System Level Impacts of V2X Enabled Vehicle Control Strategies

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System Level Impacts of V2X Enabled Vehicle Control Strategies

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Master of Science in Industrial Engineering

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M.S. DEGREE THESIS

The M.S. Degree Thesis of Vaibhav Rungta has been examined and approved by the thesis committee as satisfactory for the thesis requirement for the Master of Science degree.

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With an increasing number of vehicles on road the quantity of CO$_2$ emissions and the amount of fuel wasted because of traffic congestion have been rising. Use of alternate means of transport that generate fewer emissions does not resolve the problem of congestions and vehicle wait time at traffic signal whereas further expansion of existing network of roads is not only constrained by finite space, but any network can get saturated as the number of vehicles increase. V2X technology allows vehicles and traffic infrastructure to communicate with each other, and could facilitate better use of existing resources by providing vehicles information about their surroundings and traffic signals. The information regarding the phase of traffic signal, vehicles’ position and vehicles’ speed can be used by drivers and autonomous vehicle control algorithms to make informed decisions as they approach traffic signals. This research proposes and analyzes system level impacts of implementing a coordination heuristic over single-vehicle optimization to realize the true potential of V2X technology. The results of this research can help policymakers choose the most suitable control strategy depending on the traffic conditions and the penetration rate of V2X technology. The analysis indicates that at 900 vehicles per hour for either of the two driving strategies: coordination heuristic or single-vehicle optimization, to be more preferred over baseline driver behavior, at least 50% of the vehicles should be V2X capable. Once a threshold penetration rate of V2X vehicles is achieved, vehicles following coordination heuristic generate nearly 10% fewer CO$_2$ emissions than vehicles following baseline driver behavior, a 30% improvement over the reduction in CO$_2$ emissions obtained using single-vehicle optimization. The vehicles following the coordination heuristic also have less travel time than vehicles following single-vehicle optimization, and less wait times than vehicles following baseline driver behavior.
1. Introduction

According to National Transportation Statistics (U.S. Bureau of Transportation Statistics, 2015) over 260 million vehicles were registered in the United States in the year 2014. Traffic lights are critical to the traffic system and help maintain traffic flow and ensure driver safety. However, traffic lights also result in vehicle stoppages and require vehicles to accelerate which has been identified as one of the major factors which results in higher emission and fuel consumption (Ericsson, 2001). With technological advances, the efficiency of vehicles (miles per gallon) has improved by nearly 23.3% from 2004 to 2014 (U.S. Bureau of Transportation Statistics, 2015). During the same time as a result of more congestion, the total amount of fuel wasted has increased by 19.2% Schrank et al. (Schrank et al., 2015) which diminishes the benefits of improved vehicle efficiency. Inefficient traffic results in more emissions than free-flowing vehicles. The Federal Highway Administration in the U.S. (FHWA) suggested three solutions (FHWA, 2005) to reduce traffic-related problems:

- Adding more capacity which involves increasing the number and size of highways.
- Better use of existing capacity.
- Encouraging use of non-automotive travel modes.

Connected vehicles is an innovative technology which may facilitate better use of the existing capacity. Vehicle to everything (V2X) communication refers to the exchange of information between various elements of a transportation system which include vehicles, pedestrians, traffic signals and signs, and internet gateways. V2X technology has the potential to improve traffic safety and efficiency. V2X applications include collision warning, intersection movement assist, and remote vehicle diagnostics (Abboud et al., 2016). In 2014 The U.S. Department of Transportation’s National Highway Traffic Safety Administration (NHTSA) announced that it will take steps towards the deployment of the V2X technology (NHTSA, 2014).

Over the past decade the interest in Autonomous Vehicles (AVs) has grown significantly. By October 2015, 10 automakers have been allowed to test AVs (Meyrowitz et al., 1996). According to the report published by Fagnant and Kockelman (2015) at 50% penetration of AVs, the potential savings from the use of AVs could add up to $211.5 billion annually. These savings include the savings from avoiding crashes ($48.8 billion) and fuel savings of up to $37.4 billion. Fagnant and
Kockelman (2015) also suggest that with the V2X technology and autonomous capabilities combined the traffic efficiency could be further improved (Fagnant & Kockelman, 2015).

Figure 1 and Figure 2 demonstrate some of the inefficiencies involved with traversing a series of traffic light. The vehicles in Figure 1 and Figure 2 travel the same distance and come across exactly two traffic lights. The vehicle in Figure 1 arrives at the intersection almost towards the end of a red phase of a traffic signal. As a result, the vehicle in Figure 1 almost came to halt and then had to accelerate which resulted in higher fuel consumption and in turn more emissions. On the other hand, the vehicle in Figure 2 arrives at the intersection almost at the beginning of a red phase, comes to a complete stop and then accelerates once the traffic light turns green. The vehicle in Figure 2 had to wait at the intersection still consuming fuel and generating some emissions. Such driving patterns in which a vehicle almost comes to a halt only to accelerate or comes to a complete stop and waits at the intersection result in emissions which could be avoided by providing drivers and autonomous vehicles with efficient speeds.

![Figure 1 - Speed v/s CO2 Emission plot for a vehicle with a brief stop](image)
Figure 2 - Speed vs CO₂ Emissions plot for a vehicle with a longer stop

Figure 3 represents an efficient speed profile for a vehicle which would otherwise arrive at the intersection at the beginning of red phase as shown in Figure 1. The vehicle in Figure 3 is advised to decelerate from the time it is at a certain distance from the intersection. Since the vehicle decelerates it uses the time in red phase and arrives at the intersection at the beginning of green phase which prevents sudden deceleration. Figure 4 shows an efficient speed profile for a vehicle which would otherwise arrive at the intersection almost at the beginning of a red phase as shown in Figure 2. This vehicle is advised to slightly accelerate and avoid waiting at a red light.
The efficient driving speeds reduce fuel consumption and generate fewer CO\textsubscript{2} emissions by avoiding unnecessary speed changes and reduce vehicle wait times. The V2X technology could improve efficiency by facilitating exchange of information required to compute efficient driving speeds and then providing the information regarding efficient driving speeds back to the drivers or autonomous vehicles.

The applications of V2X technology to improve efficiency have spanned from improving the throughput of intersections by reorganizing the vehicles in platoons (Liu & El Kamel, 2016) to startup assist systems at signalized intersections (Wang et al., 2015). An algorithm to calculate a fuel-efficient speed profile for a single vehicle approaching a signalized intersection was developed by Rakha and Kamalanathsharma (2011). However, a fuel-efficient speed profile for one vehicle may impede the fuel-efficient speed of another vehicle in its vicinity. Additional gains in efficiency could be achieved by coordinating a group of vehicles approaching a signalized intersection. Analyzing cooperative strategies for a realistic vehicle mix might help us realize the system-level benefits of the V2X technology and broaden its scope. This research aims to investigate system-level benefits of coordinating vehicle responses at signalized intersections to reduce emissions and fuel consumption and analyze the impacts of adoption rates of V2X technology and autonomous vehicles on V2X technology enabled algorithm performance.

Figure 4 - Proposed speed profile for vehicle in figure 2
2. Problem Statement
The vehicles for which speed and CO$_2$ emission profiles have been shown in Figure 1 and Figure 2 represent the baseline driving pattern. This research aims to generate efficient speed profiles and coordinate a group of vehicles. Further, this research aims to quantify the impact of efficient speed profiles and the coordinating group of vehicles on the system and compare it with the impact of baseline driving pattern.

The V2X technology which could facilitate exchange of information regarding the efficient speed profiles face challenges which span from its deployment to acceptance. Previous research works by Katsaros et al. (2011) and Lee and Park (2012) have shown that as the penetration of connected autonomous vehicles increases the potential benefits of improved efficiency and reduced emissions also increase. As the acceptance for V2X technology changes, it might be interesting to study the impact of V2X enabled vehicles on the system which will also include non-V2X vehicles. The definition of an efficient speed profile may change depending on the total number of vehicles, the number of V2X enabled vehicles and the type of vehicle. In order to generate efficient speed profiles and analyze the impact of these speed profiles on the system which has different types of V2X enabled and non-V2X vehicles, this research plans to create a simulation and perform experiments. The problem can be broadly divided into 3 parts:

I. Define and implement the coordination heuristic and single-vehicle optimization strategy.
II. Create a simulation model consisting of a simple network of signalized intersections and generate flow.
III. Evaluate the impact of autonomous vehicle and V2X penetration rate on the proposed coordination heuristic and single-vehicle optimization in comparison to the baseline.

This research aims to analyze the benefits of two strategies: coordination heuristic and single-vehicle optimization for various levels of V2X penetration to help the policymakers decide which of the two methods might be suitable as V2X technology and autonomous vehicles receive more acceptance. The two strategies will be compared for performance measures which include average CO$_2$ emissions per vehicle, average trip time and average wait time per vehicle at different levels of penetration of V2X technology and number of vehicles per hour. The next section briefly discusses the V2X technology and its trends.
3. Background

V2X technology allows components of the transportation system such as vehicles, traffic lights and pedestrians to communicate with each other. The V2X technology works on the principle of dedicated short-range communication (DSRC). DSRC has been designed to support the applications of vehicular communication (Abboud et al., 2016). According to the U.S. Department of Transportation (DOT) the technology making use of vehicle-to-vehicle communication, which is based on DSRC, has the potential to reduce crashes by 82% (USDOT, 2010). The U.S. Federal Communications Commission has allocated a 75 MHz of licensed spectrum in 5.9 GHz band for DSRC communication which gives the term “Direct” to DSRC. Although there is no globally accepted or defined range of communication, “Short Range” comes from the fact that the communication takes place over a short distance (250m – 350m). The U.S DOT in collaboration with global automakers has been able to deploy and demonstrate the use of DSRC vehicle safety applications like blind spot warning, forward collision warning, intersection movement assist and emergency electronic brake light activation (Kenney, 2011).

On 1st September 2016, the U.S. DOT announced the deployment of the DSRC technology at three sites to test a broad spectrum of applications under the Connected Vehicle Pilot Deployment Program. The sites and applications are listed below (USDOT, 2017):

- I-80 in Southern Wyoming: To reduce the number and the severity of adverse weather-related incidents.
- New York City: To improve pedestrian safety and vehicle flow. Around 10,000 vehicles have been deployed with a vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) technology in high accident-prone areas.
- Tampa, Florida: To improve safety and reduce congestion during commuting hours.

The Connected Vehicle Pilot Deployment Program provides an insight not just about the possible applications of V2X technology, but also about its acceptance. Herrtwich and Nöcker (2003) describe “cooperative driving as the ultimate driver behavior”. Cooperative driving requires (Herrtwich & Nöcker, 2003):

- Providing information about the environment and adapting to it.
- Exchanging information among the participants of the traffic environment to make decisions suitable for most participants.
- Abiding the traffic rules.

Cooperative driving can be identified on three levels:

I. The first level of applications provides better information to drivers.
II. The second level includes applications which improve traffic efficiency and safety.
III. The third level is focused on cooperative approaches and complex driving situations.

