for connected bus signal priority

CV Penetration Rate (v/c=0.77)	Eco-Driving (AERIS)	Non-Congestion-Factor for Arterials
		Coefficient : 36.1 %
20 %	-0.40 %	-0.14 %
50 %	0.12 %	0.04 %
80 %	0.18 %	0.06 %
100 %	0.36 %	0.13 %

Table 5. Extrapolation of the impact of speed harmonization and collaborative adaptive cruise control for the Island of Montréal as function of CV penetration rate or volume (and platoon inter-vehicular distance for CACC) (in percent of GHG emission reductions)

CV Penetration Rate (volume=25 000 véh/h)	Speed Harmonization (AERIS)	Non-Congestion-Factor
		Coefficient : 47.1 %
5 %	0.15 %	0.07 %
10 %	0.11 %	0.05 %
20 %	0.88 %	0.41 %
40 %	1.97 %	0.93 %
60 %	2.94 %	1.39 %
80 %	3.07 %	1.45 %
100 %	4.36 %	2.05 %

Inter-Vehicular Distance (CV Penetration Rate=100 %)	Collaborative Adaptive Cruise Control (AERIS)					Highways Factor				
						Coefficient : 55.4 %				
	Volume (veh/h)					Volume (veh/h)				
	25000	*28000*	*31000*	*34000*	*37000*	*25000*	*28000*	*31000*	*34000*	*37000*
5 m	0,1 %	0,7 %	2,9 %	13,9 %	19,2 %	0.06 %	0.39 %	1.61 %	7.70 %	10.64 %
15 m	0,2 %	0,7 %	2,5 %	12,4 %	9,2 %	0.11 %	0.39 %	1.39 %	6.87 %	5.10%

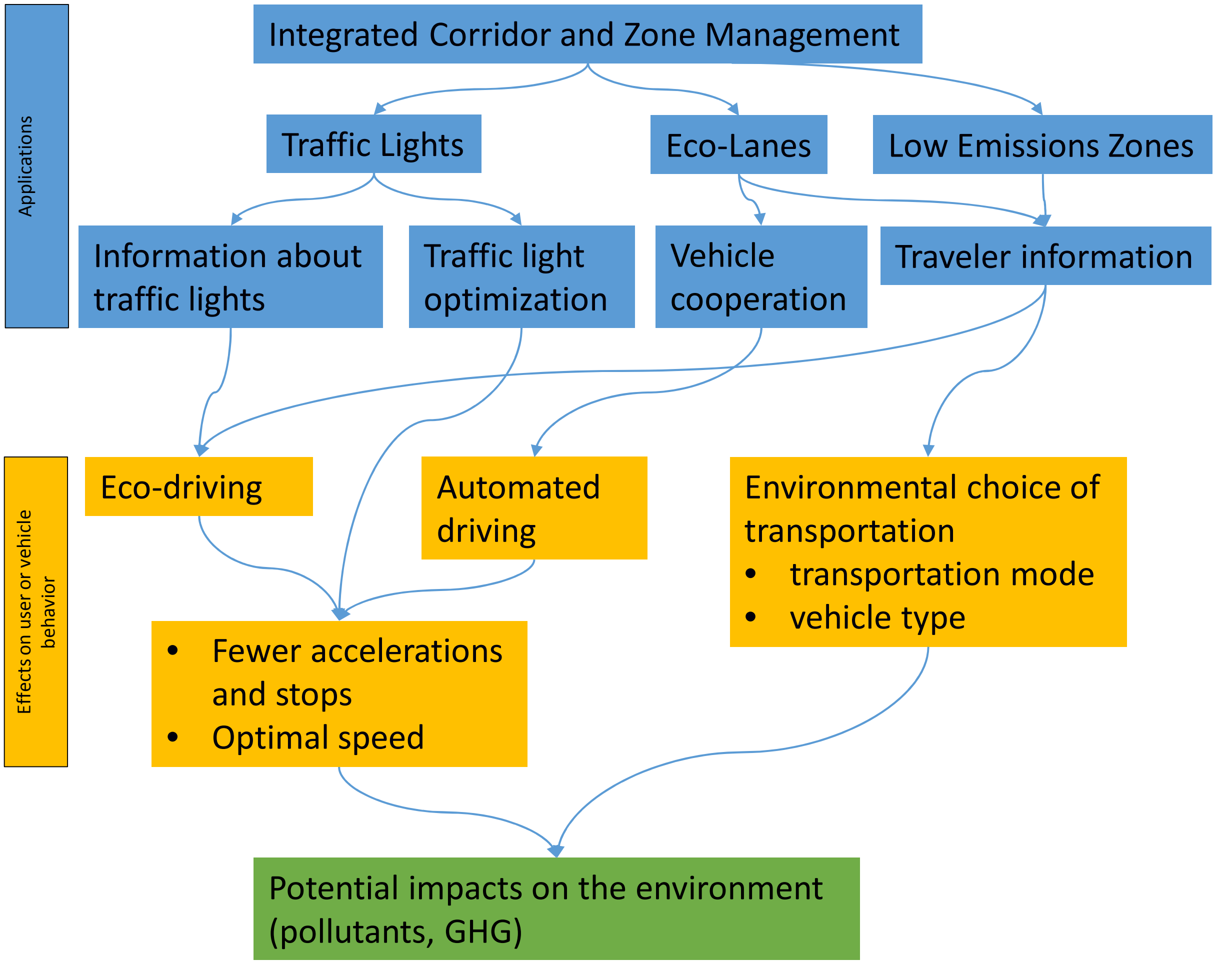

Figure 1. CV applications and their effects on users / vehicles behaviors that may have an impact on emissions