University Transportation Research Center - Region 2

Final Report

Impact of Optimization Strategy and Adoption Rate of V2X Technology on Environmental Impact

Performing Organization: Rochester Institute of Technology (RIT)

December 2017

Sponsor:
University Transportation Research Center - Region 2

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The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

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16. Abstract

This research evaluated the effects of automated vehicle control strategies on system level emissions, travel time and wait time through a series of traffic lights. The study was conducted using traffic simulation and a realistic vehicle mix. Two control strategies were evaluated including a single vehicle control strategy and a multi-vehicle coordination heuristic. The performance of each control strategy was recorded under various levels of connected and autonomous vehicle technology (V2X technology) and 3 levels of traffic flow. In the single vehicle control strategy each connected and autonomous vehicle calculated optimal speeds for itself to traverse a series of traffic lights. In the coordination heuristic, each autonomous and connected vehicle calculated optimal speeds for itself to traverse a series of traffic lights, but could also issue coordination requests that would allow preceding vehicles to increase their speed slightly, such that the requesting vehicle could also make it through the traffic signal without stopping. Results indicate that the coordination heuristic consistently outperformed the single vehicle optimization strategy and offered significant emissions reductions at high V2X penetration rates. At 1200 vehicles per hour and 100% V2X penetration rate the coordination heuristic reduced emissions by 15%. Results also indicated that both control strategies can have adverse effects at low penetration rates of connected and automated vehicle technology, and should only be employed once connected and automated vehicle technology reaches certain threshold levels that vary by traffic flow. The control strategies employed did increase average travel time, but at the same time decreased average wait time at traffic lights.

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vph	vehicles per hour
V2X	connected vehicle technology (vehicle to everything)

Executive Summary

As automated vehicles take to the roads in increasing numbers and communication technology between vehicles and traffic infrastructure (V2X technology) comes into place there exist opportunities to improve traffic flow. However, single vehicle control strategies that automated vehicles may adopt could have adverse impacts on both traditional vehicles and other automated vehicles in the system. It stands to reason that control strategies that target cooperative movements of vehicles could have positive effects on traffic flow and result in lower emissions at a system level. This research evaluated the effectiveness of two vehicle control strategies on reducing system wide emissions of vehicles travelling through a series of traffic signals. The vehicle control strategies developed consisted of a single vehicle control strategy and a multi-vehicle control strategy. The effectiveness of these strategies at different adoption rates of V2X technology and different traffic rates were evaluated.

A discrete event simulation methodology was adopted to perform the study using the Simulator for Urban Mobility (SUMO). A series of two traffic lights were modeled, consisting of two lanes of traffic moving in the same direction. The model incorporated a representative vehicle mix, and non-V2X enabled vehicles followed the car-following model developed by Krauß (1998). Multiple replications were run for each configuration, and emissions, total travel time, and total stop time were calculated for each vehicle in the system.

Results indicate that when single vehicle or multi-vehicle control strategies are introduced at low adoption rates of V2X technology that system wide emissions levels increase. While emissions of V2X controlled vehicles decrease, the emissions for non-V2X vehicles increases, and this increase outweighs the efficiency gains by V2X controlled vehicles until a certain adoption rate is reached. A traffic rate of 600 vehicles per hour required 50% of the vehicles to adopt V2X technology before system level emissions decreased, while a traffic rate of 1200 vehicles per hour required 30% V2X adoption. The reduced system level emissions coincided with slightly longer travel times through the system, but lower amounts of time spent idling at traffic lights. Analysis indicated that multi-vehicle control strategies performed significantly better than single vehicle control strategies at reducing system wide emissions, reducing emissions by up to 15% for 100% V2X penetration at 1200 vehicles per hour.

Conclusions from this work suggest that single or multi-vehicle optimization strategies for V2X enabled vehicles when implemented at low penetration rates of V2X technology can actually increase emissions levels at a system perspective. These emissions level increases are primarily driven by traditional vehicles performing maneuvers to go around V2X vehicles that are slowing down to optimally approach traffic lights. The V2X penetration rate which enabled system level emissions reduction varied by traffic level, with lower traffic rates requiring higher adoption rates of V2X technology. Once the threshold V2X penetration was reached, the multi-vehicle control strategy always outperformed the single vehicle control strategy. Potential recommendations could include delaying traffic signal communications, such as signal timings, until minimum levels of V2X technology have been deployed. An alternative recommendation could be to educate traditional vehicle operators to follow V2X enabled vehicles rather than passing them only to get caught at the next light which the V2X vehicle was optimally approaching in order to avoid stopping.

1 Background

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., 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:

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

Connected vehicle technology is an innovative technology which may facilitate the 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, Omar, & Zhuang, 2016). The applications of V2X technology to improve efficiency have spanned from improving the throughput of intersections by reorganizing the vehicles in platoon (Liu & El Kamel, 2016) to startup assist systems at signalized intersections (Wang et al., 2015).

An algorithm to calculate the 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 system-level benefits of the V2X technology and broaden its scope. This research investigated system level benefits of coordinating vehicle responses at signalized intersections to reduce emissions. The impacts of adoption rates of V2X technology and traffic levels on the performance of single and multi-vehicle traffic signal approach algorithms at a system level were evaluated.

2 Objectives

The goal of this research was to generate results which can be used to select the control strategy which generates the least amount of CO_2 emissions as V2X technology receives more acceptance. This research was conducted using results from discrete event traffic simulations. The work was roughly divided into 3 main tasks:

I. A traffic simulation model was created consisting of a simple network of two signalized intersections, two lanes of traffic, and a representative vehicle mix.

