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Contents

Section A

Section B

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Estimating the impact of Green Light Optimized Speed Advisory (GLOSA) on exhaust emissions through the integration of VISSIM and MOVES

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Abstract

U.S. Environmental Protection Agency (EPA) states that transportation is the second leading source for air pollution. Therefore, any improvement in transportation technology can bring substantial benefits by reducing the vehicle exhaust emissions. Recently, connected vehicle (CV) technologies have become increasingly popular since their penetration to the market can bring crucial benefits. This makes it necessary to study their impact in a simulation environment to assess their benefits before their actual implementation. As such, objectives of this paper are as follows: (a) to provide a framework that can convert VISSIM vehicle trajectory output to an input for EPA's Motor Vehicle Emission Simulator (MOVES), and (b) predict the impact of CV technologies on vehicle emissions developing an algorithm that makes benefit of a vehicle-to-infrastructure (V2I) communication application, namely Green Light Optimized Speed Advisory (GLOSA). For this purpose, an intersection is built in VISSIM, and GLOSA is implemented on a major leg of this intersection. The output data is also converted to a MOVES input file developing a new algorithm, named operating mode calculation algorithm (OMCA). Results of MOVES simulation for CO, NO_x, PM2.5 and PM10 show that GLOSA application has a huge potential of reducing vehicle emission in the vicinity of traffic lights as it can lead to up-to 51.2% emission reduction. In addition, vehicle stop delay and number of stops were also reduced by 83.9% and 87.9%, respectively. Findings of the study can help understand the effect of stop-and-go driving operations on the exhaust emissions, and quantify the potential operational and environmental benefits of CVs in this context.

Keywords – vehicle emissions, VISSIM, MOVES, operating mode, green light optimized speed advisory, GLOSA

1. Introduction

Global demand for transportation is gradually rising, and estimated to increase by 45% by the year of 2050 [1]. This increase is expected since transportation is a vital component of the growing economy, and it provides a large-scale mobility. Thus, the still increasing demand for transportation combined with growing world economy is driving the air pollution to the limits while threatening our daily lives with this elevated pollution levels. A challenging task, therefore, is keeping the air quality at acceptable levels, which is getting more difficult day by day, particularly at urban areas, where the traffic congestion is a huge problem. For example, as of 2013, transportation contributed more than half of the carbon monoxide (CO) and nitrogen oxides (NO_x), and almost a quarter of the hydrocarbons emitted into the air [2]. Therefore, it is crucial to assess the transportation-related greenhouse gas (GHG) emissions accurately in order to correctly assess the level of the air pollution so that better plans and policies can be developed.

Literature indicates that vehicle emission rate specifically changes with speed, acceleration and deceleration rates, delay (signal time-related or others), queuing time, queue length, idling, traffic flow rate, and vehicle composition [3]. These factors should definitely be integrated into models in order to accurately estimate the exhaust emissions [3]. Previously, emission predictions have been calculated mostly based on only volume and average speed [4, 5]; however, there are many other factors affecting the emission rates. Recent technological advances such as very powerful computers can help address this issue, and enable the calculation of the exhaust emissions based not only on volume and average speed but also on the operating mode of the vehicle (i.e., change of speed, acceleration and deceleration rate, and idling), vehicle classification, vehicle operating conditions (e.g., cold or hot start, trip length, load), and fuel type and climate conditions [6]. These technologies are especially helpful in assessing the environmental impact of the CV technologies and their penetration into the traffic.

U.S. Department of Transportation (USDOT) defines Connected Vehicle (CV) as a technology which focuses on vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) and vehicle-to-device (V2X) systems in order to enhance safety, mobility, traffic congestion and environmental applications with the help of dedicated short range communication (DSRC) technology [7]. CV technology in the U.S. does not have a long history. In 2001, USDOT started the Vehicle Infrastructure Integration program [8], which can be considered as the first milestone for this technology. It is expected that, over the upcoming decades, CV technologies will have an important effect not only on safety, mobility and traffic congestion, but also on vehicle exhaust emissions. Other benefits of CV technologies include pedestrian protection due to more efficient maneuverability and control confliction [9], crash reduction due to sensor-, radar- and computer vision-based systems [10], and intersection navigation and collision avoidance [11] as a result of better vehicle networking and identification. These benefits make it necessary to study the impact of these technologies in a simulation environment in order to assess their benefits more clearly before their actual implementation. Two well-known simulation software that can be utilized for this purpose are VISSIM, which focuses on microscopic traffic simulation and Environmental Protection Agency's Motor Vehicle Emission Simulator (MOVES), which can simulate emissions based on given traffic outputs from software such as VISSIM.

One of the most prominent V2I applications is Green Light Optimized Speed Advisory (GLOSA) [12]. This application aims to reduce stop-and-go driving by providing the information on the optimum travel speed to the driver. It uses the broadcasted traffic signal timing information to calculate the required speed needed to arrive at the intersection during the green phase of the signal. This technology utilizes the DSRC technology for communication between driver and the infrastructure. When the vehicle appears in the DSRC range of the signal, the driver receives the speed advisory information needed to arrive the next intersection at green phase. There are several studies that have applied the GLOSA in order to investigate V2I technology in the context of reducing intersection delays, travel time and vehicle emissions. For example, Sanchez et al. developed a similar algorithm to the GLOSA, called Intelligent Driver Model Prediction (IDMP). They observed that even one out of ten cars equipped with IDMP can result in 30% of reduction in fuel consumption. In addition, an increase in the average speed of a platoon was also observed due to IDMP [13]. Katsaros et al. [14], on the other hand, simulated the GLOSA algorithm on two types of intersections. As a result, 7% fuel consumption reduction and a maximum of 80% stop time reduction were observed, respectively. It was also stated that GLOSA effect on fuel consumption was more visible after 50% penetration rate of vehicles equipped with GLOSA [13]. Tielert et al. [15] used the Passenger car and Heavy duty Emission Model (PHEM) and VISSIM to estimate the effect of traffic-light-to-vehicle communication on the vehicle exhaust emissions. Their results show that, using the single vehicle and single traffic-light-to-vehicle communication, fuel consumption can be reduced by 22%, CO, NO_x and particulate matter emissions can be reduced by 80%, 35% and 18%, respectively [15]. Similarly, Li et al. [16] modelled the communication between traffic lights and the driver. According to this study, providing the optimal speed to the driver based on the traffic signal status could result in 8% reduction in fuel consumption and 7% reduction in CO_2 emission in a medium traffic congestion (volume-to-capacity ratio is 0.7) [16]. A dynamic speed advisory algorithm was also developed in another study by Mandava et al. [17], which demonstrated that providing dynamic speed advisory to the driver could result in 12-14% of energy use and emission reduction. This paper will specifically focus on VISSIM for micro-simulation purposes.

