# A Model-Based Evaluation of an ECO-Driving System Using Connected Vehicle Technologies

Matthew Muresan, MASc Student
S M Kamal Hossain, Postdoctoral Fellow
Liping Fu, Ph.D., P.Eng., Professor
iTSS Lab, Department of Civil & Environmental Engineering
University of Waterloo, Waterloo, N2L3G1, Ontario, Canada

## Abstract:

Connected vehicle technologies are often touted for their potential applications to vehicle safety. However, these technologies also have the potential to contribute to a transportation system's sustainability. Autonomous and connected vehicles provide traffic engineers with many opportunities for emissions reductions, from vehicle routing to a vehicle's acceleration pattern. This paper presents the results of traffic and emissions micro-simulations that assess an emissions-based intersection approach driving pattern. The analysis was conducted on a traffic corridor simulated using VISSIM. Communication between vehicles and infrastructure on the network was modelled in the software, and vehicles made decisions on their desired acceleration and speeds based on an emission reduction algorithm. Simulation was done for varying penetration levels, simulating mixed-market environments. The results of the VISSIM model were fed into the US EPA's MOVES2014 emission model to generate an estimate of emissions for each associated scenario. The results of the study show that automated and connected vehicle technologies have the potential to reduce vehicle emissions.

## 1 Introduction

Connected vehicles are a much-discussed topic in current literature. Broadly speaking, there are two major forms of connected vehicle technologies: Vehicle-to-vehicle (V2V) communications and vehicle-to-infrastructure (V2I) communications. These technologies could provide network operators, drivers and researchers with data on an unparalleled scale, and many different ways to take advantage of these systems have been proposed. One potential method is the use of signal phase and timing (SPaT) data that could be broadcasted using V2I communications and analysed to minimize the emissions of a vehicle. These "Eco-driving" systems have been previously proposed in the literature. The effect of driving behaviour on emissions is a well-studied phenomenon, and Eco-driving systems seek to exploit this by directing vehicles to select actions that minimize emissions. Since vehicles are likely to remain under the control of human drivers for the foreseeable future, research in this area often focuses on a driver advisory system. Under such a system, a device advises the driver of the optimal speed to travel, and the driver then adjusts their speed to meet those requirements (Xia et al 2012) (See Figure *1*). Such systems would, obviously, have limitations in real-world situations in the form of adoption (market penetration) and compliance. On the balance though, previous research has shown that these systems have potential, and similar concepts will no doubt have a role to play in the networks of the future. Although the United States Department of Transportation is conducting an extensive modelling effort under the AERIS program (United States Department of Transportation 2015), opportunities for substantial additional work still remain.

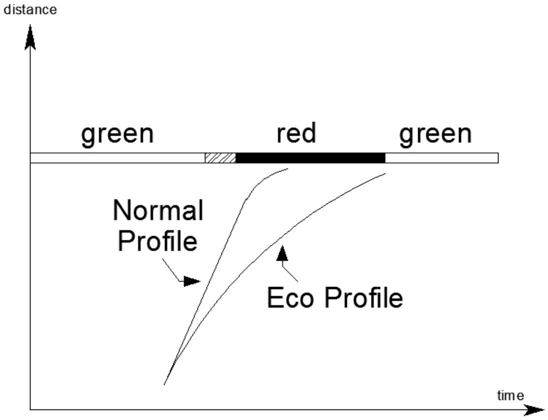

Figure 1 - This space-time diagram depicts a possible trajectory that avoids stopping/accelerating, thereby reducing emissions when compared to a trajectory involving a stop and acceleration.

While a number of studies have been conducted to date proposing methods by which ECO-driving systems could reduce emissions, few studies have evaluated its ability to do so beyond simple comparisons on individual vehicles.

## 2 Background Literature

The aspects of travel that an ECO-driving system attempts to change are similar in concept to signal-based systems. Indeed, one of the benefits of V2I communications is the increased ability to collect real-time data on traffic conditions and then adapt the signal timing to reduce emissions in much the same way an ECO-driving system would (that is, by reducing the idle-time of vehicles), as demonstrated by past research (Stevanovic et al 2009). Within the realm of ECO-driving, past research has shown a number of different ways by which emissions (and fuel consumption) can be reduced. According to (Mandava et al 2009), the simplest algorithm solves the following optimisation problem:

$$\max\left(v=\frac{D}{t_p}\right);\ \text{ where}\begin{cases} t_p \in \left[t_g, t_r\right) \text{ or } t_p = t'_g, & \text{if } s = red\\ t_p \in [0, t_r) \text{ or } t_p = t'_g, & \text{if } s = green \end{cases} \qquad \text{(Equation 1)}$$
$$\text{such that } v \le v_{limit}$$