This research can be categorized as an application which may represent a transition from the second to the third level based on the description above.
4. Literature Review

This section discusses the existing literature related to V2X technology. These applications are broadly divided into three categories depending on the classification discussed in Section 3 (Herrtwich & Nöcker, 2003).

The first requirement to achieve cooperative driving is the exchange of information among the different elements of the transportation system. The first level of applications aims to provide drivers with information that makes them pro-active rather than reactive. It provides information about the objects and events they cannot see themselves in advance. If the driver is informed in advance they are more alert about the potential hazard which they might come across. Some of the potential hazard warning applications include informing drivers about accident sites, roadwork and adverse road/weather conditions (Piao & McDonald, 2008).

A message dissemination algorithm was developed by Javad et al. (2013) using the vehicle-to-vehicle communication to avoid chain collisions. This algorithm warns the drivers about the sudden decelerations of preceding vehicles which give them more time to react. The algorithm to prevent chain collisions (Javad et al., 2013) provided a significant reduction in accident rate for V2V penetration rates of over 50%. A vehicular collision avoidance support system (VCASS) has been developed by Ueki et al. (2005). This application was developed using wireless LAN. The algorithm generates a warning before a potential collision. The metrics used for identifying the probability of a collision are Collision Risk Indicator (CRI) and CRI with acceleration (ECRI). Warnings are generated if these metrics reach a threshold. The algorithm was evaluated for five scenarios of crossing and passing. Appropriate warnings were generated for X-crossing (a situation in which the vehicles meet and cross at an X-shaped intersection). The author suggests that undesirable collision warnings were generated for S-crossing (a situation in which the vehicles meet at an S-shaped road) even at low probability of collision.

A more advanced application has been developed to prevent congestion and thus improve efficiency by Souza et al. (2014). This application helps reduce congestion in case of an accident by providing information about the crash ahead and suggests a route change to avoid the route affected by the crash. Souza et al. used a simulation to demonstrate the application. The simulation considers a 30km stretch of the SP-065 Highway in Sao Paulo, Brazil. To simulate the congestion an accident was induced when the traffic was in a steady state. The simulation was conducted
using OMNeT++ an event-based network simulator and Simulator for Urban MObility (SUMO) (Krajzewicz et al., 2012) which is used to build scenarios and vehicle mobility models. Simulation results for different vehicle densities and accident duration were analyzed for the performance metrics which included trip time, CO₂ emissions and fuel consumption. At 1000 vehicles per hour (vph), for a congestion which lasted 1800 seconds, the trip time reduced by 58%, CO₂ emissions by 25.4% and the fuel consumption reduced by 17.7%. These improvements diminish as the number of vehicles per hour increases.

A report published in 1999 describes the Automatic Incident Detection (AID) installed on motorway sections in Stockholm and Gothenburg (Van Toorenburg & De Kok, 1999). The AID system is a mechanism which automatically detects slow moving traffic and warns the oncoming traffic using warning signs. This system makes drivers more aware of the potential hazard or roadblock ahead of them. A report published in 2004 (Highways Agency UK, 2004) suggests that the controlled motorways use variable speed limits to harmonize the traffic flow. The variable speed limit system (VSL) works on a similar principle as the AID system. The VSL analyzes the traffic conditions by measuring the average speed of vehicles on the road and then adjusts the speed limit. The VSL reduces the speed limit if the average speed limit goes below a certain threshold and the new speed limit is displayed on display signs. Different speed limits are displayed on different signs depending on the signs’ locations. The speed limit upstream of the location of the incident is higher than the speed limit at a location before the incident. The cooperative VSL (C-VSL) is an extension of the VSL technology with the inclusion of the connected vehicles technology (Grumert & Tapani, 2012). The connected vehicles technology allows vehicles to receive updated speed limits more frequently via communication through the roadside units and inter-vehicle communication than by physically seeing a display sign. The simulation performed by Grumert and Tapani (2012) suggests that the C-VSL facilitates early adoption of vehicle speeds and thus reduces the acceleration and deceleration rates compared to VSL. The C-VSL is an application of the V2X technology which improves traffic flow by providing information to the driver.

The “ultimate driver behavior” of the cooperative driving is a result of a smooth harmonic flow of vehicles because of the decisions made using the information received in the connected vehicles environment. The second level of applications focuses on improving the efficiency and traffic flow
by using the information like signal phase and traffic conditions. Wang et al. (2015) proposed and tested a vehicle-to-infrastructure (V2I) based driver assistance system which generates prompts for the drivers waiting at signalized intersections using information regarding traffic phase. The field test results showed that the startup delay between two adjacent vehicles on an average was reduced from 1.42 s to 0.75 s. In a test conducted by Wang et al. (2015), all the drivers accepted the prompts of the assistance system.

The simulation model created by Widodo et al. (2000) assumes a vehicular driving assistance system that uses inter-vehicle communication. The information about the phase of the traffic light is provided to the drivers which helps them make driving decisions. Fuel consumption and emissions were evaluated using the microscopic fuel consumption and emission model (Ahn, 1998). The simulation results indicate that both the fuel consumption and emission of carbon monoxide and hydrocarbons (CO and HC) were reduced using Intelligent Vehicle Communication (IVC) for environment adaptive driving especially for high vehicle densities and long traffic cycle times.

Two specific application of vehicular communication; Green Light Optimal Speed Advisory (GLOSA) and Adaptive Route Change (ARC) were developed by Katsaros et al. (2011). As the name suggests, GLOSA is an algorithm which provides drivers with speed advice based on their current speed, acceleration, position and distance from the signal. To integrate different simulation aspects like traffic, network and application a simulation platform called VSimRTI (Schünemann, 2011) was used. Three performance measures were evaluated against penetration of vehicular communication technology: average stop time, average fuel consumption and average trip time. The results indicate that the penetration of V2X vehicles equipped with GLOSA must be at least 50% to see a significant reduction in fuel consumption. Trip time reduces significantly and quickly as penetration of V2X vehicles goes above 60%. However, Katsaros et al. (2011) has assumed that there are no vehicles waiting at the traffic light and that non-V2X vehicles do not pass V2X vehicles, and recognizes the same. An intelligent vehicle speed adaptation algorithm was proposed by Schuricht et al. (2011) which categorized the vehicles approaching the signalized intersection in four classes and calculated speed profiles to minimize fuel consumption. The algorithm used for generating the speed profile included traffic light timing chart, vehicle speed, and its distance from a stop light as well as the queue length. The simulation used by Schuricht et al. (2011) uses
a platoon of four vehicles with the fourth vehicle equipped with driver assistance system. The results show incremental fuel savings for the driver assistance system which uses queue length estimation compared to the one which doesn’t.

Rakha and Kamalanathsharma (2011) built a model with an objective to reduce fuel consumption. The speed profiling for fuel optimization was divided into two parts: arrival and departure from the signal. The results suggest that if the entire maneuver (upstream and downstream) is considered then the previous studies which suggested gradual upstream deceleration will not hold because that strategy has higher fuel consumption downstream.

The benefits from the applications discussed in level two and more acceptance of the V2X technology should make way for the cooperative driving. The third level of applications focuses on cooperative approaches and complex driving situations. A Cooperative Vehicle Intersection Control (CVIC) algorithm was proposed by Lee and Park (2012) which does not require traffic signals. The algorithm can assign safe maneuver to the vehicles approaching a signalized intersection. The objective function of CVIC minimizes the length of the overlapped trajectory along the intersection and uses nonlinear constraints. CVIC has the potential to reduce CO₂ emissions and fuel consumption by 44%. CVIC has been extended by Lee et al. (2013) for a corridor consisting of multiple intersections. A major limitation of the CVIC algorithm is that it was developed with an assumption of 100% penetration of connected and automated vehicles and considered only the passenger cars for creating the model.

An extension of the adaptive cruise control called the cooperative adaptive cruise control (CACC) was proposed by B. Van Arem et al. (2006) which allows vehicles to follow the preceding vehicle more closely. CACC allows headway gaps of as low as 0.5 seconds. CACC is a result of including V2V with adaptive cruise control. V2V technology provides more information to drivers using adaptive cruise control. The benefits of CACC on traffic stability and throughput surface for penetration rates of over 60%. At low penetration rates (20% to 60%) of CACC, the average speed reduces compared to the scenario with no CACC penetration.

A reservation-based approach to maneuver autonomous vehicles through the signalized intersections was proposed by Dresner and Stone (2008) which treated autonomous vehicles as agents in a multi-agent system. The algorithm has the potential to reduce the delay time at the
intersection by 99% for 100% penetration of autonomous vehicles but these savings drop to 7% at a 90% penetration of autonomous vehicles.

One of the challenges faced by the third level of applications is that it requires near 100% or 100% penetration of V2X technology or autonomous vehicles equipped with V2X technology to realize benefits of V2X technology. According to an article on trends in connected vehicles technology (ABI Research, 2013) by 2027, the V2X technology is expected to reach a penetration of about 60%. The second level of applications provide significant savings for penetration rates of around 60%. However, the single-vehicle optimization proposed in the second level may fail to recognize the true potential of coordinated approach because the speed profile can depend on the vehicle class. This might result in a scenario where optimal the maneuver of one vehicle might impede the optimal maneuver of other vehicles.

This research aims to bridge the gap between the second and the third level of applications by comparing a coordination heuristic with the single-vehicle optimization for different penetration levels of the V2X technology. The best strategy to use as the penetration of the V2X technology changes will be identified. This research will analyze the coordination heuristic for a realistic vehicle mix and analyze the CO₂ emissions at the system level. This will be achieved by adjusting the speed limit per lane to allow more vehicles to pass through the signalized intersection. The next section discusses the methodology and experimental plan.
Section 3 provides an outline about the V2X technology. This section discusses the details of different components of V2X technology which work together to form a system which captures the information required to make decisions regarding the efficient speed profile and then communicates the efficient speed profile to the vehicles.

Wang et al. (2015) proposed a “V2I-based startup assist system” to reduce the startup delay at traffic signals. The system architecture proposed by Wang et al. (2015) consisted of the roadside unit (RSU) and the on-board unit (OBU). The RSU is a traffic light equipped with wireless communication device capable of transmitting information regarding the signal phase and time to the vehicles approaching traffic light. The OBU proposed by Wang et al. (2015) consisted of onboard sensors to collect information regarding vehicles’ speed and acceleration, a wireless receiver to capture the information transmitted by RSU and a startup controller to start the vehicle automatically.

Lebre et al. (2015) deployed the GLOSA developed by Katsaros et al. (2011) for a simple scenario which consisted of a single vehicle on a circular track. The system created by Lebre et al. (2015) to facilitate exchange of information consisted of two traffic lights with communication device. The communication device could transmit information regarding the position of the traffic light, phase of the traffic light and the remaining time in current phase. This information from the traffic light is communicated to V2X equipment through an Ethernet connection. The V2X equipment used by Lebre et al. (2015) for the traffic signals consisted of a WiFi router and an antenna. Lebre et al. (2015) used a V2X enabled vehicle and a smart phone to receive the information from traffic lights through the V2X device embedded in the vehicle, calculate the optimal speed and provide the advisory to the driver.