MOVES, a motor vehicle emission simulation software, is widely used by the Environmental Protection Agency (EPA) and other agencies, especially in the State of Florida. However, it is not easy to deal with the preparation of complicated and detailed data inputs required by the MOVES model. It is possible to use a second-by-second vehicle traces as a model input in MOVES; however, it is extremely difficult and time consuming to collect detailed real-life data on-road operating mode conditions [18, 19]. Therefore, microscopic simulation results are generally used for this purpose since a micro simulation software offers can provide these details such as geometric and traffic characteristics, signal control and driver behaviour [20]. As such, these details can be obtained from software such as VISSIM, and can be used to create the operation mode input needed by MOVES. This information can be given to MOVES through the project level module of the MOVES software [20, 21].

In the literature, there are only few studies that have proposed integrating MOVES and VISSIM. For example, Jordan [22] created a formulation using Microsoft Excel to convert VISSIM second-by-second vehicle output to MOVES operating mode file. However, this Excel tool works only for 1 vehicle output at a time, and it requires some extra data modification such as cleaning and data aggregation with respect to the vehicle numbers before using the tool. In addition, Abou-Senna et al. [23] proposed a VISSIM/MOVES integration software consisting of four main modules to generate the operating mode distribution sheet. However, this software calculates an average operating mode distribution of all vehicles travelling on the same link. This tool is useful to avoid unnecessary accuracy and excessive data conversion if the studied network is large enough. On the other hand, it does not have enough precision to recognize minor emission changes for studies that include less vehicles. Our proposed tool, on the other hand, computes the operating mode distribution of every single vehicle by considering each vehicle's driving pattern as an individual link, which provides more accurate results.

As such, objectives of this paper are as follows: (a) to provide a framework that can convert VISSIM vehicle trajectory output to an input for EPA's Motor Vehicle Emission Simulator (MOVES), and (b) predict the impact of CV technologies on vehicle emissions developing an algorithm that makes benefit of a vehicle-to-infrastructure (V2I) communication application, namely Green Light Optimized Speed Advisory (GLOSA). The proposed framework is tested with a case study application on an intersection in the City of Tallahassee, Florida, which is known to be congested especially during peak hours. First, the intersection is built in VISSIM, and the GLOSA application is implemented on one of the major corridor legs of this intersection with different CV penetration rates. After extensive simulations, second-by-second VISSIM trajectory data is provided to MOVES through an operating mode calculation algorithm (OMCA) developed. OMCA converts this trajectory data into MOVES input files fast and efficiently in terms of links, link source types and operating mode distributions. Finally, MOVES is run in order to estimate carbon monoxide (CO), nitrogen oxides (NO_x), primary exhaust smaller than 2.5 micrometer (PM2.5) and primary exhaust smaller than 10 micrometer (PM10) emissions.

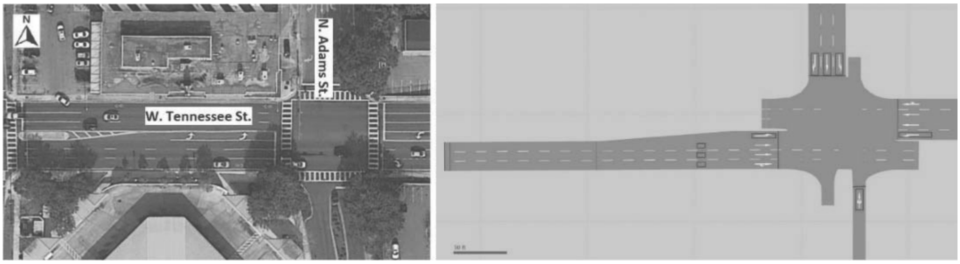
This approach aims to explore if and how CVs can bring smoother vehicle operation mode changes and less number of stop-and-go driving. Note that one of the most significant advantages of the proposed OMCA algorithm is that it does not consider the average operating mode of vehicles travelling on the same link. It rather calculates the exact operating mode distribution of each vehicle in the traffic. In order to achieve this, the distance travelled by each vehicle in the system is calculated, and then each travel is assigned to MOVES as one individual link. This gives a quite accurate result in contrast to studies in the literature that computes an average operating mode distribution for every link [22, 23]. Even though these approaches give more accurate emission results than simply considering average speed and volume rate of the links, it is less accurate than considering operating modes of every single vehicle individually, which is proposed in this study. As such, the proposed framework in this study allows us to obtain the more accurate emission rates by calculating the amount of emission for every single vehicle in the simulation, which presents the novelty of the proposed approach.

2. Methodology

In this section, the methodology will be presented, including the information on the study area, and details on the VISSIM and MOVES software as well as their data input requirements. The utmost importance will be given to the developed integration algorithm that converts VISSIM second-by-second vehicle trajectory output to MOVES operating mode input, and the GLOSA algorithm.

2.1. Study area

This study focuses on an intersection on the West Tennessee Street in the City of Tallahassee, Florida, U.S. (Figure 1a). The focused link starts at Duval Street and ends at N. Adams Street. The traffic lights are located at the four legged intersection on W. Tennessee St. and N. Adams St. The length of the link is approximately 300 ft. The link includes three through lanes and one left turn lane at the end of the link. This link is known to be the most congested link during peak hours among all links on the whole corridor, which was selected as a test bed corridor by the Florida Department of Transportation (FDOT) in 2016. As such, this study can contribute to the future CV implementations of FDOT by providing them the findings of the proposed environmental simulation analyses.



a) Image of the study corridor b) VISSIM model of the study corridor

Fig. 1 - Study area

2.2. Simulation models

Microscopic simulation is one of the methods to assess and foresee the results of engineering implementations in the context of time, safety and economy. In order to simulate GLOSA, VISSIM was used since it accepts custom vehicle controls by an external codes and algorithms through COM interface of the software. The simulation using the GLOSA algorithm is quite challenging since it requires the combined and synchronized traffic simulation model and the simulation of vehicle communication. In order to estimate the exhaust emission, one of the most advanced emission simulation model, namely EPA's Motor Vehicle Emission Simulator (MOVES) was used.