II. The logic for multi-vehicle coordination heuristic and single-vehicle optimization strategies was designed and implented within the simulation model framework.

III. Experiments were run in order to evaluate the impact of V2X penetration rate on the proposed multi-vehicle coordination heuristic and single-vehicle optimization in comparison to the baseline results of having no V2X technology.

This research analyzed the benefits of two strategies (multi-vehicle coordination heuristic and single-vehicle optimization) for various levels of V2X penetration to support decision makers in deciding which of the two methods might be suitable as V2X technology and autonomous vehicles receive more acceptance. Impacts on system level emissions, average vehicle travel time, and average vehicle stop time at traffic signals were evaluated.

3 Introduction

This section highlights the simulation experiments designed as well as the logic used for the single and multi-vehicle control strategies. The simulation model and logic described in this section was used to run the experiments described in the Summary of Work Performed Section.

3.1 *Simulation Setup*

The experimental setup used for analysis consisted 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 1). All the vehicles travelled the same distance and encountered exactly two intersections with traffic lights. The network had two lanes and the traffic flowed only from left to right. The two traffic lights were synchronous and follow the cyclic sequence: green phase (40 seconds), yellow phase (5 seconds), red phase (40 seconds) and yellow phase (5 seconds). The traffic lights turn green after the second yellow phase.

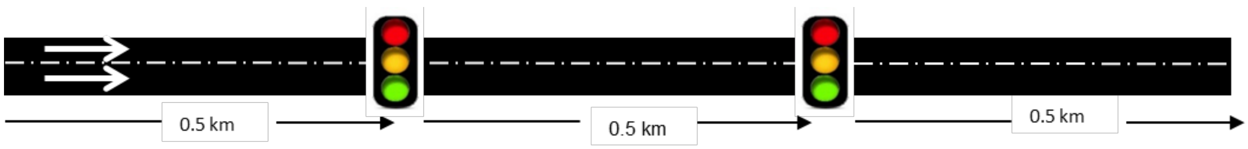

Figure 1: Roadway and signal network

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 algorithm around 500 meters ahead of the traffic light. Tielert 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. Only V2X enabled vehicles are provided traffic light information, and only V2X vehicles respond to the control algorithms.

To capture the effects of emissions by different vehicle types a vehicle mix which represents the vehicle mix provided in a report by National Transportation Statistics (U.S Bureau of Transportation Statistics, 2015) was used (Table 1).

Table 1: Vehicle Mix

Vehicle type	Percentage
Passenger Cars	56%
Van	9%
SUV	12%
Pickup	18%
Trailer	3%
Truck	2%

3.2 Model Assumptions

The model was 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.
- Information related to the state of simulation step like the distance of the vehicle from the signalized intersection, vehicle speed, the phase of the signal, etc. is available and is used to make decisions related to speed and acceleration profiles of the vehicles. Similar information will be available for making decisions when V2X technology is deployed.
- Drivers behave rationally and do not stop unless required to stop at the signalized intersection.
- Drivers can switch lanes as well as pass other vehicles.
- The V2X capable vehicles are autonomous and will be able to respond to provided instructions 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 across all vehicle types.

3.3 Vehicle Control Strategies

Two vehicle control strategies were implemented within the simulation model to control vehicles as they approached traffic lights. The single vehicle control strategy was run for each V2X vehicle individually while the multi-vehicle coordination heuristic controlled multiple vehicles at once in order to reduce emissions at a system level. The following sections describe the control strategies at a high level. For detailed descriptions of the algorithms please see Appendix A.

3.3.1 Single Vehicle Control Strategy

The single vehicle control strategy is sort of an “every vehicle for itself” type strategy. When vehicles are controlled under the single vehicle control strategy they attempt to minimize their waiting at traffic lights. When vehicles enter the system they are informed of the traffic light timings. If a vehicle can proceed through the traffic light without stopping, the vehicle will continue at the speed limit to pass through the light. However, if the vehicle finds that it will not be able to make the green light, the vehicle will adjust its velocity such that it arrives at the light just when the next green phase is about to begin, thus avoiding having to stop at the red light. The single vehicle control strategy did not take into consideration the number of cars stopped at an upcoming light.

3.3.2 Multi-Vehicle Coordination Heuristic

The multi-vehicle coordination heuristic worked under the assumption that temporarily increasing the speed of a few vehicles in order to prevent another vehicle from stopping would be beneficial from a systems perspective. In the multi-vehicle coordination heuristic, optimal speeds through the system were calculated for each vehicle, however this time, if vehicles could make it through the light by increasing their speed by 10%, a coordination request was sent out to all preceding vehicles. The 'coordination request' was implemented as a variable speed limit, where the speed limit of all preceding vehicles was increased by 10% temporarily, until the vehicles made it through the next light. Only V2X vehicles would respond to the variable speed limit messages, so it was expected that the coordination strategy would improve as higher rates of V2X technology existed on the roadways.

4 Literature Review

This section discusses the existing literature related to V2X technology. V2X technology applications are broadly divided into three categories as specified by Herrtwich and Nöcker (2003):

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.

The fist 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 could include warnings about accidents, roadwork or adverse weather conditions.

A message dissemination algorithm was developed by Javad et al. (2013) using the vehicle-to-vehicle communication (V2V) 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) indicate 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.