The two implementations of V2X technology, discussed above, proposed by Wang et al. (2015) and Lebre et al. (2015) provide a guideline to deploy V2X technology for improving traffic efficiency. Figure 5 represents an illustration of a system which could facilitate implementation of single-vehicle optimization and coordination heuristic. The traffic signal communicates the information regarding the phase of the traffic light, time left in current phase and the position of the traffic light. The vehicles provide information regarding their speed and position. These two
sets of information are used for evaluation of efficient speed profile by the RSU at the traffic signal which then communicates the efficient speed profile to each vehicle.

Figure 5 - An illustration of system which can be used to implement coordination heuristic and single-vehicle optimization
6. Algorithm to control vehicles

This section explains the single-vehicle optimization and the coordination heuristic used to control the V2X-autonomous vehicles. These algorithms calculate the speed and acceleration profiles assigned to the vehicles. The input parameters include vehicle’s speed, position and the phase of the traffic light.

6.1. Single-vehicle optimization

A flowchart of the algorithm provided in Figure 6 is a representation of the eco-drive model proposed by Rakha and Kamalanathsharma (2011). The eco-drive model Rakha and Kamalanathsharma (2011) suggests a speed advisory to the driver using the information from V2X infrastructure about the signal phase and the time for next phase change. The eco-drive model considers the following scenarios:

I. The signal will remain green for sufficient time – The vehicle continues to move at the speed limit in this scenario.

II. The signal will turn red before the vehicle arrives at the intersection –
   a) The vehicle could either proceed with slight acceleration.
   b) Or, the vehicle decelerates such that it avoids waiting at the intersection during the red phase and arrives at the intersection during next green phase.

The representation of the single-vehicle optimization model used in this research has a few differences compared to the eco-drive model prepared by Rakha and Kamalanathsharma (2011):

I. The single-vehicle optimization model uses HBEFA developed by Rexis et al. (2013) for estimating emissions whereas the eco-drive model uses VT-Micro model (Ahn et al., 2002).

II. The single-vehicle optimization model doesn’t receive information regarding the length of queued vehicles.

III. The single-vehicle optimization uses a linear objective function and maximizes the time over which the vehicle decelerates which results in a smooth transition. The eco-drive model uses a non-linear objective function for the desired arrival speed at the intersection.
Check the phase of the traffic signal

Red Phase Algorithm

Check the phase of the traffic signal

rr or yy1

Will the vehicle arrive at the intersection at the beginning of next green phase?

Yes

Continue at the current speed.

accelerate

At the current speed, will the vehicle go beyond the intersection?

No

No

Decelerate, such that the remaining time of the red phase is utilized and vehicle covers most of its distance from intersection

No

Yes

Accelerate to a speed such that the vehicle arrives at the intersection at the beginning of next green phase

No

greenlight check

Will the vehicle get through the intersection by accelerating to the speed limit?

Yes

No

Decelerate, such that the remaining time of green plus the time of subsequent red phase is utilized and vehicle covers most of its distance from intersection

Yes

No

Accelerate, to the allowed speed limit

Single-vehicle Optimization

Check the phase of the traffic signal

gg or yy2

Will the vehicle get through the intersection at its current speed in the remaining time?

Yes

No

Will the vehicle arrive at the intersection at the beginning of next green phase?

Figure 6 – Algorithm: Single-vehicle optimization
Information regarding the vehicles’ current state is extracted from every V2X vehicle which enters the simulation environment and has a traffic signal ahead.

**List of input parameters**

- **U**: Vehicles’ current speed
- **D**: Distance from the nearest intersection
- **gg, yy1, rr, yy2**: Current phase of the traffic signal
- **Δt**: Time remaining for the current phase to change
- **V_{speed~limit}**: Speed limit
- **A**: Rate of acceleration
- **V_{max}**: Maximum adjusted speed limit

**List of variables used in algorithms**

- **V**: Final speed. Speed attained after the acceleration phase
- **t_a**: Time for which vehicle accelerates
- **t_{cons}**: Time for which vehicle drives at constant speed \( v \)
- **S_a**: Distance travelled by the vehicle while accelerating
- **S_{cons}**: Distance travelled by the vehicle at constant speed \( v \)
- **a_d**: Rate of deceleration

For V2X vehicles which arrive during green phase \((gg)\) or the second yellow phase \((yy2)\) Algorithm 1 checks if the vehicle can get through the intersection for the input parameters \( u, Δt \) and \( d \). If the vehicle can get through the intersection at the current speed or by accelerating to the speed limit, it accelerates to the speed limit and then continues to drive at the speed limit. Otherwise, the vehicle decelerates.

**Red Phase Algorithm**

\[
\text{IF } u(Δt) \geq d \text{ THEN} \\
\text{Accelerate to the speed limit} \tag{1}
\]

\[
\text{ELSE IF greenlight check returns TRUE THEN}
\]
Accelerate to the speed limit

ELSE \textit{decelerate}

Decelerate at rate $a$ for time $t_a$ calculated from module \textit{decelerate}

End of Red Phase Algorithm

To check if the vehicle can get through the intersection by accelerating to the speed limit a module described using equations (2) to (6), \textit{greenlight check} is used.

\begin{equation}
  t_a = \frac{(v_{\text{speed limit}} - u)}{a} \tag{2}
\end{equation}

\begin{equation}
  t_{\text{cons}} = \Delta t - t_a \tag{3}
\end{equation}

\begin{equation}
  S_a = (u*t_a) + (0.5*a*t_a^2) \tag{4}
\end{equation}

\begin{equation}
  S_{\text{cons}} = v*t_{\text{cons}} \tag{5}
\end{equation}

\textbf{IF} (S_a + S_{\text{cons}}) \geq d \text{ THEN} \tag{6}

\textbf{Return TRUE}

\textit{End of module greenlight check}

The $v_{\text{speed limit}}$ and $a$ are input parameters. The speed limit was defined during model creation and was chosen to be 40mph. For acceleration ($a$), a value equal to 30\% of full-throttle (Rakha & Kamalanathsharma, 2011) has been selected for all the passenger vehicles. A higher value might have resulted in lower emissions for passenger vehicles hasn’t been used because of lower full-throttle value for commercial vehicles, and an unequal assignment of acceleration will affect the traffic flow.

If the equation (6) evaluates to false, the vehicle is instructed to decelerate and a module called \textit{decelerate} is used. This module uses AMPL to solve an optimization problem with non-linear constraints. The deceleration ($a$), final speed ($v$) and the time for deceleration ($t_a$) are evaluated such that $t_a$ is maximized while satisfying certain constraints.
Module *decelerate*

Objective function – Maximize: $t_a$

subject to: $v$, $t_a$, $t_{cons}$, $S_a$, $S_{cons} \geq 0$  

$v = u + (a*t_a)$  

$S_a = (u*t_a) + (0.5*a*t_a^2)$  

$S_{cons} = v*t_{cons}$  

$\Delta t = t_a + t_{cons}$  

$d \leq S_a + S_{cons}$

(7 to 11)

(12)

(13)

(14)

(15)

(16)

End of module *decelerate*

Equations (2) to (5) assign values to the variables and evaluate (6) whereas equations (7) to (16) are constraints which have to be satisfied while maximizing $t_a$. For green phase, $\Delta t$ is updated to include the time for subsequent yellow phase (yy1) and red phase (rr).

Algorithm 2 checks if the vehicle which arrives during the red phase (rr) or during the first yellow phase (yy1) arrives at the intersection just in time at the beginning of the subsequent green phase (gg). If the vehicle arrives before or after the end of the subsequent green phase, the vehicle is instructed to either decelerate or accelerate.

Single-vehicle Optimization

IF $u(\Delta t) = d$ THEN

Continue at current speed

ELSE IF $u(\Delta t) < d$ THEN

accelerate

ELSE decelerate

Decelerate at rate $a$ for time $t_a$ calculated from module *decelerate*

End of Single-vehicle Optimization
If the equation (18) evaluates to false, the rate of deceleration is calculated using the equation (7) to (16) such that the time, $t_a$ over which the vehicle accelerates is maximized. The value of $\Delta t$ is updated to include the time for subsequent yellow phase ($yy2$).

If equation (18) evaluates to true, then the speed of vehicle incremented to identify the lowest speed at which the vehicle arrives at the intersection at the beginning of the green phase. A module, accelerate, calculates the lowest speed at which the vehicle can arrive at the intersection using iteration.

### Module accelerate

$Count = 1$

$v = u + a*0.1*Count$ \hspace{1cm} (19)

$t_{cons} = \Delta t - 0.1*Count$ \hspace{1cm} (20)

$S_a = (u*0.1*Count) + (0.5*a*(0.1*Count)^2)$ \hspace{1cm} (21)

$S_{cons} = v*t_{cons}$ \hspace{1cm} (22)

IF $(S_a + S_{cons}) < d$ THEN

increment $Count$ by 1 and go to equation 19

ELSE

EXIT and allow vehicle to accelerate to $v$

End of module accelerate

#### 6.2. Coordination Heuristic

Single-vehicle optimization instructs V2X vehicles in the simulation space either to accelerate to the speed limit or to decelerate based on whether the vehicle could get through the intersection in the given time or not. Figure 8 represents the coordination heuristic. The proposed heuristic uses Cooperative – Variable Speed Limit System (C-VSLS) discussed in Section 4 at the signalized intersection. The coordination heuristic adjusts the speed limit for a group of V2X vehicles to allow more vehicles to pass through the signalized intersection.
For a trailing V2X vehicle (refer Figure 7) which may get through the current green phase at an adjusted speed limit, the coordination heuristic determines the lowest higher speed limit at which it can get through the signalized intersection. Only those V2X vehicles which are preceding the V2X vehicle which has requested coordination will receive and react to the adjusted speed limit. An algorithm, *coordination*, is used to determine if the vehicle will get to travel at an adjusted speed limit. The equations which follow explain the algorithm and the module used to make the decision and to calculate the speed at which the V2X vehicle can travel respectively. The coordination heuristic uses a threshold speed adjustment parameter $V_{\text{max}}$ which provides an upper limit on the extent to which speed gets adjusted.