In equation (1), $t_g$ and $t_r$ are the green and red times respectively of the signal, $t_p$ is the phase time being considered for optimisation, *D* is the distance to the signal and *v* is the optimised velocity of the vehicle. The goal is to find the maximum speed that avoids a stop at the traffic light. This algorithm considers only the signal ahead of the vehicle, but other studies have shown that more optimal paths may be found if multiple signals are considered in the evaluation (De Nunzio et al 2013). The downside of this approach is that the intended path a vehicle wishes to choose must be known, and that relevant SPaT (or speed) information also be provided to the vehicle. In an advisory context, drivers may be more distrustful of the system if it appears to intentionally skip green lights that would otherwise be achievable.

On a per-vehicle basis, a previous study by Li et al (Li et al 2009) has shown that an individual vehicle has the potential to reduce its emissions and fuel consumption by up to 7% and 8% respectively, and another by Barth et al (Barth et al) showed potential reductions in fuel consumption and CO2 emissions by about 12%. Another study done by Xia (Xia et al 2013) analysed the effect of a number of different parameters on an advanced algorithm that included V2I-based communications. The researchers conducted a sensitivity analysis and found that communication range had a strong effect on their algorithm's effectiveness. Fuel savings ranged from 30% with infinite range to below 5% with only 200m of communication. The range of any communication system will ultimately depend on the technology applied; and can theoretically be limitless.

## 3 Methodology

This paper seeks to explore the effect of an eco-driving system on an entire network, at varying penetration levels. While many studies have explored the benefits of such proposals on a per-vehicle basis, few studies have examined these effects on a network-level and even fewer consider this in the context of a connected-vehicle paradigm. Therefore, to achieve the aims of the research, a traffic micro-simulation model and the US EPA's pollution micro-simulation model (MOVES2014) were selected. Both models are robust and highly configurable. The following sections highlight relevant details about each tool and the proposed scenarios. A summary of the overall modelling process is shown in Figure *2* and relevant details are provided in the following sections.

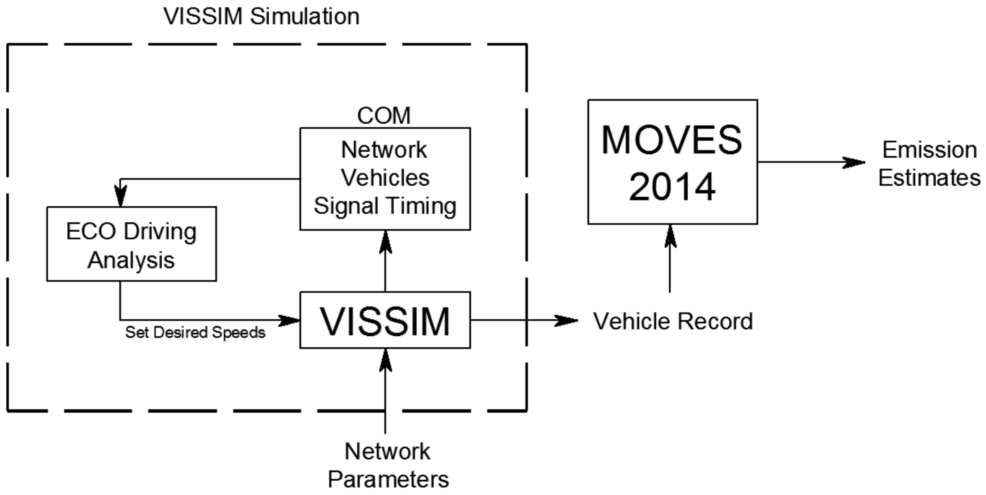

Figure 2 - An ECO-driving program runs with the traffic micro-simulation model (VISSIM), setting desired speeds for vehicles when relevant. The results are passed to MOVES2014 to estimate emissions.

### 3.1 Traffic Micro-simulation

This research was conducted with the use of VISSIM, which is a commercial micro-simulation model capable of simulating many aspects of a network's operation. The modeller is required to specify a number of parameters as well as supply or design a network complete with traffic signals. Although outside the scope of this research, it is important to recognize that the default values supplied for many of the parameters may not reflect actual local conditions, as indicated by previous studies (Jie et al). While this caveat limits the transferability of any results generated, it is believed to not detract significantly from analysing the merits or lack thereof of the proposed system.