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 (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) (Behrisch et al., 2011) 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, CO_2 emissions and fuel consumption. At 1000 vehicles per hour (vph), for a congestion which lasted 1800 seconds, the trip time reduced by 58%, CO_2 emissions by 25.4% and the fuel consumption reduced by 17.7%. These improvements diminish as the number of vehicles per hour increase.

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 (VSLS) works on a similar principle as the AID system. The VSLS analyzes the traffic conditions by measuring the average speed of vehicles on the road and then adjusts the speed limit. The VSLS 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 VSLS (C-VSLS) is an extension of the VSLS 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 et al. (Grumert & Tapani, 2012) suggests that the C-VSLS facilitates early adaption of vehicle speeds and thus reduces the acceleration and deceleration rates compared to VSLS. The C-VSLS 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. (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 emissions (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 metrics 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 GLOSA controlled vehicles must be at least 50% to see a significant reduction in fuel consumption. Trip time reduces significantly and quickly for penetrations above 60%. However, (Katsaros et al., 2011) has assumed that there are no vehicles waiting in the traffic light 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 constrains. CVIC has the potential to reduce CO_2 emissions and fuel consumption by 44%. CVIC has been extended by Lee et al. (2013) for a corridor consisting 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. 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 the optimal manuever of one vehicle impedes the optimal manuever of other vehicles.

This research aims to bridge the gap between the second and the third level of applications by comparing the coordination heuristic with the single-vehicle optimization for different penetration level of the V2X technology and identify the best strategy to use as the penetration of the V2X technology grows. This research will analyze the coordination heuristic for a realistic vehicle mix and analyze the CO_2 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 under the cooperative approach. The next section discusses the experimental plan, results and findings.

5 Summary of the Work Performed

This section provides details on the data collected including the experimental runs performed as well as the recorded performance measures. The details of the experiments are followed by a summary of the results and findings.

5.1 Data Collected and Analysis Performed

The experiments look at the effect of three factors on the performance measures of interest: the number of vehicles per hour, the percentage of V2X vehicles, and the strategy used to control V2X enabled vehicles. Table 2 provides the levels used for each of the factors. Ten replicates were used for every combination of these factors which generated 600 simulations. Each simulation was run for 1 hour.

Table 2: Experiment Factors and Levels Analyzed

Factor	Levels
Vehicles per hour	600, 900, 1200
Percentage of V2X vehicles	0,10, 20, 30, 40, 50, 60, 70, 80, 90, 100
Vehicle control strategy	Single-vehicle optimization
	Multi-vehicle coordination heuristic

Three performance measures have been used to compare the different simulation runs: average CO_2 emissions per vehicle, average travel time through the system, and average wait time during red phase. 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 & Kamalanathsharma, 2011) considers only the fuel consumption.

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 auto makers will be required to meet the fleet wide standards instead of emission standards for individual vehicles. The travel time and wait time are important because these are dependent on speed profile assigned to the vehicles and it's desired that these performance metrics do not increase.

T-tests were performed using a 95% confidence interval to determine if results were statistically different from one another across factor levels.

5.2 Results and Discussion

The results will be discussed per performance measure starting first with impacts to emissions, followed by impacts to travel time, and finally impacts to waiting time at traffic signals will be discussed.

5.2.1 Vehicle Control Strategies and Emissions

The simulation experiments provided insight into the effect of different control strategies and V2X technology adoption rate on system level and per vehicle type emissions. Figure 2 illustrates the relationship between V2X adoption rate, vehicle control strategy, and traffic level on average vehicle emissions. For the 900 vehicle per hour runs, T-tests performed indicate that the multi-vehicle control strategy performed significantly better than the single vehicle control strategy at V2X penetration rates higher than 50%. At V2X penetration rates lower than 50% both algorithms provided similar performance.