![Figure 7 – Representation of coordination heuristic](image)

<table>
<thead>
<tr>
<th>Coordination Heuristic</th>
</tr>
</thead>
<tbody>
<tr>
<td>IF $u(\Delta t) \geq d$ THEN</td>
</tr>
<tr>
<td>Accelerate to the speed limit</td>
</tr>
<tr>
<td>ELSE IF <em>greenlight check</em> returns TRUE THEN</td>
</tr>
<tr>
<td>Accelerate to the speed limit</td>
</tr>
<tr>
<td>ELSE IF <em>coordination speed</em> returns TRUE and $V_{coord}$ THEN</td>
</tr>
<tr>
<td>Accelerate to $V_{coord}$</td>
</tr>
<tr>
<td>ELSE decelerate</td>
</tr>
<tr>
<td>End of Coordination Heuristic</td>
</tr>
</tbody>
</table>
Check the phase of the traffic signal

- **Red Phase Algorithm**

  - *rr or yy1*

  Will the vehicle arrive at the intersection at the beginning of green phase?
  - Yes
    - Continue at the current speed.
  - No
    - At the current speed, will the vehicle go beyond the intersection?
      - Yes
        - Accelerate to a speed such that the vehicle arrives at the intersection at the beginning of the green phase
      - No
        - Decelerate, such that the deceleration value is minimum and the remaining time of the red phase is utilized

  Will the vehicle get through intersection at its current speed in remaining time?
  - Yes
    - greenlight check
    - Yes
      - Accelerate, to the allowed speed limit
    - No
      - Decelerate, such that deceleration value is minimum and the remaining time of green plus the time of subsequent red phase is utilized
  - No
    - Accelerate to a speed such that the vehicle arrives at the intersection at the beginning of the green phase

- **Coordination Heuristic**

  - *gg or yy2*

  Will the vehicle get through intersection by accelerating to speed limit?
  - Yes
    - Decelerate, such that deceleration value is minimum and the remaining time of green plus the time of subsequent red phase is utilized
  - No
    - Can the vehicle get through the signalized intersection with some adjustment of the speed limit?
      - Yes
      - Adjust the speed limit.
      - Instruct the preceding vehicles to facilitate trailing vehicle.
      - Allow the trailing vehicle to accelerate up to the adjusted speed limit
      - No

*Figure 8 – Algorithm: Coordination heuristic*
The first two conditions which check if the vehicle can get through the intersection at the speed limit remain the same as the single-vehicle optimization. The third condition which checks if the vehicle can get through the intersection at an adjusted speed limit distinguishes coordination heuristic from the single-vehicle optimization. Equations (25 to 30) describe the module \textit{coordination speed}, used to determine if the vehicle could get through the intersection at an adjusted speed limit and the speed at $V_{coord}$ at which the vehicle needs to travel.

In order to allow the trailing vehicle for which the speed limit has been adjusted to pass through the signalized intersection the preceding vehicles will be required to coordinate (refer to Figure 7), i.e; drive at the new adjusted speed limit. This requires the preceding vehicles to accelerate which will result in incremental emissions. The underlying assumption while performing the coordination heuristic is that the incremental emissions from the group of vehicles will be less than the emissions from the trailing vehicle had it decelerated and then accelerated.

\begin{verbatim}
Module \textit{coordination speed}

\textit{Count} = 1

\textbf{WHILE} $V_{coord} < v_{speed\ adjusted}$

\hspace{1cm} $V_{coord} = u + a*0.1*\text{Count}$ \hfill (25)

\hspace{1cm} $t_{cons} = \Delta t - 0.1*\text{Count}$ \hfill (26)

\hspace{1cm} $S_a = (u*0.1*\text{Count}) + (0.5*a*(0.1*\text{Count})^2)$ \hfill (27)

\hspace{1cm} $S_{cons} = V_{coord} * t_{cons}$ \hfill (28)

\hspace{1cm} IF ($S_a + S_{cons}) < d$ \textbf{THEN}

\hspace{4cm} increment \textit{Count} by 1 and go to equation 26

\hspace{1cm} ELSE

\hspace{4cm} Return \textit{TRUE} and \textit{V_{coord}}

\textbf{Return False}

\textbf{End of module \textit{coordination speed}}
\end{verbatim}
7. Experimental Approach
This section describes the methodology and the tools used for creating the experiment setup and performing the runs. The section also outlines the performance measures used for analyzing the results and the model assumptions. The section is divided into three sub-section each of which explains a finer aspect of the experiment and simulation used in the research.

7.1. Experimental Setup
The experimental setup used for analysis consists of a 1.5 km long road with two traffic signals which divide the 1.5 km road into three equal segments of 0.5 km each (Figure 9). All the vehicles travel the same distance and will come across exactly two traffic lights indicated by the two white arrows in Figure 9. The network has two lanes and the traffic flows only from left to right. The two traffic lights are synchronous.

V2X vehicles receive information regarding the phase of the traffic light and the time for next phase change as soon they enter the simulation space. V2X vehicles begin to adopt the speed profile computed by the algorithms discussed in section 6.1 and 6.2 around 500 meters ahead of the traffic light. Tieler et al. (2010) reports diminishing benefits on emission reduction if the information regarding speed profile were provided to the vehicles more than 500 meters away from the traffic signal.

7.2. Experimental Factors
The goal of this research is to provide policymakers a guideline to select a vehicle control strategy depending on the traffic conditions and the percentage of V2X vehicles. Therefore, the experiments compare the performance measures for three factors: the number of vehicles per hour, the percentage of V2X vehicles and the strategy used to control vehicles. Table 1 describes each of these factors and the number levels in each factor. Ten replicates have been used for every combination of these factors which generated 600 simulations equivalent to more than 600 hours of traffic simulation.
Table 1 - Factors analyzed and levels used for each factor

<table>
<thead>
<tr>
<th>Name of the factor</th>
<th>Number of levels</th>
<th>Levels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicles per hour</td>
<td>3</td>
<td>600, 900 and 1200 vehicles per hour</td>
</tr>
<tr>
<td>Percentage of V2X vehicles</td>
<td>10</td>
<td>10% to 100% with 10% increments</td>
</tr>
<tr>
<td>Vehicle control strategy</td>
<td>3</td>
<td>Baseline driver behavior, single-vehicle optimization, and coordination heuristic</td>
</tr>
</tbody>
</table>

The performance metrics were also calculated for the baseline driver behavior for the 3 values of vehicles per hour mentioned in Table 1. The baseline driver behavior is the scenario in which none of the vehicles are V2X capable and do not receive and information regarding an optimal driving speed or the time in which the phase of traffic light is expected to change. The same 10 replicates have been used for the baseline driver model which were used for the other two vehicle control strategies. These 30 runs were performed without any V2X vehicle in the vehicle mix. For any simulation run, vehicles arrive during the first one hour of the simulation runtime and the simulation ended once all the vehicles exited the network.

7.3. Performance Measures
Three performance measures have been used to compare different strategies: CO$_2$ emissions, travel and wait time. These are some of the common performance metrics used by many research works in past like Katsaros et al. (2011). Some other works haven’t considered all of these metrics like Tielert et al. (2010) which considers NOx emissions and particulate matter emissions but not the travel time and wait time whereas Rakha and Kamalanathsharma (2011) consider only the fuel consumption.

The average CO$_2$ emission per vehicle over the trip is the total amount of CO$_2$ emissions generated by all the vehicles in the simulation averaged over the number of vehicles. In this research, we have evaluated average CO$_2$ emissions for the entire fleet of vehicles instead of analyzing the CO$_2$ emissions by vehicle class. This choice is in line with EPA 20 (U.S. Environmental Protection Agency, 2012) guideline which requires the fleet-wide emission levels of 163 grams/mile for the model year 2025. The new EPA standards will be based on CO$_2$ emissions footprint curves and the automakers will be required to meet the fleet-wide standards instead of emission standards for individual vehicles.
The travel time used for comparing different driving strategies is the total time it took a vehicle to travel 1000m, through the two traffic lights. Wait time is the time for which a vehicle has almost come to a stop (speed less than 2.25 mph). The wait time has been calculated irrespective of phase of the traffic light in order to also capture the wait time which might arise because of slow moving or vehicles about to move at the beginning of green phase. Average wait time per vehicle for a replicate is the summation of instances for which vehicle’s speed is less than 1m/s (2.25 mph) divided by the number of vehicles which drove at such speeds during the simulation.

Average wait time per vehicle = \[ \frac{1}{|V|} \sum_{i \in V} \sum_{j \in T} S_{ij} \]

Where:

- \( V \) denotes set of vehicles which attain a speed less than or equal to 1m/s
- \( S_{ij} \) = 1 if velocity of vehicle \( v \) from set \( V \) at instance \( j \) is less than or equal to 1m/s
  = 0 otherwise
- \( T \) set of instances in simulation run time for a vehicle
8. Implementation of Simulation

This section describes the simulation tool and the modeling parameters used to create the desired simulation environment and the entities. The section is further divided into six sub-section each of which is aimed to provide information which might facilitate recreation of a similar simulation.

8.1. Simulation Tool

A simulation helps in evaluating a policy or an application before the policy is deployed. The simulation package for the proposed research should model driver behavior, provide flexibility to model and alter vehicle attributes, replicate road networks and traffic conditions and most importantly gather data to evaluate scenarios. Simulation of Urban MObility (SUMO) (Behrisch, Bieker, Erdmann, & Krajzewicz, 2011) is a traffic modeling tool which allows inclusion of road networks, demand models and captures the information about the state of the vehicle at each and every step of the simulation.

To estimate emissions and fuel consumption SUMO uses a continuous model (Krajzewicz et al., 2015) which derives necessary values from the Handbook Emission Factor for Road Transport (HBEFA) (Rexeis et al., 2013). HBEFA is an emission factor database. The emissions are categorized based on vehicle category, vehicle size, fuel type, technology, load factor, road gradient and driving cycle. The emissions are calculated based on driving patterns which depend on kinematic parameters.

SUMO has been used in the past for the development and analysis of V2X applications which aim to reduce emissions and congestion like (Souza et al., 2014) and (Grumert & Tapani, 2012). The results published by VALEO Advanced Technology development (Lebre et al., 2015) in 2015 compared results from a real scenario with simulation results from SUMO and found the results comparable.

8.2. Agent-Based Simulation

Rabelo (2014) describes agent based modeling as a simulation framework that allows users to model dynamic processes using autonomous agents. Autonomous means that the agents can respond on their own without any guidance. This property of agent-based modeling can be leveraged to model real world scenarios where complexity arises due to individual behavior and interaction among individuals. According to Rabelo (2014), an agent-based model has three elements: agents, agent relationship and agents’ environment. SUMO, in the framework of agent-
Agent-based simulation has agents like vehicles and traffic signals which interact with one another according to certain underlying relationships in a simulation environment represented by a network of roads. The subsequent sections explain the essential elements used for implementation of the simulation in SUMO.

Figure 10 - Agent-Based Simulation framework for SUMO

8.3. Modeling Assumptions
To analyze the potential benefits of the coordinated approach, the model has been built with certain assumptions. Here are the assumptions considered while building the model:

- The two signalized intersections are synchronous.
- The vehicle mix used for experimentation is not representative of a particular location (rural or urban) but represents the vehicle mix of the United States, rural and urban vehicle mix combined.
- V2X technology will be able to provide the information like the distance of the vehicle from the signalized intersection, vehicle speed, the phase of the signal, etc. which is used to make the decision related to speed and acceleration profile of the vehicles.
- Drivers behave rationally and do not stop unless required to stop at the signalized intersection.
- The V2X capable vehicles are autonomous and will adapt to the control strategy advice with 100% accuracy.
- All the vehicles of a particular type have the same emission values.
- The adoption rate of V2X technology is assumed to be uniform for all vehicle categories.
- Vehicles can pass slow moving vehicles by switching lanes.