2.3. Simulation inputs

Although both VISSIM and MOVES require common types of data, MOVES requires more detailed vehicle-, traffic- and environment-related data as inputs. In this study, this required data was obtained from different types of sources. Traffic data (hourly volume including the off-peak and on-peak rates and hourly average link speed) were obtained from a private company, namely CITILABS through an on-going collaboration whereas vehicle composition and signal timing data were obtained from the Florida Department of Transportation (FDOT) [24]. Several other types of data such as those related to the vehicle age fraction and fuel formulation were based on the default values given in the MOVES since these data were not able to researchers.

2.4. The VISSIM model with GLOSA

VISSIM, developed by PTV [25], basically has two main internal components: the traffic flow simulator and signal state generator. One of the most important feature of VISSIM is that it accepts users to develop external codes, which allows the use of GLOSA model within VISSIM. The intersection mentioned above is built in VISSIM, and the GLOSA application is implemented on one of the major corridor legs of this intersection, the most congested one, with different CV penetration rates. Studying the most congested leg specifically helps observe the behaviour of the GLOSA in the total volume range. There are various studies that utilize GLOSA within a micro-simulation software using different languages to build the algorithm [9], [12], [23]. This study uses Visual Basic for the implementation. Basically, the objective of GLOSA algorithm is to inform the drivers about the desired speed needed to arrive at the intersection without stopping when the traffic light is green. Note that the volume data of the test link at this intersection during the peak hour and off-peak hour were used and a sensitivity analysis was conducted based on the gradual increase between these two volume values. Although there was very small difference between the desired volume value and the number of vehicles appeared in the simulation, we calibrated the volume data in VISSIM model using real-world historical data provided by CITILABS. However, calibration did not create a significant change on the results.

In the GLOSA algorithm, first, when the vehicle appears at the beginning of the VISSIM simulation link, GLOSA checks whether the vehicle is within the Dedicated Short Range Communication (DSRC) range or not. If the vehicle is in the range, the algorithm calculates the travel time of the vehicle until the vehicle's arrival at the intersection by its' current speed and position. This computation is required to understand if the vehicle is going to arrive at the intersection on green phase, and therefore, signal timing information such as cycle length and green time are required. If the condition is false, there will be no advisory on the speed which is indicated as 'Exit' in the flowchart. On the other hand, if it is possible to arrive at the intersection on the green phase within predefined possible maximum speed and minimum speed values, the GLOSA advises a desired speed to the driver. However, catching the green phase may not even be possible within that speed range. For this specific case, which is also indicated as 'Exit' in the flowchart, GLOSA advises the driver to slowly decelerate so that vehicle can stop at the red light. The algorithm also considers the intersection queue conditions in order to provide more accurate speeds for upcoming drivers. Previous studies show that there are multiple ways to decide whether a vehicle is in the queue or not. For example, Stevanovic et al. [12] demonstrated that a vehicle can be considered in a queue at the point when the vehicles' velocity drops under 2.2 mph. However, different micro-simulation software have their own representations and use different default values for this condition. For example, VISSIM has the default speed value of 3.1 mph to understand if a vehicle is in a queue or not [28]. In this study, this default speed value of VISSIM was used. The flowchart of the GLOSA process can be found in Figure 2.

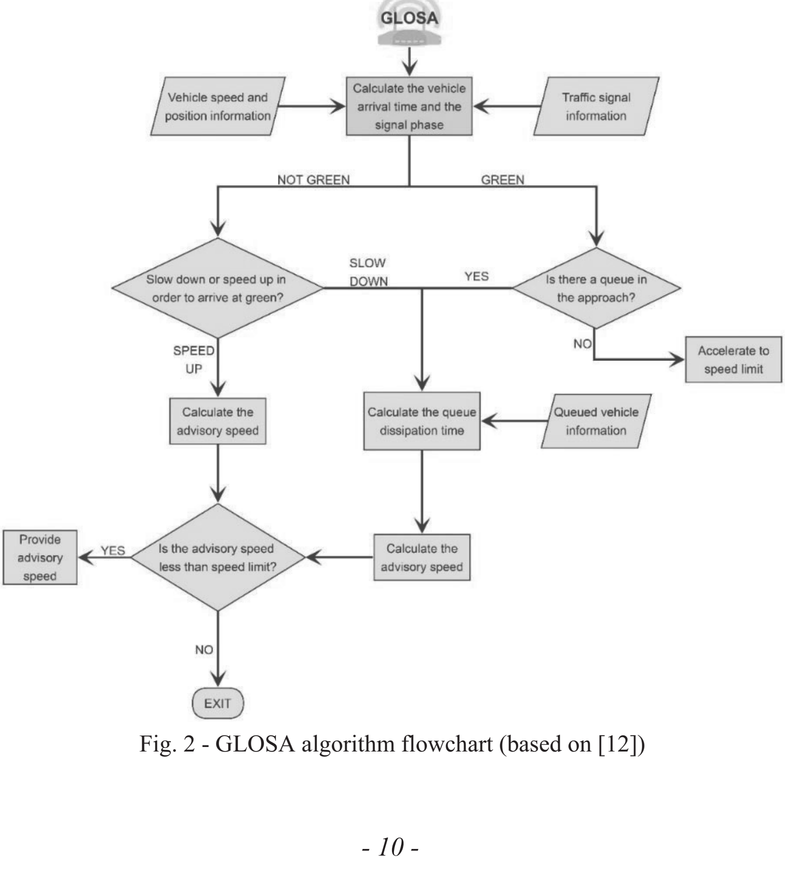


Fig. 2 - GLOSA algorithm flowchart (based on [12])

2.5. The MOVES model

In the late 1970s, the U.S. Environmental Protection Agency (EPA) developed a software called MOBILE to estimate exhaust emissions from a variety of different vehicle types [29]. The model is updated several times over the years until 2004. Later, EPA provided an upgraded software, namely MOVES, which extended the capabilities of MOBILE [30]. MOVES is a motor vehicle emission simulation software, which is able to calculate very accurate emission results. In addition, it is capable to calculate a great variety of air pollutant emissions including the particulate matter (PM) compared to other emission simulators. Many emission estimation software does not allow one to calculate the emission values for PM. However, prediction of PM emissions is crucial since particulate matter is quite hazardous for human health and environment. For example, a long term exposure to PM2.5 can result in not only cardiovascular and pulmonary diseases but also even DNA changes [31]. There are different levels of running MOVES, which are named as scales: national, county and project. For the purposes of this study, the most appropriate scaling was the project level since the focus is on a specific intersection rather than an area. The following data were used as inputs to the MOVES model:

- **Links:** Allows user to input link characteristics such as link volume, average link speed, link length and link grade.
- **Link Source Types:** Vehicle types and percentage of each vehicle type are the required information for this input tab. As mentioned before, vehicle composition data is obtained online from the Florida Department of Transportation [24]. Average vehicle composition is extracted from the lists and types of number of vehicles specifically for the Leon County, in which Tallahassee is located.
- **Fuel:** Fuel formulation, fuel supply, fuel usage fraction and alternative vehicle fuel table are needed as an input of fuel tab. Default values in MOVES are used.
- **Age Distribution:** MOVES default values for the age distribution of the vehicles are used.
- **Meteorology:** For the study location, MOVES default meteorology data are used as follows: temperature (80 F) and relative humidity (82%).
- **Operating Mode Distribution:** This tab allows user to enter the information on how vehicle is operated during the trip in terms of constant speed, acceleration, deceleration, cruising, braking and idling.

MOVES project level emission simulation also requires some general information related to the year, month, time, location and type of the roadways, for which summary of the input parameters are listed in Table 1.

2.6. Operating mode

Vehicle operating mode is basically the amount of time that vehicle has travelled in various driving conditions. Some of the driving conditions include acceleration, deceleration, braking, idling, and cruising. One of the most important input files for MOVES is the operating mode distribution file since vehicle exhaust emission depends mostly on the vehicle’s different operating modes. In this study, the operating mode distribution file was generated by an algorithm developed in an open source software, namely Python 3.0. The algorithm basically serves as the data conversion tool between VISSIM and MOVES, which uses the second-by-second vehicle trajectory data obtained as an output of VISSIM simulation, and provides the inputs needed by MOVES using this data. In order to assign a vehicle’s operating mode at any specific time, vehicle specific power was calculated first. In MOVES, there are 62 different operating mode bins; however, only 23 of them are for running pollutant process except the tirewear/brakewear pollutant process.

Tab. 1 - Summary of parameters

Location	Leon County, Florida
Year	2018
Month	July
Time	17:00–17:59:59 (1h)
Weekday/weekend	Weekday
Temperature	80 F
Humidity	82 %
Roadway type	Urban restricted
Types of vehicles	Passenger cars, single unit short-haul trucks, school buses
Type of fuel	Gasoline for passenger cars; diesel fuel for single unit short-haul truck and diesel fuel for school buses
Link Length	300 ft
Link traffic volume	120 to 1800 veh/hour
Average road grade	0 %
Link average speed	35 mph
Pollutants	CO, NO_x, PM2.5, PM10

2.7. Vehicle specific power

MOVES operating mode distribution bins were separated by both vehicle specific power (VSP) and speed snapshots of the specific time. Vehicle specific power is defined as the instantaneous power per unit mass of the vehicle [32]. The power is used to overcome air drag force and rolling resistance and if needed, to increase a vehicle's kinetic energy. Equation (1) was used to calculate a vehicle's specific power.

$$VSP = \frac{(C_R * v_t) + (C * v_t^2) + (C_D * v_t^3) + (m * v_t * a_t)}{m} \tag{1}$$

where

VSP: Vehicle specific power (kW/ton)
C_R: Vehicle rolling resistance (kW-sec/m)
C: Vehicle rotating resistance (kW-sec^2/m^2)
C_D: Vehicle air drag coefficient (kW-sec^3/m^3)
V_t: Velocity (m/sec)
a: Acceleration (m/sec^2)
m: Weight (metric ton)

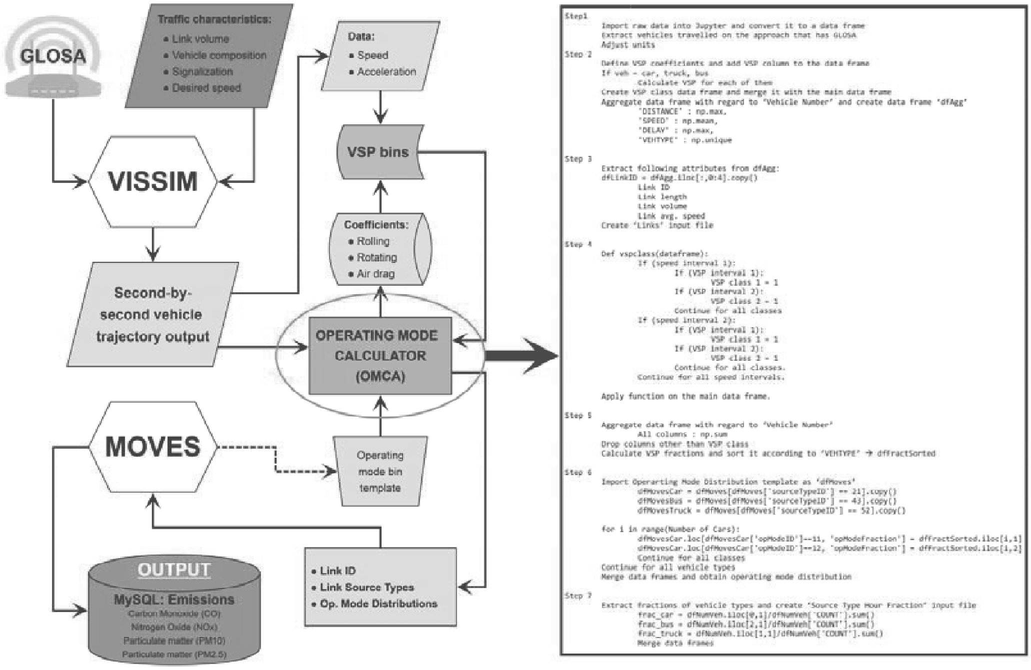
2.8. Operating Mode Calculation Algorithm (OMCA)

As aforementioned, the main purpose of developing the OMCA is to create the MOVES operating mode distribution input based on the second-by-second vehicle trajectory data obtained from the VISSIM model simulation. A powerful open source programming language, Python 3.0 was used to develop the algorithm. Note that second-by-second vehicle trajectory includes the following variables for every 0.1 second of the simulation:

- Simulation second
- Acceleration
- Speed
- Vehicle type
- Vehicle no
- Distance travelled
- Delay