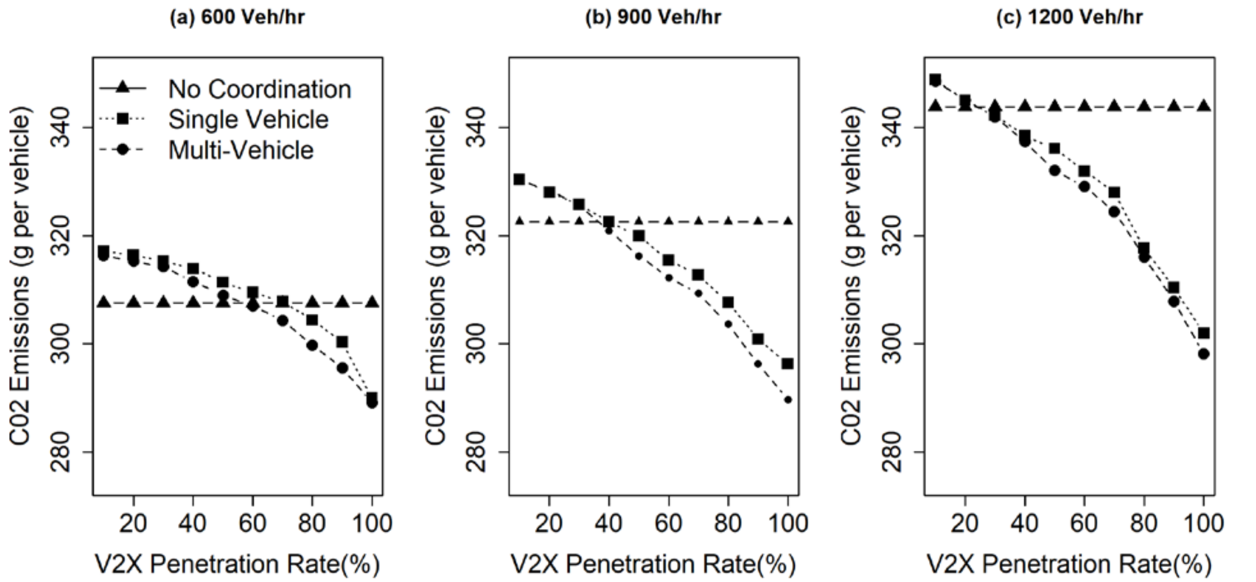

Figure 2: Average CO2 Emissions Per Vehicle

Of note in Figure 2, is that significant V2X penetration is required before simulation runs employing V2X control strategies showed reduced emissions over the baseline. The required V2X penetration rate before a reduction in emissions was observed depended on the traffic flow. At 600 vehicles per hour 50% V2X penetration was required before the coordination heuristic produced lower emissions, while at 1200 vehicles per hour only 30% V2X penetration was required before average emissions decreased below the baseline. The penetration rate at which control strategies reduce overall emissions decreases as traffic levels increase.

A surprising finding was that when V2X penetration rates are low the average emissions per vehicle increases. To understand this finding the average emissions for V2X and non-V2X vehicles were plotted for the 900 vehicle per hour scenario for the multi-vehicle coordination heuristic. The results, as seen in Figure 3, show that while the control strategies lower emissions for the V2X vehicles, the emissions for non-V2X vehicles increase. Further analysis revealed that the primary source of increased emissions for the non-V2X vehicles was their passing activity. While V2X vehicles were instructed to approach traffic lights at an optimal speed in order to avoid stopping, non-V2X vehicles would catch up to these vehicles, slow down, then accelerate back up to the speed limit as they pass them. These extra instances of acceleration increased the average emissions of non-V2X vehicles in the system.

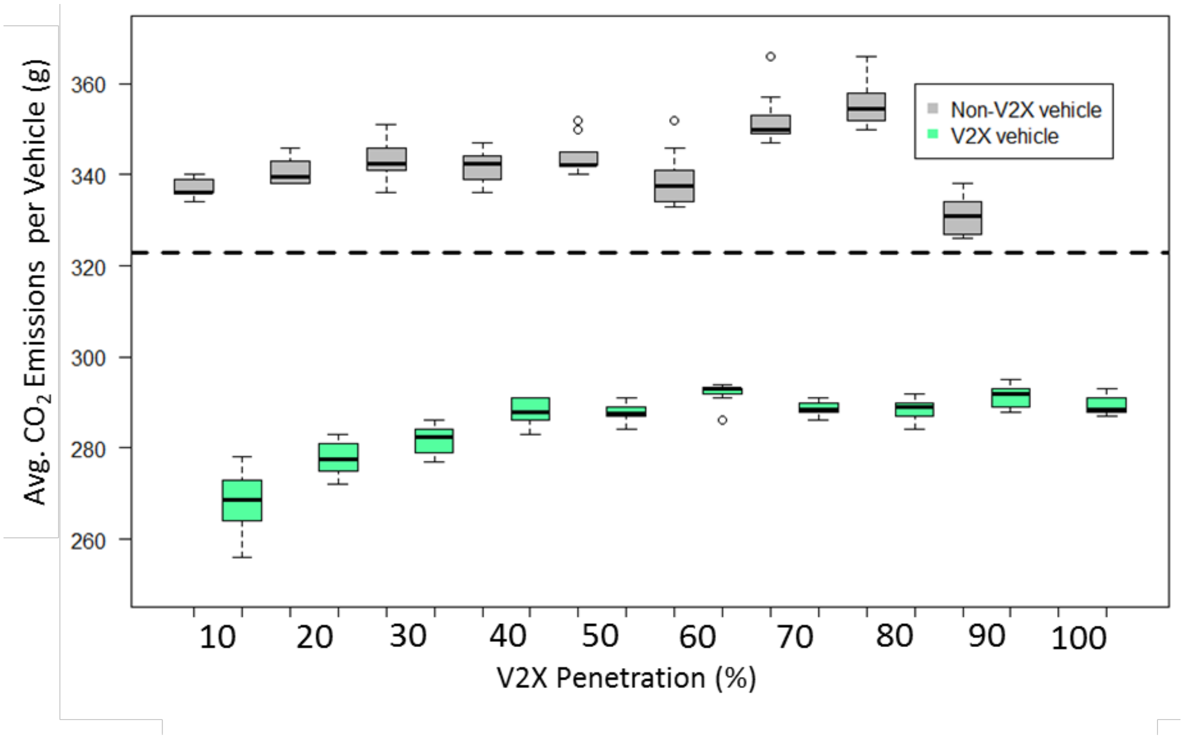

Figure 3: Emissions Per Vehicle Type (V2X Controlled vs Uncontrolled)

5.2.2 Travel Time Per Vehicle

The effects of control strategies on emissions cannot be considered without also evaluating the impact on other measures of quality related to driving. One such quality measure is travel time through the system. In general, drivers want to reach a destination as quickly as possible, so impacts to drive time are an important factor to consider. Results of the experiments with respect to travel time can be seen in Figure 4. Figure 4 shows the average travel time per vehicle for the first 1000 meters. As the rate of V2X penetration increased, the average travel time through the system also increased when control strategies were employed. This was an expected result because the V2X controlled vehicles accelerate more slowly in order to conserve fuel, a behavior which naturally increases trip time. The multi-vehicle coordination strategy produced lower average trip times than the single vehicle control strategy at all traffic densities and V2X penetration rates. Interestingly, as the vehicle traffic level increased, the percentage increase in overall travel time through the system decreased. For example, for the 600 vehicles per hour case at 100% V2X penetration using the coordination strategy, the average travel time increased from

98 seconds to 112 seconds, or 14 percent. However, for the 1200 vehicle per hour system, travel time increased from 118 seconds to 124 seconds, an increase of only 6%.