### 8.4. Vehicles

SUMO allows users to choose vehicles from a broad category. In SUMO, vehicles are agents. Agents are individual entities with their own behavior and attributes (Rabelo, 2014). A vehicle is defined by its attributes like the length, weight, maximum speed, maximum acceleration and the emission type. These attributes depend on the type of vehicle used in simulation.

#### Table 2 - Vehicle mix

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Percentage</th>
<th>Vehicle color</th>
<th>Symbol</th>
<th>Emission type in SUMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedan</td>
<td>56%</td>
<td>Yellow</td>
<td>![Yellow Symbol]</td>
<td>PC_G_EU5</td>
</tr>
<tr>
<td>Light duty vehicle</td>
<td>18%</td>
<td>Cyan</td>
<td>![Cyan Symbol]</td>
<td>LDV</td>
</tr>
<tr>
<td>SUV</td>
<td>12%</td>
<td>Magenta</td>
<td>![Magenta Symbol]</td>
<td>P_7_7</td>
</tr>
<tr>
<td>Van</td>
<td>9%</td>
<td>Blue</td>
<td>![Blue Symbol]</td>
<td>P_7_7</td>
</tr>
<tr>
<td>Trailer</td>
<td>3%</td>
<td>Green</td>
<td>![Green Symbol]</td>
<td>HDV</td>
</tr>
<tr>
<td>Truck</td>
<td>2%</td>
<td>Red</td>
<td>![Red Symbol]</td>
<td>HDV</td>
</tr>
</tbody>
</table>

Table 2 provides attributes and the percentage of every vehicle type used in the experiments. The percentage population provided by the U.S. Bureau of Transportation Statistics (2015) has been used for the experiments. SUMO provides many vehicles categories to choose from. The categories used in our experiment are passenger, delivery, trailer and truck. Of the vehicle types mentioned in Table 2, Sedan, Van and SUV all come under the same vehicle class called passenger. The vehicle mix used for identifying the percentage of every vehicle type has been the simulation has been By default, SUMO distinguishes the vehicles types of a vehicle class primarily based on size of vehicles. Sedan used in the simulation have length of 4.3m whereas the vans are 4.7m long. To replicate the emissions corresponding to different vehicle types, sedans have been assigned an emission class “PC_G_EU5” which represents emissions from a gasoline driven Euro 5 passenger car. Van and SUV on the other hand have been assigned “P_7_7”, indicative of bigger Euro 4 engine. The light duty vehicles have been assigned default length and emission of 6.5m and “LDV” respectively. “LDV” represents emission corresponding to average light duty vehicles in SUMO. Trucks and trailers have been assigned the default of emission class of “HDV” which in SUMO represents emissions from heavy duty vehicles.
8.4. Network Creation

A network is a set of connecting edges or roads. In SUMO the network serves as the agents’ environment. Rabelo (2014) defines agents’ environment as the space in which the agents live and interact with other agents. The network creation begins by assigning coordinates to the nodes which form the building block of a network. An edge can be defined with two nodes. Two edges which intersect at common a node form an intersection. An intersection can be signalized depending on the experiment by changing the property of the node. Further, the number of lanes, speed limit and connections are some of the key attributes which are defined for the edges to create a network.

To create the network of 3 connecting roads used in our experiments (Figure 9) 4 nodes have been used. Each node is separated by 500m from the adjacent node. Node 2 and Node 3 (Figure 11) serve as traffic signals. Each of three segments of roads between adjacent nodes have same attributes. The attributes used to define a segment of road are speed limit, number of lanes and the direction of traffic flow. Default value for speed limit (40mph) and number of lanes (2) has been used. The direction of traffic flow is from left to right, indicated by the two white arrows in Figure 9. For the coordination heuristic, speed adjustments of only up to 10% above the original speed limit are allowed which makes the threshold speed adjustment parameter $V_{\text{max}}$ equal to 44mph.

Node 1    Node 2    Node 3    Node 4

*Figure 11 - Arrangement of nodes*

8.5. Traffic Signal

SUMO creates traffic signals at the defined nodes and the program which controls the intersection during network creation. The programs for traffic signals differ from the ones which exist. SUMO defaults to traffic signal cycles of duration 90 seconds. The duration of yellow phase depends on the speed limit and is equal to 5 seconds for the traffic signals used in our experiments. The two traffic lights are synchronous and follow the cyclic sequence: green phase ($gg$, 40 seconds), yellow phase ($yy1$, 5 seconds), red phase ($rr$, 40 seconds) and yellow phase ($yy2$, 5 seconds). The traffic lights turn green after the second yellow phase. The second yellow phase is unlike the traffic light sequence in the United States. The sequence of traffic lights generated in SUMO is similar to the
one pointed out in a study published by Federal Highway Administration (2014a) which analyzes the design and operation of traffic signals in some of the European countries. According to Federal Highway Administration (Federal Highway Administration, 2014b), the second yellow phase shows up for a brief period with red phase, is an indication of subsequent green phase and the vehicles cannot begin leaving the intersection during this phase. In SUMO, the implementation of second yellow phase is different from real traffic signals as it is a brief phase of yellow light after the red phase instead of combination of red and yellow phase.

8.6. Arrival Process
Simulations are useful for analyzing stochastic systems. SUMO allows the user to randomize vehicles’ times of arrival, vehicles’ speeds, vehicles’ routes and vehicles’ type. Each of these attributes can be randomized individually or using the module, randomTrips.py provided by SUMO. To provide the number of vehicles entering the simulation space in an hour SUMO uses an option period (p), which uniformly inserts one vehicle every 3600/p seconds. The option p has been assigned three values: 3, 4 and 6 to generate 1200, 900 and 600 vehicles per hour. According to Zheng and Liu (2017) a Poisson process is commonly used to model vehicle arrivals in a traffic simulation. The arrivals followed a binomial distribution where the maximum number of arrivals at a time was 1 and the expected arrival rate was 600, 900 or 1200 vehicles per hour. A binomial distribution becomes a Poisson distribution as the number of samples or instances approach infinity. Figure 12, Figure 13, Figure 14 show the arrival rates of one of the replicates for 600 vehicles per hour, 900 vehicles per hour and 1200 vehicles per hour used in the simulation.

Table 2 describes the vehicle distribution used for the simulations. The distribution assigns a probability for each vehicle type being selected. Table 3 provides the total number vehicles and the total number sedans entering the simulation space averaged over all the replicates. It also shows the standard deviation for total number of vehicles and sedans across all replicates.

<table>
<thead>
<tr>
<th>Expected total number of vehicles per hour</th>
<th>Total number of vehicles averaged over all replicates</th>
<th>Std. Dev. of total number of vehicles arrived</th>
<th>Expected number of Sedan (56% of total expected vehicles)</th>
<th>Sedans averaged over all replicates</th>
<th>Std. Dev. of Sedans over all replicates</th>
</tr>
</thead>
<tbody>
<tr>
<td>600</td>
<td>600.22</td>
<td>32.76</td>
<td>336</td>
<td>333.22</td>
<td>16.9</td>
</tr>
<tr>
<td>900</td>
<td>891.5</td>
<td>29.81</td>
<td>504</td>
<td>499.88</td>
<td>18.1</td>
</tr>
<tr>
<td>1200</td>
<td>1191.6</td>
<td>24.1</td>
<td>672</td>
<td>664.77</td>
<td>14.3</td>
</tr>
</tbody>
</table>
Figure 12 – Distribution of inter-arrival time at 600 vehicles per hour

Figure 13 – Distribution of inter-arrival time at 900 vehicles per hour
8.7. Simulating Driver Behavior
SUMO models individual cars, by default, according to the car-following model developed by Stefan Krauß (Krauß, 1998). The car-following model is based on safe speed paradigm. The drivers keep a safe distance from the preceding vehicle to avoid any collision in case the preceding vehicle decelerates, but at the same time go as fast as possible.

8.8. Simulating Communication and Implementation of Algorithms
To implement the coordination heuristic and single-vehicle optimization, the algorithm requires following input parameters: vehicles’ speed, vehicles’ distance from the traffic signal, the phase of traffic signal and the time for next phase change. This information is used to make decisions regarding speed profile. The speed profile is then returned to the V2X capable autonomous vehicle which drive according to the suggested speed profile. In a real-world system, the exchange of information between vehicles and traffic signals is expected to be facilitated by Road Side Units and On-board Units. In the experiments used in these simulations uses Traffic Control Interface (TraCI), a module provided by SUMO to simulate exchange of information between vehicles and traffic signals. TraCI (Wegener et al., 2008) provides a set of python commands to retrieve information regarding different objects in the simulation environment and change the attributes of the objects during runtime. All the algorithms and modules except the module called *decelerate*, 

![Figure 14 - Distribution of inter-arrival time at 1200 vehicles per hour](image)
discussed in the Section 6 have been implemented in python. The module *decelerate* has been implemented in AMPL (Fourer et al., 2003). In the simulations supporting this thesis, python has been used to exchange information between the simulation platform SUMO and the optimization tool AMPL.

Figure 15 represents the order in which information is captured from SUMO, processed in AMPL or python depending on the module and returned back to SUMO. The bidirectional arrow number 1 represents the set of TraCI commands which capture the current state of the simulation and the arrow pointing left and numbered 4 represents the TraCI commands which provide the speed profiles calculated by the algorithms back to the simulation as input parameters in real time. The arrow number 2 set of python commands which provide input parameters to AMPL for the *decelerate* module and the arrow number 3 represents the output generated by AMPL. The values calculated from the *decelerate* module are returned to the simulation during run time through of TraCI commands indicated by arrow number 4. The *decelerate* module takes some time to find an optimal solution and the simulation pauses during that time.

![Figure 15 - Representation of exchange of information between simulation and optimization platform](image)

*Figure 15 - Representation of exchange of information between simulation and optimization platform*
9. Model Validation and Verification

Simulation models are used to facilitate decision making. The obvious concern for the stakeholders is whether the model and the results generated from the model are correct. Model verification and model validation help address these queries (Sargent, 2011).

Model validation is the process of ensuring that the model closely represents a real scenario. A few of the many validation techniques discussed by Sargent (2011) are a comparison to other models and parameter variability. The former technique involves a comparison of the model results to other results that have been validated. The latter technique involves changing the input parameters and analyzing the effect on performance measures of the model. We have validated the model for certain parameters using both the techniques mentioned above.