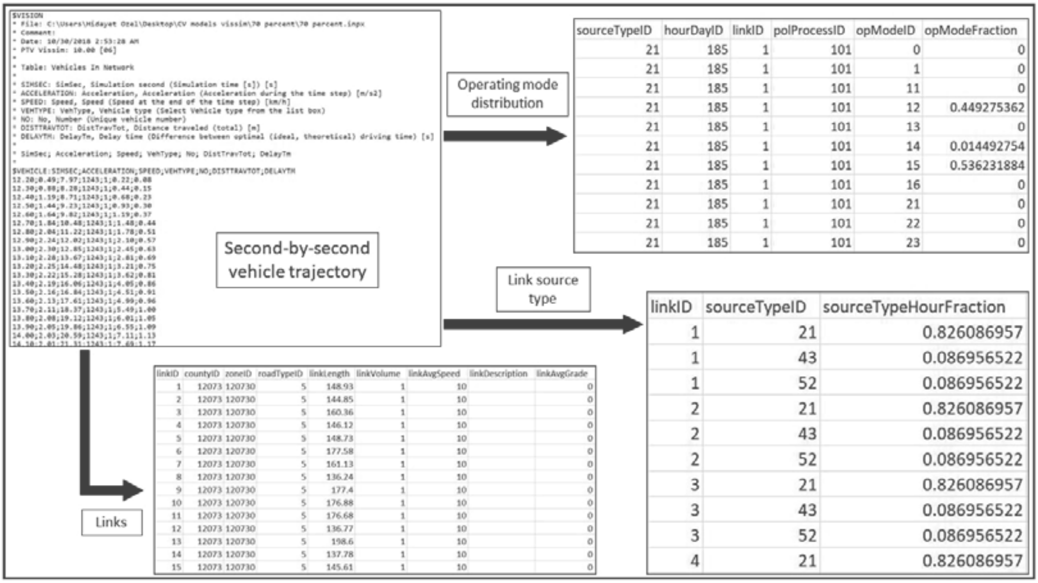
The overall process of the algorithm is demonstrated through the flowchart shown in Figure 3. The pseudo code of the algorithm is also given in the Appendix A. For MOVES, the key input files are “Links”, “Link Source Type” and “Operating Mode” for the emission calculation since other inputs are mostly include default data such as the fuel formulation and vehicle age distribution. The biggest challenge of directly integrating VISSIM and MOVES is the fact that they are not compatible. That is, VISSIM’s input cannot be directly used as an input to MOVES. As such, there is a need to convert the data to an entirely different format while keeping all the necessary information with it. Second-by-second trajectory data of VISSIM has extremely detailed tracking information consisting of millions of rows. However, operating mode distribution file needed to run MOVES only stores summarized data such as VSP proportions of vehicles. The OMCA algorithm starts the conversion process by calculating the VSP of every vehicle for each tenth of a second and assigns it to the related operating mode number specified in MOVES operating mode excel sheet. This is followed by assigning these numbers to every vehicle in order to calculate emission values. Brief of file contents can be found in Figure 4.

As mentioned, one of the most significant advantages of OMCA is that it does not consider the average operating mode of vehicles travelling on the same link. It rather calculates the exact operating mode distribution of each vehicle in the traffic. In order to achieve this, the distance travelled by each vehicle in the system is calculated, and then each travel is assigned to MOVES as one individual link. In contrast to this detailed calculation, studies in the literature compute an average operating mode distribution for every link [22], [23]. Even though this approach gives more accurate emission results than simply considering average speed and volume rate of the links, it is less accurate than considering operating mode of every single vehicle individually, which is proposed in this study.



```
Step1
        Import raw data into Jupyter and convert it to a data frame
        Extract vehicles travelled on the approach that has GLOSA
        Adjust units
Step 2
        Define VSP coefficients and add VSP column to the data frame
        If veh = car, truck, bus
                Calculate VSP for each of them
        Create VSP class data frame and merge it with the main data frame
        Aggregate data frame with regard to 'Vehicle Number' and create data frame 'dfAgg'
                'DISTANCE' : np.max,
                'SPEED' : np.mean,
                'DELAY' : np.max,
                'VEHTYPE' : np.unique

Step 3
        Extract following attributes from dfAgg:
        dfLinkID = dfAgg.iloc[:,0:4].copy()
                Link ID
                Link length
                Link volume
                Link avg. speed
        Create 'Links' input file

Step 4
        Def vspclass(dataframe):
                If (speed interval 1):
                        If (VSP interval 1):
                                VSP class 1 = 1
                        If (VSP interval 2):
                                VSP class 2 = 1
                        Continue for all classes
                If (speed interval 2):
                        If (VSP interval 1):
                                VSP class 1 = 1
                        If (VSP interval 2):
                                VSP class 2 = 1
                        Continue for all classes.
                Continue for all speed intervals.

        Apply function on the main data frame.

Step 5
        Aggregate data frame with regard to 'Vehicle Number'
                All columns : np.sum
        Drop columns other than VSP class
        Calculate VSP fractions and sort it according to 'VEHTYPE' → dfFractSorted

Step 6
        Import Operarting Mode Distribution template as 'dfMoves'
                dfMovesCar = dfMoves[dfMoves['sourceTypeID'] == 21].copy()
                dfMovesBus = dfMoves[dfMoves['sourceTypeID'] == 43].copy()
                dfMovesTruck = dfMoves[dfMoves['sourceTypeID'] == 52].copy()

        for i in range(Number of Cars):
                dfMovesCar.loc[dfMovesCar['opModeID']==11, 'opModeFraction'] = dfFractSorted.iloc[i,1]
                dfMovesCar.loc[dfMovesCar['opModeID']==12, 'opModeFraction'] = dfFractSorted.iloc[i,2]
                Continue for all classes
        Continue for all vehicle types
        Merge data frames and obtain operating mode distribution

Step 7
        Extract fractions of vehicle types and create 'Source Type Hour Fraction' input file
                frac_car = dfNumVeh.iloc[0,1]/dfNumVeh['COUNT'].sum()
                frac_bus = dfNumVeh.iloc[2,1]/dfNumVeh['COUNT'].sum()
                frac_truck = dfNumVeh.iloc[1,1]/dfNumVeh['COUNT'].sum()
                Merge data frames
```