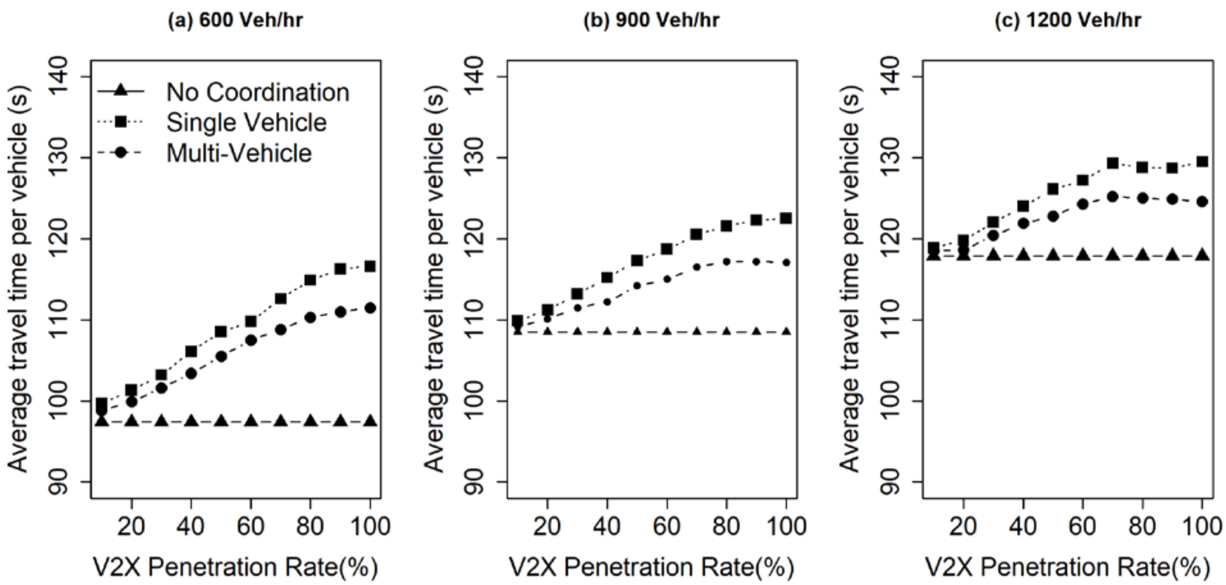

Figure 4: Average Vehicle Travel Time Through System

5.2.3 Average Wait Time

A second quality measure that affects driver satisfaction is the amount of time spent waiting at traffic signals. For this performance measure, the amount of time a vehicle spent moving slower than 2.5 mph was captured and an average time spent waiting was calculated for all vehicles in a simulation run. Results of the wait time analysis can be seen in Figure 5, and indicate that as vehicle control strategies are introduced, the average wait time for vehicles immediately decreases. As V2X penetration rate increases average wait time further decreases. The single and multi-vehicle control strategies performed similarly with regards to wait time, with the single vehicle control strategy providing slight benefits over the multi-vehicle control strategy in some cases.