As the number of vehicles per hour increase, more vehicles are expected to wait at the red phase. Table 4 indicates that the number of vehicles which stopped while following the baseline driver behavior at the first traffic light, averaged over all the replicates, increased with the number of vehicles per hour.

\[
\text{Table 4 - Number of vehicles which stop at the first intersection increase with number of vehicles per hour} \\
\begin{array}{|c|c|}
\hline
\text{Vehicles per hour} & \text{Number of vehicles which stopped} \\
\hline
1200 & 1192.7 \\
900 & 892.6 \\
600 & 552.3 \\
\hline
\end{array}
\]

Average CO\textsubscript{2} emissions from a smaller vehicle like a passenger car should be less than the average emissions generated from a heavier vehicle like a truck over the trip. Further, as indicated in Table 4, more vehicles stop at the intersection as the number vehicles per hour increase. Thus, it is expected that the total CO\textsubscript{2} emissions at system level should increase. Table 5 shows the average CO\textsubscript{2} emissions generated from passenger vehicles and trucks averaged over all the replicates for the first 500 meters of the trip. According to Table 5, the average CO\textsubscript{2} emission per vehicle for passenger cars is much less than average CO\textsubscript{2} emission per vehicle for trucks. Table 5 also indicates that the average CO\textsubscript{2} emission per vehicle for passenger cars and trucks increases with the number of vehicles per hour.
Table 5 - Number of vehicles of each type and the CO\(_2\) per hour

<table>
<thead>
<tr>
<th>Performance metric</th>
<th>Vehicle type</th>
<th>Vehicles per hour</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>600</td>
</tr>
<tr>
<td>Total CO(_2) emissions from all vehicles of each type (g)</td>
<td>Passenger Vehicle</td>
<td>26589</td>
</tr>
<tr>
<td></td>
<td>Truck</td>
<td>7302</td>
</tr>
<tr>
<td>Total number of vehicle of each type (averaged over 10 replicates)</td>
<td>Passenger Vehicle</td>
<td>306</td>
</tr>
<tr>
<td></td>
<td>Truck</td>
<td>14</td>
</tr>
<tr>
<td>Average CO(_2) emission per vehicle (g)</td>
<td>Passenger Vehicle</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>Truck</td>
<td>533</td>
</tr>
</tbody>
</table>

Vehicles generate more emissions at higher accelerations (Ericsson, 2001). The results from the emission model used for the simulation can be validated for this behavior. Figure 16 shows the variation of CO\(_2\) emissions with instantaneous acceleration. The CO\(_2\) emissions are high everytime the instantaneous acceleration is greater than 0 and the emissions reduce or become 0 when acceleration is less than or equal to 0.

![Chart showing the relationship between instantaneous acceleration and CO\(_2\) emissions](image)

*Figure 16 – Relationship between instantaneous acceleration and CO\(_2\) emissions*
As the percentage of vehicles equipped with V2X technology increase, more vehicles are expected to respond to a coordination request from a trailing V2X vehicle. This can be validated from Figure 17 and Figure 18. The two figures show the number of instances for which a coordination was requested by a trailing vehicle and the number of preceding vehicles which facilitate a coordination request. Figure 17 and Figure 18 represent the scenario for 900 vph at 60% V2X and 100% V2X penetration respectively. At 60% V2X penetration on an average 3.8 V2X vehicles facilitate a coordination request. At 100% V2X on an average 6.3 V2X vehicles facilitate a coordination request.

![Figure 17 - Number of vehicles which facilitate a coordination request at 900 vph, 60% V2X](image)
Model verification is the process of ensuring that the model or the computer program has been correctly implemented (Sargent, 2011). Two of the verification techniques recommended by (Robinson, 1997) are checking the code and visual checks. The proposed simulation model can be verified by checking if the vehicle reaches the signalized intersection at the time which the algorithms described in section 6.1 and 6.2 suggest that the vehicle should reach by running the simulation in single steps. Besides this, the simulation software SUMO generates a “trace” every second for all the vehicles in the system. Trace is an XML file which has the information about vehicles’ speeds and positions. This information has been used to verify if the vehicles are adopting the speed which the model suggests. Figure 19 and Figure 20 show the distance and speed profiles for two vehicles following the coordination heuristic (Vehicle A and Vehicle B) which entered the simulation environment at various times. Table 6 provides the parameter values for the two vehicles under consideration and the decisions made by coordination heuristic based on the parameter values.
Figure 19 - Speed-Distance trace for Vehicle A

Figure 20 - Speed-Distance trace for Vehicle B
### Table 6 - Model verification for Vehicle A and Vehicle B

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Traffic Light 1</th>
<th>Traffic Light 2</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Vehicle A</td>
<td>Vehicle B</td>
<td>Vehicle A</td>
<td>Vehicle B</td>
</tr>
<tr>
<td>Speed (m/s)</td>
<td>14.8</td>
<td>0.3</td>
<td>4</td>
<td>5.2</td>
</tr>
<tr>
<td>Current phase</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
<td>Green</td>
</tr>
<tr>
<td>Current time</td>
<td>106</td>
<td>564</td>
<td>180</td>
<td>635</td>
</tr>
<tr>
<td>Time remaining in current phase (s)</td>
<td>16</td>
<td>24</td>
<td>40</td>
<td>35</td>
</tr>
</tbody>
</table>

### Evaluation steps

<table>
<thead>
<tr>
<th>First if condition of coordination algorithm</th>
<th>Will vehicle get through the intersection at current speed in given time?</th>
<th>No</th>
<th>No</th>
<th>No</th>
<th>No</th>
</tr>
</thead>
<tbody>
<tr>
<td>Second if condition of coordination algorithm</td>
<td>Will the vehicle get through the intersection by accelerating?</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>First if condition of Algorithm 2</td>
<td>Time remaining for next green phase?</td>
<td>66</td>
<td>74</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Second if condition of Algorithm 2</td>
<td>For the next green phase, is the current speed high or low?</td>
<td>High</td>
<td>Low</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Decision</th>
<th>Decelerate</th>
<th>Accelerate</th>
<th>Accelerate</th>
<th>Accelerate</th>
</tr>
</thead>
</table>

10. Results and Discussion
This section presents and discusses the results generated from the simulations. The section is divided into three subsections which discuss the three performance measures mentioned section 5.4: average CO$_2$ emissions per vehicle over the trip, average travel time per vehicle and average wait time per vehicle. Each of the performance measures has been evaluated across 10 values of V2X penetration, for 3 values of vehicles per hour and compares the performance measure across the three driving strategies; baseline model (BASE), single-vehicle optimization (SV) and coordination heuristic (CH) for 10 replicates.

10.1 Emissions
The average CO$_2$ emission per vehicle over the trip is the total amount of CO$_2$ emissions generated by all the vehicles in the simulation averaged over the number of vehicles. Figure 21 compares average CO$_2$ emissions for all vehicle types averaged over all the replicates for increasing penetration of the V2X technology across different strategies and number of vehicles per hour. According to Figure 21 the average emissions per vehicle increase as the value of vehicles per hour increases. This can be attributed to the increased number of vehicles stopping at the intersections. This observation is in line with the findings of the 2015 Urban Mobility Score Card (Schrank. et al., 2015) which suggests that as more vehicles have to stop at intersections, the amount fuel wasted increases.

The underlying principle for the two algorithms discussed in section 6.1 and 6.2, single-vehicle optimization and coordination heuristic respectively is to avoid stoppages and accelerations. A comparison of CO$_2$ emissions for increasing value of vehicles per hour (vph) indicate that more reduction is achieved at a higher value of vehicles per hour. At 600 vph for 100% V2X penetration, the coordination heuristic reduces CO$_2$ emissions by 6.14% compared to the baseline case when no optimization is used, whereas the CO$_2$ emissions reduce by 13.23% at 1200 vph for 100% V2X penetration. This indicates that use of a coordination heuristic or single-vehicle optimization technique might generate better results at higher values of vehicles per hour.
Both single-vehicle optimization and the coordination heuristic begin to show benefits over no optimization only after V2X penetration reaches a certain threshold value. This threshold value is lower for higher values of vehicles per hour. At 600 vph the coordination heuristic and the single-vehicle optimization begin to outperform the baseline case at 60% or higher penetration of the V2X technology. This threshold value for 1200 vph occurs around 30% range. This finding might help the decision makers and the city planners to identify V2X penetration at which coordination heuristic can be introduced depending on their city’s traffic volume.

Figure 21 also indicates that the average CO$_2$ emissions per vehicle for coordination heuristic is less than single-vehicle optimization. Figure 22 compares the average emission per vehicle for single-vehicle optimization and coordination heuristic for different replicates used in the simulation at 900 vph for increasing penetration of V2X vehicles. The black dashed line represents the average emissions (across 10 replicates) for the baseline driver behavior. According to Figure 22, once the V2X penetration reaches its threshold value of about 50% for the vehicle density of 900 vph the CO$_2$ emissions generated from the coordination heuristic are less than the CO$_2$ emissions generated from single-vehicle optimization strategy. Table 7, Table 8 and Table 9 provide t-statistic at 95% confidence level to compare baseline driver behavior, single-vehicle optimization strategy and coordination heuristic with each other. The coordination heuristic generates significantly less CO$_2$ emissions compared to the other two driving strategies once penetration of V2X technology becomes 50%.
Figure 22 – Comparing CO₂ emissions for coordination heuristic and single-vehicle optimization at different penetration levels of V2X technology

Table 7 - Comparison of mean emissions generated from vehicles following the single-vehicle optimization and the coordination heuristic

<table>
<thead>
<tr>
<th>V2X penetration (%)</th>
<th>Mean CO₂ emissions for coordination heuristic</th>
<th>Mean CO₂ emissions for single-vehicle optimization</th>
<th>t-stat</th>
<th>p-val</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>330</td>
<td>330</td>
<td>-0.09</td>
<td>0.9283</td>
</tr>
<tr>
<td>20</td>
<td>328</td>
<td>328</td>
<td>0.36</td>
<td>0.7200</td>
</tr>
<tr>
<td>30</td>
<td>326</td>
<td>326</td>
<td>-0.19</td>
<td>0.8545</td>
</tr>
<tr>
<td>40</td>
<td>321</td>
<td>323</td>
<td>-1.28</td>
<td>0.2184</td>
</tr>
<tr>
<td>50</td>
<td>316</td>
<td>320</td>
<td>-3.29</td>
<td>*0.0044</td>
</tr>
<tr>
<td>60</td>
<td>312</td>
<td>315</td>
<td>-2.46</td>
<td>*0.0244</td>
</tr>
<tr>
<td>70</td>
<td>309</td>
<td>313</td>
<td>-3.19</td>
<td>*0.0052</td>
</tr>
<tr>
<td>80</td>
<td>304</td>
<td>308</td>
<td>-3.46</td>
<td>*0.0028</td>
</tr>
<tr>
<td>90</td>
<td>296</td>
<td>301</td>
<td>-4.46</td>
<td>*0.0003</td>
</tr>
<tr>
<td>100</td>
<td>290</td>
<td>296</td>
<td>-7.92</td>
<td>*0</td>
</tr>
</tbody>
</table>