Fig. 3 - The OMCA algorithm



```
$VISION
* File: C:\Users\Hidayet Ozel\Desktop\CV models vissim\70 percent\70 percent.inpx
* Comment:
* Date: 10/30/2018 2:53:28 AM
* PTV Vissim: 10.00 [06]
*
* Table: Vehicles In Network
*
* SIMSEC: SimSec, Simulation second (Simulation time [s]) [s]
* ACCELERATION: Acceleration, Acceleration (Acceleration during the time step) [m/s2]
* SPEED: Speed, Speed (Speed at the end of the time step) [km/h]
* VEHTYPE: VehType, Vehicle type (Select Vehicle type from the list box)
* NO: No, Number (Unique vehicle number)
* DISTTRAVTOT: DistTravTot, Distance traveled (total) [m]
* DELAYTM: DelayTm, Delay time (Difference between optimal (ideal, theoretical) driving time) [s]
*
* SimSec; Acceleration; Speed; VehType; No; DistTravTot; DelayTm
*
$VEHICLE:SIMSEC;ACCELERATION;SPEED;VEHTYPE;NO;DISTTRAVTOT;DELAYTM
12.20;0.49;7.97;1243;1;0.22;0.08
12.30;0.88;8.28;1243;1;0.44;0.15
12.40;1.19;8.71;1243;1;0.68;0.23
12.50;1.44;9.23;1243;1;0.93;0.30
12.60;1.64;9.82;1243;1;1.19;0.37
12.70;1.84;10.48;1243;1;1.48;0.44
12.80;2.04;11.22;1243;1;1.78;0.51
12.90;2.24;12.02;1243;1;2.10;0.57
13.00;2.30;12.85;1243;1;2.45;0.63
13.10;2.28;13.67;1243;1;2.81;0.69
13.20;2.25;14.48;1243;1;3.21;0.75
13.30;2.22;15.28;1243;1;3.62;0.81
13.40;2.19;16.06;1243;1;4.05;0.86
13.50;2.16;16.84;1243;1;4.51;0.91
13.60;2.13;17.61;1243;1;4.99;0.96
13.70;2.11;18.37;1243;1;5.49;1.00
13.80;2.08;19.12;1243;1;6.01;1.05
13.90;2.05;19.86;1243;1;6.55;1.09
14.00;2.03;20.59;1243;1;7.11;1.13
14.10;2.01;21.31;1243;1;7.69;1.17
```

sourceTypeID	hourDayID	linkID	polProcessID	opModeID	opModeFraction
21	185	1	101	0	0
21	185	1	101	1	0
21	185	1	101	11	0
21	185	1	101	12	0.449275362
21	185	1	101	13	0
21	185	1	101	14	0.014492754
21	185	1	101	15	0.536231884
21	185	1	101	16	0
21	185	1	101	21	0
21	185	1	101	22	0
21	185	1	101	23	0

linkID	sourceTypeID	sourceTypeHourFraction
1	21	0.826086957
1	43	0.086956522
1	52	0.086956522
2	21	0.826086957
2	43	0.086956522
2	52	0.086956522
3	21	0.826086957
3	43	0.086956522
3	52	0.086956522
4	21	0.826086957

linkID	countyID	zoneID	roadTypeID	linkLength	linkVolume	linkAvgSpeed	linkDescription	linkAvgGrade
1	12073	120730	5	148.93	1	10		0
2	12073	120730	5	144.85	1	10		0
3	12073	120730	5	160.36	1	10		0
4	12073	120730	5	146.12	1	10		0
5	12073	120730	5	148.73	1	10		0
6	12073	120730	5	177.58	1	10		0
7	12073	120730	5	161.13	1	10		0
8	12073	120730	5	136.24	1	10		0
9	12073	120730	5	177.4	1	10		0
10	12073	120730	5	176.88	1	10		0
11	12073	120730	5	176.68	1	10		0
12	12073	120730	5	136.77	1	10		0
13	12073	120730	5	198.6	1	10		0
14	12073	120730	5	137.78	1	10		0
15	12073	120730	5	145.61	1	10		0

Fig. 4 - Data conversion operation through the OMCA

As such, the proposed framework allows us to obtain more accurate emission rates by calculating the amount of emission for every single vehicle in the simulation. However, this approach also brings an issue that limits the size of the data input to MOVES since average values are not considered anymore. By this approach, the calculation of the distribution of every single vehicle results in tremendous amount of data. The limit of the operating mode distribution file of MOVES is around 70 thousands of rows, which indicates that it can calculate only around 750 or less number of vehicles at the same time for given pollutants in this study. However, the proposed approach is still viable due to the technological advances and can provide better emission estimates than other approaches in the literature. Another solution is dividing the VISSIM tracking output into small pieces and creating each operating mode file by OMCA, which is less than 70 thousands of rows. After calculating the emission results for each file and summing up the results, the total emission values of vehicles are obtained even the network contains more than 750 vehicles.

3. Results and discussion

In this paper, a VISSIM-MOVES integration framework was developed to calculate the most accurate emission rate for each vehicle individually travelling through an intersection. Moreover, the effect of GLOSA on the vehicle exhaust emission was investigated. Total emission changes, with respect to volume changes and connected vehicle penetration rates, were examined for four main pollutants: carbon monoxide (CO), nitrogen oxides (NOx), primary exhaust smaller than 2.5 micrometer (PM2.5) and primary exhaust smaller than 10 micrometer (PM10). The off-peak and peak hour volume values for the link were 120 veh/h and 1,800 veh/h, respectively, and they were obtained from CITILABS. Six different gradually increasing volume rates were simulated starting from 120 veh/h to 1,800 veh/h (Table 2 and Table 3). The simulation time was up to 1 hour in MOVES and 15 minutes for VISSIM. Working with the large size of data on MOVES is very time consuming; however, although VISSIM is capable to run 3,600 secs of simulation quickly, running external GLOSA code on the VISSIM's COM interface made the simulation even longer. Therefore, we used six volume rates only. For each volume rate, six different connected vehicle penetration rates were considered. That is, values ranging from 0% to 100% were simulated in the increments of 20%. Again, because of the time and computational power limitations, this range was also limited by six values only. Since the data conversion and post-processing steps as well as the simulation itself were computationally time intensive, six gradually increasing volume data points were utilized, which is a limitation of the study. This can be expanded in order to have the volume rates in between. Also, the peak reduction rates obtained were site-specific given the specific traffic characteristics, and will be different at another intersection.