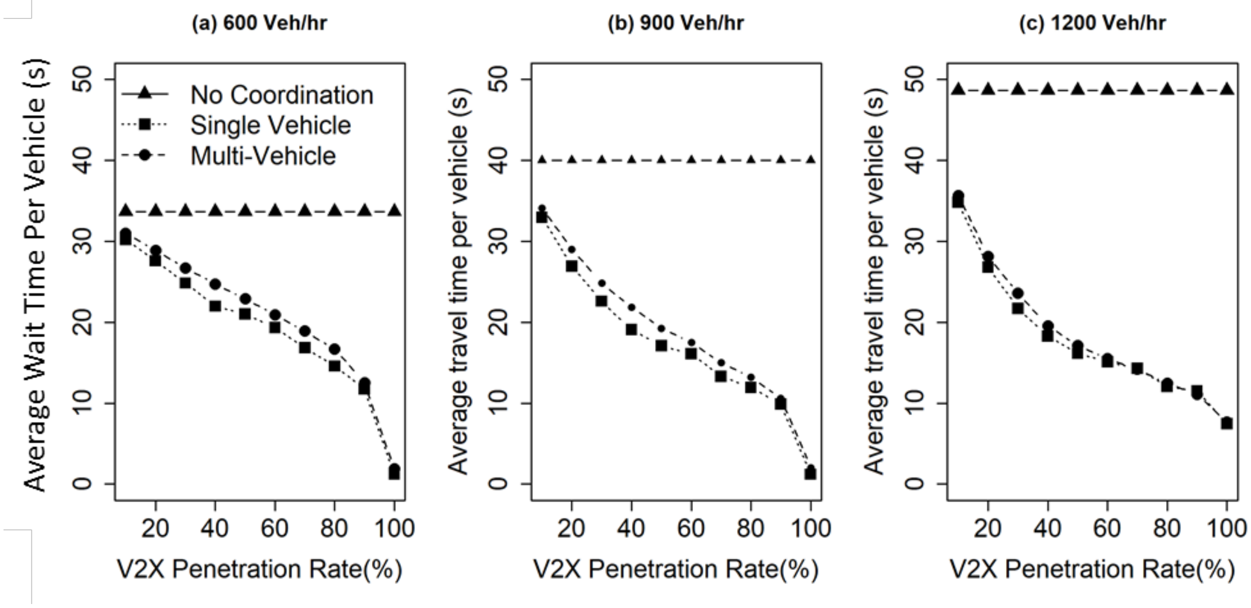

Figure 5: Average Wait Time Per Vehicle

6 Conclusions and Recommendations

This research proposes a coordination heuristic to reduce CO_2 emissions for vehicles approaching signalized intersections. The coordination heuristic uses variable speed limits to adjust the speed limit at traffic signals and allow more V2X vehicles to get through. The results indicate system level benefits like lower emissions and travel time for coordination heuristic over single-vehicle optimization. The CO_2 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 emissions for coordination heuristic is less than baseline driver behavior decreases as the number of vehicles per hour increases. The results also suggest that once the threshold is reached the coordination heuristic always generates fewer CO_2 emissions compared to single-vehicle optimization. At 100% V2X with 900 vehicles per hour, the coordination heuristic generates 10% less emissions compared to baseline driver behavior, while the single-vehicle optimization reduced emissions by only 7%. 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. However the increase in travel time is somewhat mitigated by the decrease in wait time at traffic lights. 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 smooth traffic flow is achieved.

The coordination heuristic generates less CO_2 emissions and has lower travel time compared to single-vehicle optimization strategy, and should be therefore preferred over single-vehicle optimization strategy to realize the true potential of V2X technology. However, neither the single vehicle or coordination strategy should be pursued below the threshold penetration rates, otherwise average system emissions will increase.

Certain aspects of the coordination heuristic can be further analyzed to make it more beneficial. In the current implementation of the coordination heuristic a V2X vehicle requests coordination from preceding 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 CO_2 emissions at a system level. It might be beneficial to limit the number of vehicles facilitating a coordination request. The extent to which 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 coordination heuristic for more complex networks. Lastly with more acceptance of electric vehicles which have different fuel consumption profiles compared to gasoline vehicles it might be useful to analyze the system level benefits of the coordination heuristic with inclusion of electric vehicles in the vehicle mix.

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Appendix A : Control Strategy Details

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 & 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 the 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 presented in Rakha and Kamalanathsharma (2011), most notably:

I. The single-vehicle optimization model we created uses HBEFA (Rexeis, Hausberger, Kühlwein, & Luz, 2013) for estimating emissions whereas the eco-drive model uses VT-Micro model (Ahn, Rakha, Trani, & Van Aerde, 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 a desired arrival speed at the intersection.