* = statistically significant difference
Table 8 - Comparison of mean emissions generated from vehicles following the single-vehicle optimization and baseline driver behavior

<table>
<thead>
<tr>
<th>V2X penetration (%)</th>
<th>Mean CO₂ emissions for baseline driver behavior</th>
<th>Mean CO₂ emissions for single-vehicle optimization</th>
<th>t-stat</th>
<th>p-val</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>323</td>
<td>330</td>
<td>-5.74</td>
<td>*0</td>
</tr>
<tr>
<td>20</td>
<td>323</td>
<td>328</td>
<td>-4.09</td>
<td>*0.0007</td>
</tr>
<tr>
<td>30</td>
<td>323</td>
<td>326</td>
<td>-2.53</td>
<td>*0.0212</td>
</tr>
<tr>
<td>40</td>
<td>323</td>
<td>323</td>
<td>0.04</td>
<td>0.9666</td>
</tr>
<tr>
<td>50</td>
<td>323</td>
<td>320</td>
<td>2.09</td>
<td>0.0515</td>
</tr>
<tr>
<td>60</td>
<td>323</td>
<td>315</td>
<td>5.36</td>
<td>*0</td>
</tr>
<tr>
<td>70</td>
<td>323</td>
<td>313</td>
<td>7.91</td>
<td>*0</td>
</tr>
<tr>
<td>80</td>
<td>323</td>
<td>308</td>
<td>11.82</td>
<td>*0</td>
</tr>
<tr>
<td>90</td>
<td>323</td>
<td>301</td>
<td>18.11</td>
<td>*0</td>
</tr>
<tr>
<td>100</td>
<td>323</td>
<td>296</td>
<td>23.78</td>
<td>*0</td>
</tr>
</tbody>
</table>

Table 9 – Comparison of mean emissions generated from vehicles following the coordination heuristic and baseline driver behavior

<table>
<thead>
<tr>
<th>V2X penetration (%)</th>
<th>Mean CO₂ emissions for baseline driver behavior</th>
<th>Mean CO₂ emissions for coordination heuristic</th>
<th>t-stat</th>
<th>p-val</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>323</td>
<td>330</td>
<td>6.46</td>
<td>*0</td>
</tr>
<tr>
<td>20</td>
<td>323</td>
<td>328</td>
<td>4.81</td>
<td>*0.0002</td>
</tr>
<tr>
<td>30</td>
<td>323</td>
<td>326</td>
<td>2.12</td>
<td>*0.0478</td>
</tr>
<tr>
<td>40</td>
<td>323</td>
<td>321</td>
<td>-1.41</td>
<td>0.1762</td>
</tr>
<tr>
<td>50</td>
<td>323</td>
<td>316</td>
<td>-5.45</td>
<td>*0.0001</td>
</tr>
<tr>
<td>60</td>
<td>323</td>
<td>312</td>
<td>-7.93</td>
<td>*0</td>
</tr>
<tr>
<td>70</td>
<td>323</td>
<td>309</td>
<td>-11.37</td>
<td>*0</td>
</tr>
<tr>
<td>80</td>
<td>323</td>
<td>304</td>
<td>-15.52</td>
<td>*0</td>
</tr>
<tr>
<td>90</td>
<td>323</td>
<td>296</td>
<td>-22.42</td>
<td>*0</td>
</tr>
<tr>
<td>100</td>
<td>323</td>
<td>290</td>
<td>-29.40</td>
<td>*0</td>
</tr>
</tbody>
</table>

Table 7 provides t-statistic which compares mean CO₂ emissions generated by the vehicles following the single-vehicle optimization and the coordination heuristic. The t-statistic and p-value suggest that the mean CO₂ emissions generated by the vehicles following the two algorithms become significantly different only after V2X penetration is at least 50% at 900 vph. Table 7 also indicates that the CO₂ emissions generated from coordination heuristic are less than the CO₂ emissions generated from the single-vehicle optimization.
Table 8 provides the t-statistic for mean CO\(_2\) emissions generated by the vehicles following the single-vehicle optimization and baseline driver behavior. The t-statistic indicates that after the V2X technology reaches a penetration of 50% or more, the mean CO\(_2\) emissions generated by vehicles adopting single-vehicle optimization are significantly less than the mean CO\(_2\) emissions generated by the vehicles following baseline driver behavior. Table 9 shows a similar trend for the coordination heuristic and baseline driver behavior. From Table 7 and Table 9, we conclude that at a 50% V2X penetration the mean CO\(_2\) emissions generated by vehicles following the coordination heuristic is significantly lower than the mean CO\(_2\) emissions generated by the vehicles following single-vehicle optimization and baseline driver behavior respectively.

A comparison of single-vehicle optimization and coordination heuristic would indicate that the two algorithms work in an analogous manner for the vehicles arriving during the red phase. During the red phase both the algorithms suggest speed and acceleration values such that the vehicles arrive at the intersection just when the phase of the traffic signal is about to turn green. However, the two algorithms differ for the green phase. The single-vehicle optimization strategy instructs the vehicle which may not get through the intersection to decelerate while the coordination heuristic allows more vehicles to pass through the intersection by adjusting the speed limit. As a result, the V2X capable vehicles which may avoid stopping with some speed adjustment slightly accelerate and generate incremental emissions. The underlying assumption for performing the experiments was that the incremental emissions from the slight acceleration of a group of vehicles should be less than the emissions generated from a single-vehicle which otherwise would have come to a stop and then accelerate. Figure 22 and Table 7 suggest that the underlying assumption for coordination heuristic is correct and the incremental reduction in emissions for the coordination heuristic can be attributed to the adjustment of the speed limit for the V2X vehicles.

Since average CO\(_2\) emissions per vehicle generated by the coordination heuristic are consistently less than the single-vehicle optimization after a penetration 50% V2X vehicles is reached at 900 vph might be desired for the policymakers to choose the coordination heuristic over the single-vehicle optimization strategy once a required acceptance of V2X vehicles is reached depending on the number of vehicles per hour. Figure 21 indicates that the required acceptance of V2X vehicles for the emissions of coordination heuristic to be significantly less than the single-vehicle optimization is higher for lower values of number of vehicles per hour. At 600 vph the number the
emissions for coordination heuristic is significantly less than the emissions from single-vehicle optimization at V2X penetration of over 60% whereas at 1200 vph the emissions for coordination heuristic are significantly less than the emissions from single-vehicle optimization at V2X penetration of about 40%.

As the coordination heuristic generates less CO₂ emissions than single-vehicle optimization, the remaining discussion in this section further analyzes the coordination heuristic to a greater detail. A common observation for Figure 21 and Figure 22 is that only once the V2X penetration reaches a threshold does the coordination heuristic begin to show its benefits. In fact, prior to this threshold average CO₂ emissions per vehicle increase. Figure 23 compares the CO₂ emissions generated from the vehicles following the coordination heuristic and non-V2X vehicles in the same environment. The black dashed line represents the average CO₂ emissions from all the vehicles for the baseline scenario. Figure 23 suggests that CO₂ emissions generated from non-V2X vehicles are consistently more than average emissions generated in absence of the vehicles following coordination heuristic. In other words, the coordination heuristic is causing non-V2X vehicles to generate more emissions. Figure 23 reveals that the vehicles following the coordination heuristic begin to generate fewer emissions compared to the baseline driver behavior, a scenario when no V2X technology is used, even at low penetrations of V2X technology. The average CO₂ emission reduction for the vehicles following the coordination heuristic compared to the emissions generated for vehicles following the baseline driver behavior decrease as the V2X technology receives more penetration.

Non-V2X vehicles generate more emissions in the presence of V2X vehicles following the coordination heuristic. The performance of V2X and non-V2X vehicles has been compared by Katsaros et al. (2011) according to which the non-V2X vehicle perform better in presence of the V2X vehicles. Katsaros et al. (2011) assume that the non-V2X vehicles do not pass the V2X vehicles when the V2X vehicles drive slow in order to avoid stopping at a red light. The experiments performed in this research allow non-V2X vehicles to pass V2X vehicles. The non-V2X vehicles when stuck behind a slow-moving V2X vehicle, accelerate while changing lane to pass the V2X vehicle, and thus generate more emissions. Figure 24 shows the average number of lane changes per non-V2X vehicle at 900 vph for increasing value of V2X penetration for the first 500m of the trip. The average number of lane changes nearly double as the penetration of V2X
vehicles increase from 0 to 10% and then remain nearly constant, at a higher value, around 1.3 lane change per non-V2X vehicle, up from 0.63 with when there are no V2X vehicles.

Figure 23 - Comparing CO$_2$ emissions for coordination heuristic and non-V2X vehicle at different penetration levels of V2X technology

Figure 24 – Average number of lane changes performed by non-V2X vehicles at 900 vph
Figure 25 shows total CO₂ emissions per non-V2X passenger vehicle over the first 500m against the number of lane changes. It’s evident that the increased CO₂ emissions for non-V2X vehicles could be a result of frequent lane changes. Thus, restricting lane changes for non-V2X vehicles might generate better system level results particularly at lower levels of V2X penetration when the coordination heuristic generates more emission than the baseline driver behavior.

This section analyzed the CO₂ emissions generated by the vehicles adopting a coordination heuristic, single-vehicle optimization and baseline driver behavior. The coordination heuristic generates the least amount of CO₂ emissions compared to the other two driving strategies once a threshold for V2X penetration is achieved. This threshold depends on number of vehicles per hour. These findings can be useful for policymakers to choose coordination heuristic to reduce CO₂ emissions depending on the city’s traffic conditions and the acceptance of V2X technology.

10.2 Travel Time
Travel time is the total time it took a vehicle to travel 1000m, through the two traffic lights. Figure 26 compares the average travel time per vehicle across different driving strategies at increasing values of V2X penetration and the number of vehicles per hour. According to Figure 26 the average
travel time increases with the number of vehicles per hour. The average travel time is least for the vehicles which follow the baseline driver behavior and the travel time for single-vehicle optimization is more than the coordination heuristic. The travel time for single-vehicle optimization and the coordination heuristic increases with the penetration of V2X technology.

For the baseline driver behavior, the average travel time increases by 21% as the number of vehicles per hour increase from 600 to 1200 vehicles per hour. For the coordination heuristic, the average travel time increases by only 11.75% with the increase in number of vehicles per hour from 600 to 1200. The relative difference between average travel time for coordination heuristic and the baseline driver behavior reduces with increase in the number of vehicles per hour from 14.5% at 600 vehicles per hour to 5.7% at 1200 vehicles per hour. These values indicate that although travel time for coordination heuristic is higher than baseline driver behavior it increases at a lower rate compared to the baseline driver behavior as the number of vehicles per hour increase.