A traffic corridor consisting of 5 intersections (as shown in Figure *3*) was designed in the traffic micro-simulator for this study. The network modelled is a corridor with a layout derived from a real-world urban roadway in Hamilton, Ontario. Of the five signalised intersections, four are "minor" and one is "major". The corridor roadway is a two lane road, which was selected to maximize the perceptibility of the benefits of a speed advice system. Vehicles assigned to follow an ECO-driving profile by the methods described in section 3.2 will force vehicles behind to also slowdown, theoretically increasing the potential benefits at lower penetrations since vehicles cannot pass it. This potential effect, while not directly examined in this paper, is an interesting concept, and a comparison between different roadway types, including multi-lane cases, is worth further research.

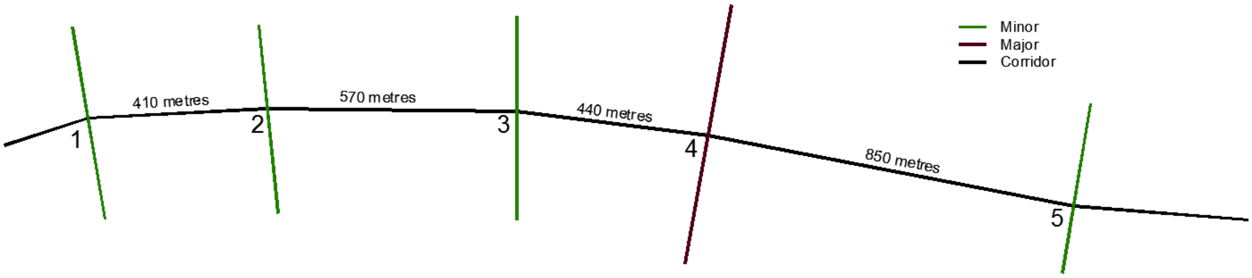

Figure 3 - The network, showing all intersections, used in the simulation

Past research has shown that high congestion can decrease the effectiveness of eco-based intervention (Ilgin Guler et al 2014) (Li et al 2009), but also that ECO-driving systems are less effective when volumes are too low (Xia et al 2013)  Parameters for this network were chosen to reflect moderate-use conditions. A variety of different conditions could be tested, but limitations in terms of time and computing power meant only certain scenarios can be tested. Since the market penetration of such systems is highly variable and influential, for this research, volume and signal configuration remained static throughout the analysis while penetration rate was varied. The following table summarises the volumes for each of the roadways.

Table 1 - Summary of Volume Inputs

| Roadway | Volume (vph) | Roadway | Volume (vph) |
|---|---|---|---|
| EB Corridor (1→5) | 500 | Major Street (both ways) | 750 |
| WB Corridor (5→1) | 350 | Minor Street (both ways) | 200 |

Vehicles are permitted to turn at intersections, and turning movement ratios were set at 5% each for left and right turns at minor intersections and 10% at the major intersection. Vehicle composition was set at 10% light commercial vehicles (i.e. trucks) and 90% passenger cars. Speed limits on all roads were set at 50kph, however the micro-simulation platform allows for vehicles to exceed or fall short of set limits. The selection of a speed limit will likely influence results strongly, as higher limits enable more flexibility with the selection of an ECO-Driving speed. This study is designed to reflect typical conditions that motorists would face on an urban roadway. In these cases, at least in Canada, speed limits often fall between 50 and 60kph. Proper optimisation of the signals was also identified as important in this study, as platoons of vehicles able to ride a “green wave” can pass through all signals unhindered without intervention from an ECO-driving system. Signals were optimised according to methods prescribed in the Highway Capacity Manual (National Research Council 2010) using the volumes specified in the table above. Accordingly, offsets were also set to minimize delay, giving good signal progression across all minor streets in the primary (EB) direction. The major intersection operates independently and has a cycle length different than those on the minor street. This configuration was selected to maximise applicability to real-world scenarios and to allow the system evaluated to show positive effects as well.