Each scenario was simulated 10 times, which makes a total of 360 simulations in total in VISSIM. Then, total stop delay per vehicle and total number of stops per vehicle were calculated as shown in Table 2 and 3. Total stop delay per vehicle is the total delay calculated by stops divided by number of vehicles on the approach. Total number of stops per vehicle, on the other hand, is the total number of stops occurred in the approach divided by the number of vehicles. Last column of the tables indicates the percentage of emission reduction, which is the maximum reduction rate that occurs between 0% and 100% CV penetration.

Findings indicate that reduction rates for the stop delay can be up to 83.9% and the number of stops per vehicle can be reduced by 87.9% as a result of utilizing the GLOSA application within the proposed framework. This is consistent with the findings of Anderson et al. [33], which shows that CVs lead to fewer stop-and-go driving under V2I connectivity. Also, this loss-time reduction values are even better compared to the results of the study by Erdmann [34]. The study found out that the delay was reduced up-to 72% on the link by utilizing GLOSA with a volume rate changing between 200 veh/h and 2,000 veh/h.

Tab. 2 - Total stop delay (veh/sec)

Volume (veh/h)	**Connected Vehicle Penetration (%)**						**Reduction Rate (%) (between 0-100)**
	0	**20**	**40**	**60**	**80**	**100**	
120	16.19	13.47	12.77	11.66	7.86	3.33	79.4
480	19.08	13.74	11.91	8.69	6.12	3.55	81.4
780	20.79	17.64	14.21	9.72	4.99	3.78	81.8
1,120	24.71	18.72	13.1	7.48	5.03	4.06	83.6
1,450	31.61	23.56	17.17	11.15	7.94	6.28	80.1
1,800	32.66	24.01	15.34	10.05	6.21	5.27	83.9

Tab. 3 - Total number of stops per vehicle

Volume (veh/h)	**Connected Vehicle Penetration (%)**						**Reduction Rate (%) (between 0-100)**
	0	**20**	**40**	**60**	**80**	**100**	
120	0.99	0.77	0.72	0.64	0.33	0.12	87.9
480	0.96	0.85	0.73	0.52	0.46	0.16	83.3
780	1.03	0.87	0.75	0.54	0.48	0.29	71.8
1,120	1.24	1.15	1.15	0.72	0.51	0.39	68.5
1,450	1.48	1.39	1.36	1.24	1.03	0.61	58.8
1,800	1.6	1.57	1.52	1.31	1.06	0.81	49.4

A closer look at our results show that the maximum reduction in the stop delay occurs at the peak volume; however, the maximum reduction in the number of stops per vehicle occurs at the lowest traffic volume.

Future direction of research will be tailored to study this interesting phenomenon. Total number of stop reduction by GLOSA-equipped vehicle penetration is the clearest result of this study. Although GLOSA has a significant effect on number of stops, volume rate is another major effect on this variable. By increasing the volume rate, the amount of reduction on number of stops diminishes. Therefore, GLOSA efficiency is reduced for high volumes regarding the number of stops.

In addition to the findings associated with operational benefits, MOVES results also indicate clear reduction in emission rates. Emission rates of each pollutant were estimated for running and idling operating modes separately. In total, 36 different simulation scenarios were built and run in MOVES. Total and average reduction rate of pollutants for different volume rates can be found in Table 4. Note that total reduction rates for each volume rate is the maximum reduction rate which occurs between 0 % and 100% CV penetration rates. Results indicate that the maximum reduction (40.3%) occurs for the NO_x. This value is very close to the NO_x reduction (35%) shown in Tielert et al. [15]. CO, on the other hand, is reduced by 26% whereas PM2.5 and PM10 are reduced by 39.4% and 39.5%, respectively. Note that these values are the average reduction rates calculated by using six different volume scenarios. In addition, the findings indicate that the peak reduction rates were obtained either at 480 veh/h or at 1,450 veh/h volume rates. The variation of the reduction rates is the result of different traffic characteristics and different GLOSA-equipped vehicle penetration rates. Also, the length of the link has an effect on the variation since it directly affects the traffic congestion.

Results show that both delay and pollutant emissions are reduced significantly by the proposed framework that utilizes the GLOSA application. Reduction rate with respect to volume for CO, NO_x, PM2.5 and PM10 can be up to 30.5%, 49.5%, 51.09% and 51.2%, respectively. Note that PM2.5 and PM10 emission rates are different; however, the reduction rates are similar, which indicates that there is a strong correlation for PM emission values even though their sizes are different. Results also indicate that idling emission reduction is quite higher than running emission reduction, which is expected since GLOSA decreases the number of stops and total stop time. In addition, findings indicate that the stop delay can be reduced by 83.9% and the number of stops per vehicle can be reduced by 87.9%.

Visual comparison of the change in running and idling emission values of pollutants with respect to different volumes are shown in Figure 5 through Figure 8. According to the findings, all pollutant values were reduced substantially, up to 93% reduction for the idling mode. This is a considerable reduction especially for particulate matters since idling emission rates of particulate matters are relatively high compared to running emissions of all other pollutants.

Tab. 4 - Emission reduction rates

Pollutant	**VOLUME (veh/h)**						**Average Reduction rate (%)**
	120	**480**	**780**	**1,120**	**1,450**	**1,800**	
CO	21.8625	30.1016	25.7698	20.6467	30.5325	26.8471	26.0
NOx	27.9387	49.5058	42.5313	29.567	48.4834	43.6123	40.3
PM2.5	21.7539	51.0895	43.4309	26.6031	49.5029	43.9799	39.4
PM10	21.936	51.2008	43.5421	26.7295	49.5951	44.0915	39.5