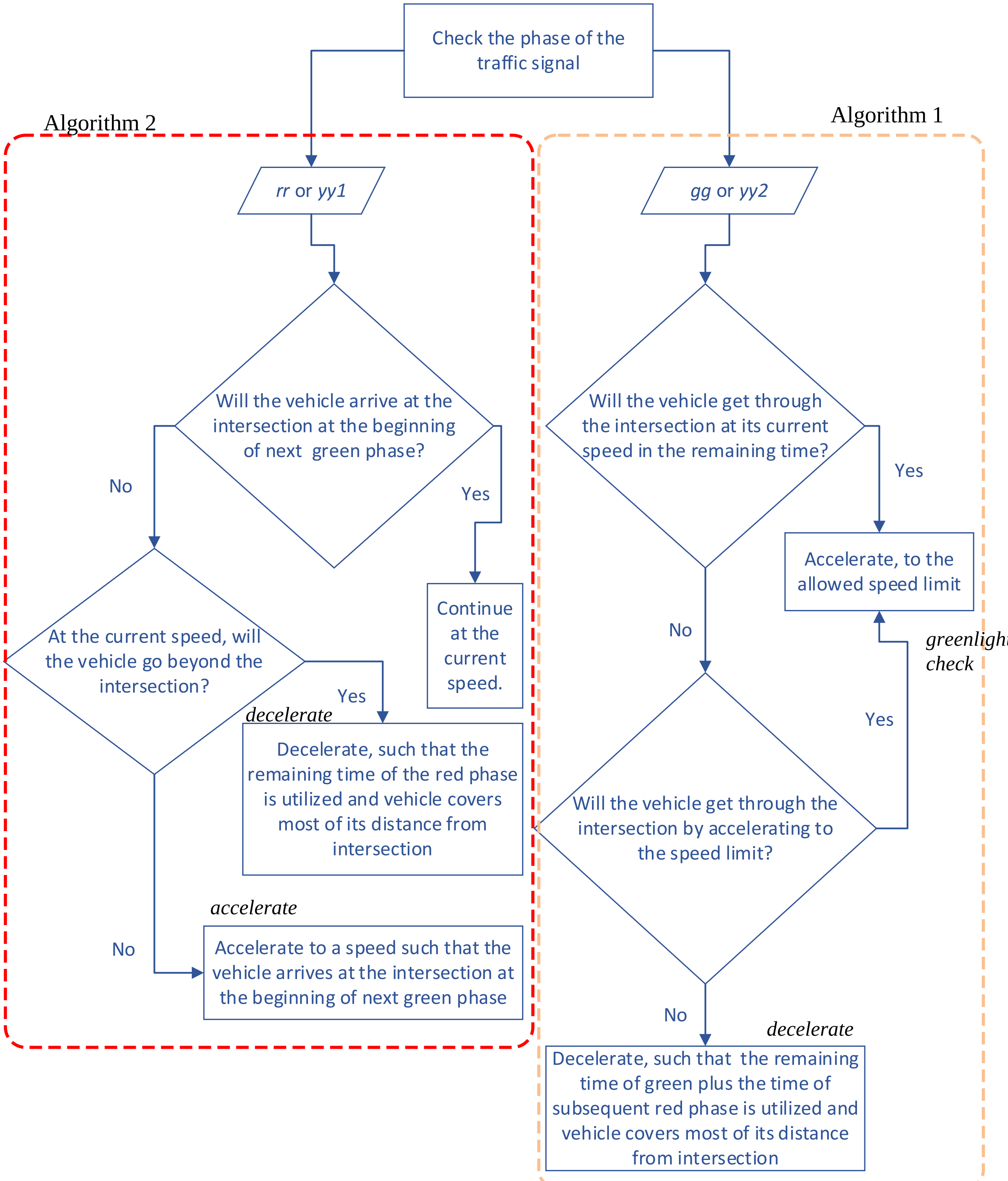

Figure 6 – Algorithm: Single-vehicle optimization

Information regarding the vehicles' current state is extracted from every V2X vehicle which enters the simulation environment and has a traffic signal ahead. This information serves as the input parameters for the algorithm and includes a vehicle's current speed *(u)* and its distance from the nearest intersection *(d)*. The algorithm also uses information related to the current state of the simulation as an input parameter and this includes the current phase of the traffic signal *(gg (green), yy1(yellow after green), rr (red), yy2(yellow after red))* and the time remaining for the current phase to change *(*Δt*)*.

List of algorithm inputs	
u	Vehicle's current speed
d	Distance to nearest intersection
gg, yy1, rr, yy2	Current phase of traffic signal
Δt	Time remaining for current phase to change
$v_{speed\ adjusted}$	The maximum allowed speed during coordination
List of variables used in algorithm	
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

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.

Algorithm 1

IF $u(\Delta t) >= d$ THEN (1)

    Accelerate to the speed limit

ELSE IF *greenlight check* returns TRUE THEN

    Accelerate to the speed limit

ELSE *decelerate*

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

End of Algorithm 1

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

Module *greenlight check*

Given

$v_{speed\ limit}$ = speed limit of the roadway

a = allowed acceleration level

Evaluate

$t_a = (v_{speed\ limit} - u)/a$ (2)

$t_{cons} = \Delta t - t_a$ (3)

$S_a = (u*t_a) + (0.5*a*t_a^2)$ (4)

$S_{cons} = v*t_{cons}$ (5)

IF $(S_a + S_{cons}) >= d$ THEN (6)

Return TRUE

ELSE

Return FALSE

End of module *greenlight check*

The $v_{speed\ limit}$ 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.

If the equation (6) evaluates to false, the vehicle is instructed to decelerate and a module called *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 t_a is maximized while satisfying certain constraints.

Module *decelerate*

Objective function – Maximize: t_a

subject to

$v, t_a, t_{cons}, S_a, S_{cons} >= 0$ (7 to 11)

$v = u + (a*t_a)$ (12)

$S_a = (u*t_a) + (0.5*a*t_a^2)$ (13)

$S_{cons} = v*t_{cons}$ (14)

$\Delta t = t_a + t_{cons}$ (15)

$d <= S_a + S_{cons}$ (16)

End of module *decelerate*

For green phase, Δt 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.

Algorithm 2

IF $u(\Delta t) == d$ THEN (17)

  Continue at current speed

ELSE IF $u(\Delta t) < d$ THEN (18)

  accelerate

ELSE *decelerate*

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

End of Algorithm 2

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 Δt 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 an iteration based algorithm.

Module *accelerate*

Count = 1

$v = u + a*0.1*Count$ (19)

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

$S_a = (u*0.1*Count) + (0.5*a*(0.1*Count)^2)$ (21)

$S_{cons} = v*t_{cons}$ (22)

IF $(S_a + S_{cons}) < d$ THEN (23)

Count ++ go to equation 19

ELSE

EXIT and allow vehicle to accelerate to *v*

End of module *accelerate*

Multi-Vehicle 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) 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 to 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.

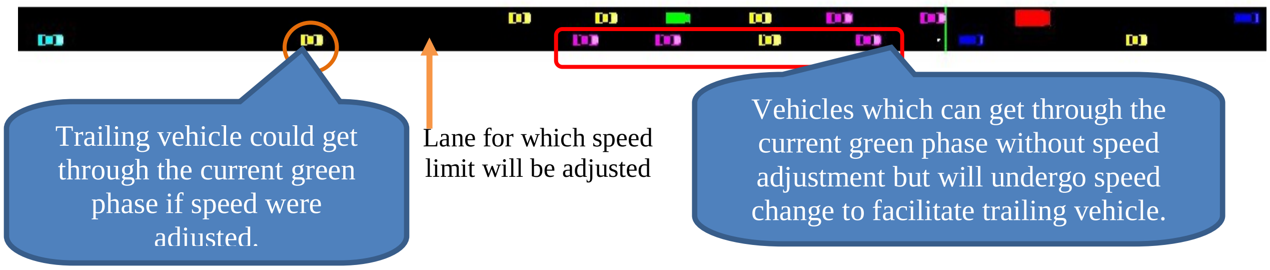

Figure 7 – Representation of coordination heuristic

Algorithm *coordination*

IF $u(\Delta t) >= d$ THEN (24)

Accelerate to the speed limit

ELSE IF *greenlight check* returns TRUE THEN

Accelerate to the speed limit

ELSE IF *coordination speed* returns TRUE and V_{coord} THEN

Accelerate to V_{coord}

ELSE *decelerate*

End of algorithm *coordination*

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 the coordination heuristic from the single-vehicle optimization. Equations (25 to 30) describe the module *coordination speed*, used to determine if the vehicle could get through the intersection at an adjusted speed limit and the speed V_{coord} at which the vehicle needs to travel.