![Figure 26 - Average travel time at different values of vehicles per hour](image)

Lower average travel time for baseline driver behavior compared to the coordination heuristic can be attributed to higher acceleration values for baseline driver behavior. The average acceleration per vehicle over the trip for baseline driver behavior averaged for all the vehicles over every replicate is 0.43 m/s² while for the coordination heuristic the average acceleration per vehicle over the trip is 0.27 m/s².
Figure 27 compares the average travel time for single-vehicle optimization versus the coordination heuristic. The average travel time for either of the two strategies is more than average travel time for the vehicles following the baseline driver behavior indicated by the black dashed line in Figure 27. Table 10 shows the t-statistic and p-values which compare the average travel time between the coordination heuristic and single-vehicle optimization at 900 vph. The average travel time for the coordination heuristic is less than single-vehicle optimization. The absolute value of t-statistic increases with penetration of V2X technology and the difference becomes significant after V2X technology reaches a penetration of 20%.

The reduction of average travel time for the coordination heuristic can be attributed to the adjusted speed limit values. The adjusted speed limit values also results in less number of vehicles which are in transit or are waiting in the middle segment of the network between the two traffic signals.

Figure 28 compares the number of vehicles in transit for the two driving strategies, averaged over 60 instances of red phase, between the two traffic lights at 100% penetration of V2X technology. The number of vehicles in transit for the coordination heuristic is less than single-vehicle optimization and the difference increases with the number of vehicles per hour. Table 11 shows the t-statistic to compare the number of vehicles waiting or in transit during the red phase for
coordination heuristic and single-vehicle optimization. At 100% V2X technology the difference becomes significant at 900 vehicles per hour.

Figure 28 - Number of vehicles which didn’t go through second traffic light during green phase at 100% V2X

Table 10 - Comparison of average travel time per vehicle for coordination heuristic and single-vehicle optimization at 900 vph

<table>
<thead>
<tr>
<th>V2X penetration (%)</th>
<th>Mean travel time for coordination heuristic</th>
<th>Mean travel time for baseline driver behavior</th>
<th>t-stat</th>
<th>p-val</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>109.2</td>
<td>109.9</td>
<td>-1.40</td>
<td>0.1785</td>
</tr>
<tr>
<td>20</td>
<td>110.1</td>
<td>111.2</td>
<td>-2.95</td>
<td>*0.0088</td>
</tr>
<tr>
<td>30</td>
<td>111.5</td>
<td>113.2</td>
<td>-3.79</td>
<td>*0.0013</td>
</tr>
<tr>
<td>40</td>
<td>112.2</td>
<td>115.2</td>
<td>-5.10</td>
<td>*0.0002</td>
</tr>
<tr>
<td>50</td>
<td>114.2</td>
<td>117.3</td>
<td>-8.60</td>
<td>*0</td>
</tr>
<tr>
<td>60</td>
<td>115</td>
<td>118.7</td>
<td>-10.09</td>
<td>*0</td>
</tr>
<tr>
<td>70</td>
<td>116.5</td>
<td>120.5</td>
<td>-9.20</td>
<td>*0</td>
</tr>
<tr>
<td>80</td>
<td>117.2</td>
<td>121.6</td>
<td>-14.76</td>
<td>*0</td>
</tr>
<tr>
<td>90</td>
<td>117.2</td>
<td>122.3</td>
<td>-14.14</td>
<td>*0</td>
</tr>
<tr>
<td>100</td>
<td>117.1</td>
<td>122.5</td>
<td>-13.05</td>
<td>*0</td>
</tr>
</tbody>
</table>
This section analyzed the travel time for vehicles adopting baseline driver behavior, coordination heuristic and single-vehicle optimization. The average trip time for baseline driver behavior is the least. V2X vehicles which follow the coordination heuristic require less travel time compared to the vehicles following single-vehicle optimization, and therefore coordination heuristic is more suitable compared to single-vehicle optimization. Further, the average travel time for coordination heuristic increases at much lower rate compared to baseline driver behavior as the number of vehicles per hour increases. While the travel time does increase over the baseline results, the increase is only 5.7% at 100% penetration of V2X vehicles at 1200 vph which might be acceptable considering more fuel efficient trips. Despite incremental travel time, coordination heuristic reduces emissions significantly.

10.3 Wait time
Wait time is the time for which a vehicle has almost come to a stop (speed less than 2.25 mph). Figure 29 compares the wait time for the three driving strategies with increasing number of vehicles per hour and penetration of V2X technology. The average wait time per vehicle increases with the number of vehicles per hour for the baseline driver behavior. For the coordination heuristic and single-vehicle optimization strategies, the average wait time sometimes reduces for higher values of vehicles per hour. The wait time for baseline driver behavior is more than either of the two driving strategies even at low penetration of V2X technology. For the coordination heuristic and single-vehicle optimization, the wait time reduces with increasing penetration of V2X technology and is nearly zero for 100% V2X at 600 vph and 900 vph. The results in Figure 29 also suggests that the average wait time per vehicle for vehicle using the coordination heuristic is more than average wait time for vehicle using the single-vehicle optimization strategy.
At the beginning of experiments, it was anticipated that the average wait time per vehicle will increase with the number of vehicles per hour. The average wait time per vehicle increases for the baseline driver behavior. However, for the coordination heuristic and single-vehicle optimization, the average wait times sometimes decreases with increasing number of vehicles per hour. The average wait time is a ratio and depends on total duration of stoppages for all the vehicles which stopped and the number of vehicles which stopped. Figure 30 and Figure 31 represent the total duration of stoppages and the number of vehicles which stopped both of which increase with the number of vehicles per hour as anticipated. The ratio of the values represented by these graphs depends on relative change in these values and reduces for certain values of V2X penetration as seen in Figure 29.

The average wait time per vehicle reduces with the penetration of V2X vehicles. The V2X vehicles are under the influence of single-vehicle optimization or coordination heuristic. The two strategies use information regarding the phase of traffic light, time in which the phase will change, vehicle’s speed and position to suggest a speed profiles which reduces the wait by decelerating over the entire red phase or by adjusting the speed limit to avoid the red phase. This results in near zero wait times particularly at higher penetration of V2X capable vehicles and lower values of vehicles per hour.
The average wait time per vehicle is less for the single-vehicle optimization strategy. During the green phase, the coordination heuristic adjusts the speed limit for V2X vehicles to increase the throughput. To facilitate coordination, the vehicles ahead of the V2X vehicle should also be V2X capable and drive at the adjusted speed limit. This may not necessarily happen every time and there might be situations where a V2X vehicle drives at an adjusted speed limit and arrives at the
intersection only to wait during red phase. Single-vehicle optimization, during green phase, instructs V2X vehicle to decelerate if it evaluates that the vehicle cannot get through the intersection. As a result, fewer vehicles arrive early during the red phase and the average wait time per vehicle is reduced. It’s also observed that at 900 vph, the average wait time per vehicle reduces by 70% and 69% single-vehicle optimization and coordination heuristic respectively as V2X penetration increase from 10% to 90%. The average wait time per vehicle further reduces by 87.7% and 81% for single-vehicle optimization and coordination heuristic as V2X penetration increase from 90% to a 100%.

This section marks the end of discussion on results. The average wait time for V2X vehicles following either of the driving strategies is much less than baseline driver behavior. The average wait for V2X vehicles reduces with increase in percentage of V2X capable vehicles and does not necessarily increase with the number of vehicles per hour like other performance measures.
11. Conclusions and Future Work

This research proposes a coordination heuristic to reduce CO₂ emissions for vehicles approaching signalized intersections. The coordination heuristic uses C-VSLS to adjust the speed limit at traffic signals and allow more V2X vehicles to get through. The results indicate system level benefits for the coordination heuristic like lower CO₂ emissions and travel time over single-vehicle optimization and lower CO₂ emissions and wait time over baseline driver behavior. The CO₂ emissions begin to diminish compared to baseline driver behavior only when the population of V2X vehicles reaches a certain percentage of all vehicles. This percentage or threshold, beyond which the CO₂ emissions generated by vehicles following coordination heuristic is less than baseline driver behavior depends on the number of vehicles per hour. At 600 vph the coordination heuristic and single-vehicle optimization begin to generate lower emissions than the emissions generated by baseline driver behavior for V2X penetration of 60% whereas at 1200 vph the two strategies begin to generate lower emissions than the baseline driver behavior at 30% penetration of V2X vehicles. The results also suggest that once the threshold is reached, despite higher speeds, coordination heuristic always generates fewer CO₂ emissions compared to single-vehicle optimization. At 100% V2X with 900 vehicles per hour, the coordination heuristic generates 10% less emissions compared to the baseline driver behavior. The coordination heuristic reduced CO₂ emissions by 30% more than single-vehicle optimization. These findings can be useful for policymakers who wish to deploy these strategies to reduce emissions depending on traffic conditions and acceptance of V2X technology.

The average travel time for the coordination heuristic and single-vehicle optimization is more than the baseline driver because of lower values of allowed acceleration. The average travel time for the two driving strategies increase at a lower rate compared to baseline driver behavior with increasing number of vehicles per hour. Smaller travel times for the coordination heuristic compared to single-vehicle optimization can be attributed to adjusted speed limits. The difference becomes particularly significant at higher number of vehicles per hour. The average wait time for the coordination heuristic is less than the average wait time for baseline driver behavior. At higher penetration of V2X technology and lower values of vehicles per hour the average wait time reaches nearly zero and a smooth traffic flow is achieved.
The coordination heuristic generates less CO₂ emissions and has smaller travel time compared to single-vehicle optimization strategy and should therefore be preferred over single-vehicle optimization strategy to realize the true potential of V2X technology.

Certain aspects of the coordination heuristic can be further analyzed to make it more beneficial. In the coordination heuristic a V2X vehicle requests coordination from all preceding V2X vehicles. The number vehicles which receive this request depends on the penetration of V2X vehicles and the number of vehicles per hour. There are instances where more than 15 and sometimes 30 V2X vehicles received a coordination request and had to accelerate to facilitate a trailing vehicle. Not every coordination request necessarily reduces CO₂ emissions at a system level. It might be beneficial to limit the number of vehicles facilitating a coordination request. Besides, the coordination heuristic adjusts speed limit for all the preceding V2X vehicles and not all the V2X vehicles might be necessarily in the way of V2X vehicle which requests coordination. Only adjusting the speed limit for vehicles which might be in the way of the V2X vehicle requesting coordination will prevent excess emissions generated from some of the preceding V2X vehicles. The extent to which the speed limit adjustments are allowed is another important parameter which could be analyzed. Currently speed limit adjustments of less than 10% of the speed limits are allowed. The speed limit adjustment could depend on the vehicle mix and the existing speed limits. The experiments used in this research have assumed that the vehicles travel only in one direction and do not turn. It might be interesting to analyze the coordination heuristic for more complex networks. Further, the coordination heuristic and single-vehicle optimization use the information related to the phase and the timing of just the nearest traffic signal. Better results might be obtained by using the information of traffic lights further ahead of them. Lastly with more acceptance of electric vehicles which have different fuel consumption profiles compared to gasoline vehicles it might useful to analyze the system level benefits of the coordination heuristic with inclusion of electric vehicles in the vehicle mix.
12. References


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