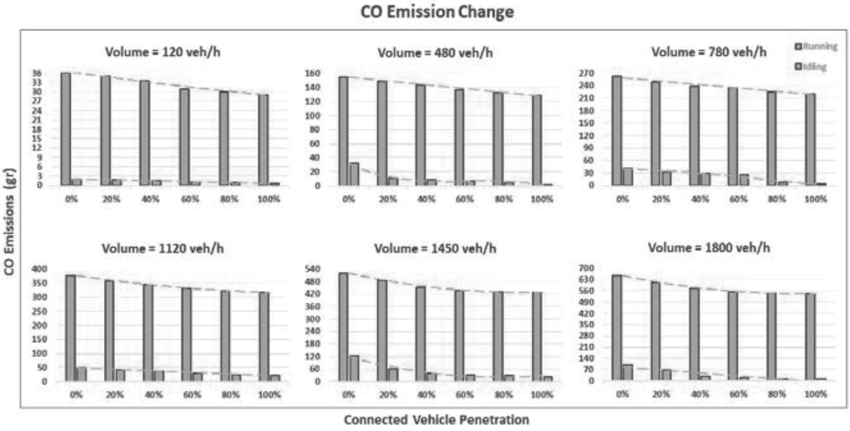


Fig. 5 - CO Emissions

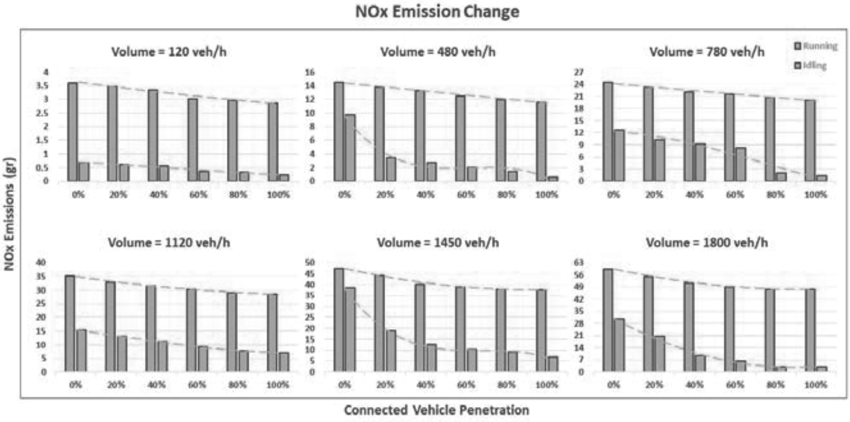


Fig. 6 - NO_x Emissions

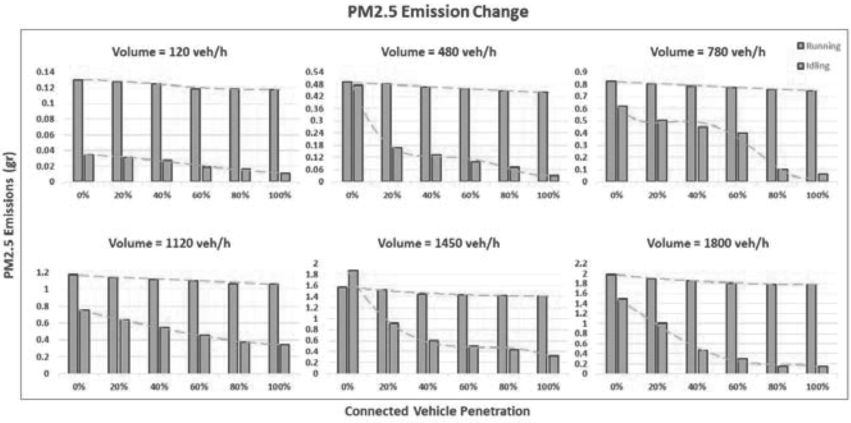


Fig. 7 - PM2.5 Emissions

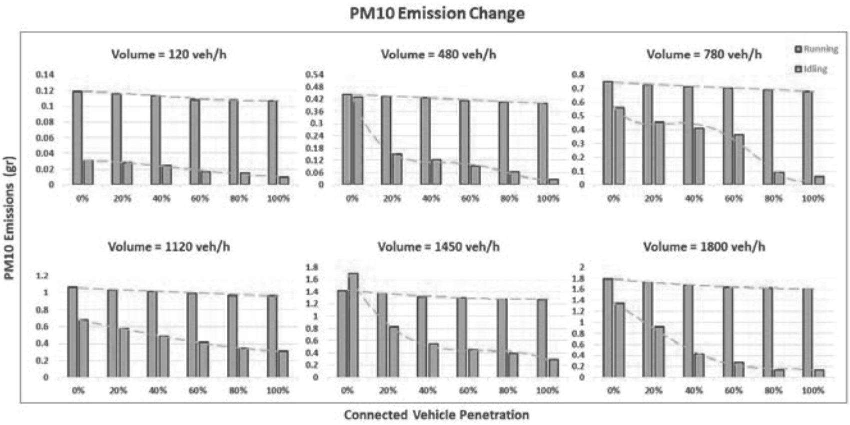


Fig. 8 - PM10 Emissions

4. Conclusions and future work

This paper develops an integrated framework, which makes use of two well-known simulation software, namely VISSIM and EPA's Motor Vehicle Emission Simulator (MOVES). First, an intersection in the City of Tallahassee, Florida was built in VISSIM, and one of the widely used vehicle-to-infrastructure (V2I) communication application called Green Light Optimized Speed Advisory (GLOSA) was implemented on the major leg of this intersection with different CV penetration rates. This was followed by simulations run for six different volume rates from off-peak hour volume to on-peak hourly volume. Obtained second-by-second VISSIM trajectory data was fed into MOVES after converting the data to MOVES input format using the developed operating mode calculation algorithm (OMCA). This algorithm was developed only for this specific data transformation: VISSIM trajectory output file to MOVES input files in terms of links, link source types, and operating mode distribution. Finally, MOVES was run in order to estimate carbon monoxide (CO), nitrogen oxides (NO_x), primary exhaust smaller than 2.5 micrometer (PM2.5) and primary exhaust smaller than 10 micrometer (PM10) emissions.

GLOSA-equipped vehicle impact on traffic was investigated in terms of emission results, number of stops per vehicle and stop delay per vehicle. Results show that both delay and pollutant emissions are reduced significantly by the proposed framework that utilizes the GLOSA application. Reduction rate with respect to volume for CO, NO_x, PM2.5 and PM10 can be up to 30.5%, 49.5%, 51.09% and 51.2%, respectively. Note that PM2.5 and PM10 emission rates are different; however, the reduction rates are similar, which indicates that there is a strong correlation for PM emission values even though their sizes are different. Results also indicate that idling emission reduction is quite higher than running emission reduction, which is expected since GLOSA decreases the number of stops and total stop time. In addition, findings indicate that the stop delay can be reduced by 83.9% and the number of stops per vehicle can be reduced by 87.9%. Findings of the study can aid researchers in understanding the effect of smoother and lower number of stop-and-go driving operations on the exhaust emission due to the CV involvement, and in quantifying the potential operational and environmental benefits of CVs.

As a future work, other parameters can be added to the calculations. For example, the link grade and weather information [35] or vehicle-induced turbulence [36] for high speed corridors can be