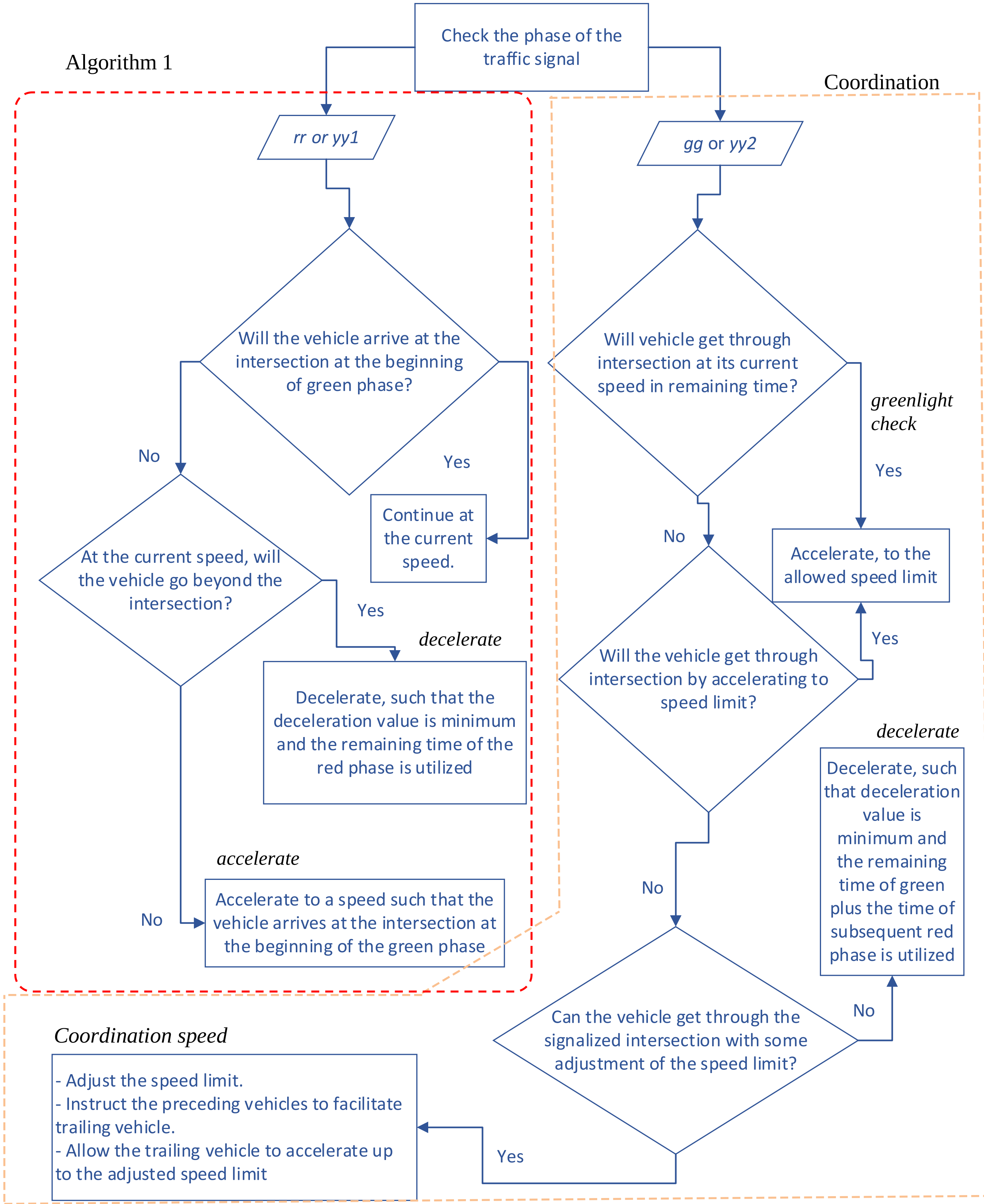

Figure 8 – Algorithm: Coordination heuristic

In the pseudo code (equations 25 to 30) an iterative method is used to identify the coordination speed. If a coordination speed, V_{coord}, is found that is below the maximum adjusted speed limit of $v_{speed\_adjusted}$ then the algorithm returns TRUE and v_{coord}, otherwise the algorithm returns FALSE. 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 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.

Module *coordination speed*

Count = 1

WHILE $V_{coord} < v_{speed\_adjusted}$ (25)

  $V_{coord} = u + a*0.1*Count$ (26)

  $t_{cons} = \Delta t - 0.1*Count$ (27)

  $S_a = (u*0.1*Count) + (0.5*a*(0.1*Count)^2)$ (28)

  $S_{cons} = V_{coord} * t_{cons}$ (29)

  IF $(S_a + S_{cons}) < d$ THEN (30)

    Count ++ go to equation 26

  ELSE

    Return TRUE and V_{coord}

Return FALSE

End of module *coordination speed*

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