### 3.2 The Component Object Model (COM) & ECO-Driving System

Although VISSIM provides no easy way to natively simulate the concepts studied in this paper, the software is highly customizable through its Component Object Model (COM) system. This system allows the modeller to obtain all the details of the current simulation, such as vehicle positions, traffic signal states and network configuration, and also allows the modeller to change a variety of parameters, such as a vehicle’s desired speed or the current signal timing. The COM interface can be accessed from a variety of different programming languages, including Python, C# and Visual Basic for Applications. The selection of a specific language is up to the modeller, and in this instance C# was selected due to familiarity. To simulate the effects of the proposed eco-driving system, a C# program was written to interface with the traffic micro-simulation model. This program uses vehicle position and signal phase timing to recommend speeds to vehicles assigned to follow an eco-driving model. The program is constrained by the parameters of the traffic micro-simulation model described in section **Error! Reference source not found.** and recommends speeds based on the equation (1) in section 2. Additionally, the range of communications is limited to 400 metres (vehicles in excess of 400m from a signal drive normally), and the model only considers the nearest signal. This represents one of the easiest form of ECO-Driving to deploy, and arguably the form that is most likely to occur if such systems are deployed on a wide scale. Under this model, no information regarding the path of a vehicle is required. Since the traffic micro-simulation platform includes a robust car following model and since setting a vehicles desired speed still forces it to accelerate or decelerate in a realistic manner, no additional effort is required from the ECO-Driving program; however, speeds were retargeted on a per-second basis to accommodate variability in driving conditions and acceleration/deceleration rates.

### 3.3 MOVES2014

The MOtor Vehicle Emissions Simulator (MOVES) is a tool developed by the United States Environmental Protection Agency (EPA) to simulate and analyse emissions from mobile sources. The MOVES suite is the successor to the older MOBILE models developed by the EPA and is a well-researched and analysed model. MOVES is a multiple-scale analysis tool and comes loaded with an extensive database and facilitates analysis on a nation, state, county or project level. At the project level, MOVES is able to estimate emissions from individual links based on provided input. In this case, the vehicle record (that is, the position, speed and acceleration for each vehicle each second) was exported from the traffic micro-simulator and converted into a format MOVES can understand. Because of limitations inherent in MOVES project-level analysis, only one hour can be simulated at a time. Although MOVES is primarily aimed at US counties and cities, it is possible to add user-prepared data if it is available. For the purposes of this work, an arbitrary region was selected for the modelling which provides a starting set of default inputs for the model. These inputs include weather data, vehicle age distributions, fuel source types and a variety of other inputs. These inputs, in combination with vehicle inputs (trajectory, vehicle type), are used by MOVES to estimate the emissions of a proposed network. No additional inputs were provided to MOVES beyond those generated from the micro-simulation model (vehicle type and trajectory).

### 3.4 Simulation Runs

For this research, four scenarios were run. The first scenario was a benchmark, with no modifications, running at default conditions. The remaining scenarios modified the trajectories of vehicles at varying penetration rates, with the aim of gauging the effect of market penetration. Tests were done at 10%, 25% and 50% penetration. Because of the computational load placed on MOVES when provided with extensive vehicle trajectories, and because of limitations of computing power, each scenario could only be run once. The micro-simulation model used in this study allows specification of a seed which it uses to generate vehicle flows and other random parameters. In lieu of multiple runs, the same seed was used for each run.

## 4 Results

MOVES is a highly configurable model, able to output data on a variety of pollutants. For this research, MOVES was configured to output data on total energy consumed (KJ), $CO_2$ emissions, and other emissions such as NOx. The relevant outputs are summarized in Figure *4* relative to the control scenario. These figures are aggregated for all vehicles in the scenario, including those not operating under an ECO-driving plan. For the most part, as has been noted in previous studies (Xia et al 2013), a decrease in fuel consumption translated to a similar reduction in emissions. The results of this simulation show some potential for emissions and fuel consumption reductions, but the values were not as high as expected. Improvements to the algorithm, by way of increasing the communication distance or through the consideration of multiple signals could improve the situation; however, as is the case in the real world, ECO-driving strategies are only effective if a vehicle would otherwise be stopping at an intersection. In the case of these scenarios, steps were taken to optimise the traffic signals by setting signal offsets and green ratios based on traffic volumes. This aspect has often not been considered in previous studies that examine these effects on a network level (Xia et al 2013) for reasons of simplification. However, the ability of vehicles to form "green waves" and avoid stopping at lights altogether can mute the positive benefits of these strategies. This is also evident in the lack of a strong response when changing the penetration rate, though some positive benefits were still observed. Despite this, these results highlight that benefits can still be seen even, though the strength of these benefits will vary substantially depending on individual network configurations. It is also worth mentioning that the algorithm employed is one of the simplest possible. While the optimal speed for an ECO-vehicle is calculated, deceleration and acceleration profiles were not amended, but left to the micro-simulator's simulation logic. This course was chosen to maximise the applicability of the simulation to the real-world as in an advisory context, it would be difficult to also prescribe an acceleration profile (especially in the limited distance).

