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Student's name: Kshitij Rajvanshi

This work and its defense approved by:

Committee chair: Dharma Agrawal, D.Sc.

Committee member: Rui Dai, Ph.D.

Committee member: Chia Han, Ph.D.
Multi-Modal Smart Traffic Signal Control Using Connected Vehicles

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By
Kshitij Rajvanshi,

Bachelor of Technology in Computer Science and Engineering,
Amity University, India, 2011

Thesis Committee:
Dr. Dharma Agrawal, Advisor
Dr. Chia Han
Dr. Rui Dai
Abstract

As the technology is advancing day by day, the intelligent transportation industry is also experiencing a advancement in vehicle communication technology. The future for the automotive industry are the self-driving vehicles. Next-generation cars and other automobiles are getting equipped with unique electronics sensors like LIDAR, ultrasonic sensors, radar sensors. These sensors monitor different aspects of vehicle movements such as vehicle’s speed, position, longitudinal and lateral acceleration. The vehicle communication technology exists, but vehicles rarely communicate their information with the road side infrastructures. The connected vehicle initiative and the deployment of wireless communication techniques will help in improving vehicle safety and also reduce traffic congestion. The traffic signal control timing plans are designed in such way that they can minimize the vehicle travel delay based on conditions such as historical traffic volumes. In-pavement induction loop detectors and video detectors make small adjustments to signal timings, but they are unreliable and limited in terms of range. With the connected vehicle initiative, vehicles can communicate with the roadside infrastructure such as traffic signal control within 300 meters of an intersection through communication techniques like the Dedicated Short Range Communication (DSRC).

A unique algorithm is proposed which uses a concept of vehicle platooning as the vehicle control model. Vehicle platooning helps in increasing the throughput of a
particular road. The vehicle control is based on Cooperative Adaptive Cruise Control (CACC) mechanism. The proposed algorithm also uses a global nature inspired optimization algorithm known as Multi-objective Bat Algorithm. This algorithm takes into consideration different input such as the queue length of the intersection roads and actual flow rate and give out the optimized value of the green signal time for the next phase signal to be implemented. The effective performance of the intersection signal control model is measured on the basis of mobility and environmental factors through simulation studies. The suggested traffic signal control model can reduce average waiting time by a maximum of 30.7%, reduce fuel consumption by a maximum value of 11% and CO₂ emissions by a maximum value of 9% based on the three simulation scenarios. To perform better than current systems, the minimum required for the connected vehicle penetration rate is 25%.
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Chapter 1: Introduction

1.1 Research Motivation

Urban areas and cities of all sizes are experiencing increased traffic volumes, congestion and high-levels of greenhouse emissions. The Texas A&M Transportation Institute and INRIX jointly published the 2015 Urban Mobility Scorecard, which indicated that congestion caused citizens in America, about 7 billion more hours in travel time and about 3 billion of more fuel purchase (in gallons), for a value of one hundred sixty billion dollars (in terms of congestion) [1]. The Federal Highway Administration (FHWA) predicts that half of the traffic congestion is due to poor management of traffic signal control timings, work zones and traffic incidents [2].

Many Advanced Traffic Management Systems (ATMS) have been proposed and implemented, but most of them are designed to be as offline based systems [3, 4]. Some of the proposed methods use historical data such as hourly traffic volume or ramp metering for signal optimization. These historical data are sometimes supplemented with point detection techniques such as induction loop detectors and video detectors. The main disadvantage of point detection is that it cannot cover the large area of roadway and hence the data is aggregated over time. Even the cost of installation and maintenance for these detectors are quite high.
1.1.1 Traffic Signal Control Systems

Traffic systems basically coordinate and control individual signal controls to fulfill grid based traffic operations. Normally, these kind of systems have a group of intersection signal controls, a communication network, and a concept based on central network of computers, to handle the system. In the United States, the traffic controllers are standardized by the NEMA. They have defined standards for connectors, operating limits, and intervals. The traffic signal timing plan is designed to act according to calculated peak duration with adjustments which are based on the vehicle arrival rates. These adjustments are measured by detectors usually placed at stop bars and sometimes upstream.