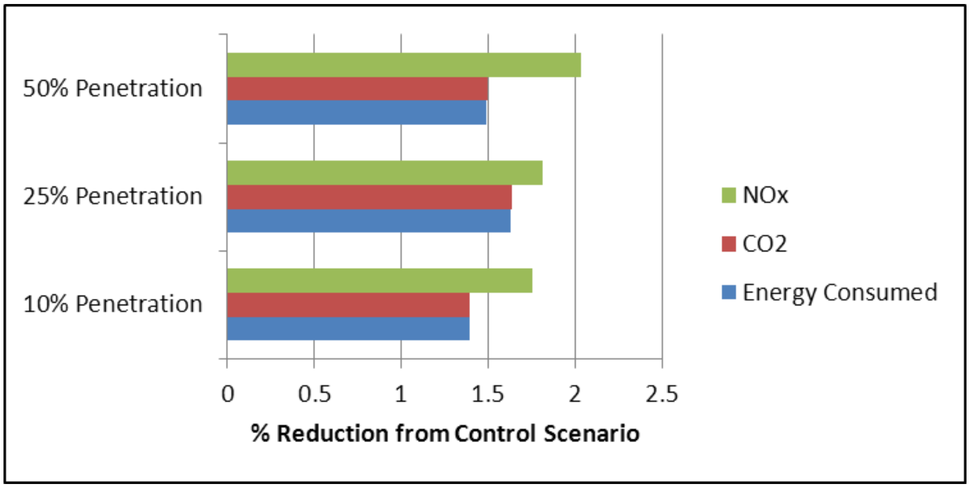

Figure 4 - Results of the MOVES analysis by penetration rate

## 5 Concluding Remarks

This paper explores only the effect of the market penetration of an ECO-drive system on a network's overall emissions. The scale of this work is very taxing in terms of computing power and time needed, taking multiple hours at each step (simulations were run on an AMD Phenom X6 desktop at 4.0GHz and 16GB RAM, MOVES was run in a virtual environment with two workers). Reductions in scale would reduce this burden, but would limit the applicability of the assessment as certain network behaviours are better modelled on larger networks (i.e. vehicle arrivals and queuing, signal progression, etc). Within the literature, there is room for improvement through applications of V2V communications (to extend communication range and to obtain queue-length knowledge). At higher volumes, queues waiting at intersections can negatively affect eco-driving strategies. Studies have shown that connected vehicle technologies can be used to estimate queue length (Li et al 2009), and this information could be used to further improve an ECO-driving algorithm.

The results generated from this research show some potential for ECO-driving strategies, even when large networks with signal timings are considered. To improve this study, future research could explore this concept with real world traffic flows and signal timings. There remains still a substantial gap quantifying the benefits of ECO-driving systems in networks that model real-world systems.

As the decision to adopt and follow the advice of the systems discussed in this paper is purely voluntary, there exists a great deal of uncertainty with regards to the potential benefits of these technologies if they became available. Indeed, the validity of the model's underlying assumptions hinges on a number of aspects that cannot be assessed without real-world data. Even if a driver chooses to install an eco-based advice system, there is no guarantee that they will follow its advice all the time. Despite this, previous research has suggested that many drivers are willing to adopt more eco-friendly approaches to driving. An extensive survey of over 5000 individuals done in 2012 by Trommer and Hotl on drivers in Europe found that most people perceive systems such as the ones discussed in this paper to be useful (Trommer and Hotle 2012). Respondents also generally agreed that such systems could help save fuel and contribute positively to the environment. However, respondents also indicated a preference to allowing such systems to be turned off at their discretion. Many respondents also indicated that such systems would not be worth paying extra money for. In addition to the issue of adoption, Trommer and Hotle also suggest that speed advice systems may not be beneficial in all cases. Such systems could pose a distraction to the driver, and it remains to be seen whether or not any other safety issues would arise from their use.

## 6 Acknowledgements

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