Traffic Signal Timing Parameters

This section defines the parameters which are used primarily during the functioning of traffic signal systems.

- **Cycle Length**: It is equal to the amount of time required to finish a full sequence of signal intervals (phases).

- **Phase**: It is defined as the part of the full phase signal cycle assigned to any combination of valid traffic movements. This combination receives the right of way during an interval.

- **Interval**: It is defined as period where the signal indications such as vehicles or pedestrian remain the same.

- **Split**: It is defined as some small value of the total cycle length allocated to phases in the signal timing plan.
Types of Intersection environments

- **Isolated**: It is a type of signalized intersection that is generally remote from other intersections and does not have any benefit from the signal coordination.

- **Arterial**: It is a type of signalized intersection that is one of the many in a series of adjacent intersections, benefiting from signal coordination.

- **Grid**: It is a type of intersection that is one of the many in a series of adjacent intersection in a grid of short blocks, found in high density urban neighborhoods and business districts.

Types of Traffic Signal Control operations

According to different variations in the design of these systems, the traffic signal are classified according to operational type as:

- Fixed-timed (or pre timed),
- Actuated, and
- Adaptive.

In a fixed-timed traffic control system, the phases are implemented for a fixed amount of duration every cycle. The number of vehicles and the pedestrian count at a particular intersection does not affect the duration of the pre-timed signal system. These phase duration values are fixed based on the historical data obtained from the traffic intersection.

The actuated systems employs vehicle and pedestrian detectors to activate a particular phase such as changing the signal from red to green. The duration of green
time is based on the count of vehicles by the induction-loop detectors. Actuated traffic control system can be classified into fully actuated and semi actuated systems. Fully actuated system is that system where are all the lanes of the intersection use detectors. Semi-actuated systems uses the concept of both pre-timed and detectors for calculation of phases. In adaptive intersection traffic control systems, the phase signal plans changes based on the actual traffic demand. This type of system requires vehicle detection and can dynamically adjust the cycle, offset and splits on the basis of current demand.

Adaptive traffic systems are the future of intelligent transpiration systems. The fact remains is that traditional point detectors have several disadvantages. For example, the loop detectors, which are based on electromagnetic induction, require wires be installed into slots made in the in-road pavement. For maintenance purposes, the lanes should be closed. Additionally, the slots made in the road-side pavement allow the moisture to get inside the pavements, thus increasing the chance of faster deterioration. Video detection techniques which are less expensive as compared to loop detectors, show many false and missed detections [5, 6, 7].

Wireless communication may help in improving the operation of traffic signal control in the near future. Traffic signals will get information from the real-time environment scenarios and by analyzing that data, can act accordingly. Instead of using point detection systems such as loop-detectors, that sense presence of vehicles at that point locations, data from the in-vehicle sensors can be transmitted to the signal controller wirelessly. The data can include information related to arrival rate, speed, position and queue length of a particular lane or the whole intersection.
Previous attempts of improving the performance of the traffic signal control have been very complex. This is one of the main factors that adaptive control methodology is less adopted. This brings the need of a simple, implementable traffic control system which will incorporate the connected vehicle technology without interfering with vehicle’s privacy.

1.1.2 Introduction to Connected Vehicles

The concept of connected vehicle is defined as a vehicle that has a wireless local area network and also has an access to the Internet. This concept allows vehicles to exchange information with devices present inside and outside of the vehicles. Connected vehicle technology is being research and developed to enable safe, networked wireless communication among different cars (Vehicle-to-Vehicle communication), road infrastructure (Vehicle-to-infrastructure communication). Connected vehicle research is promoted and sponsored by the Department of Transpiration (DoT) in United States.

Connected Vehicle Deployments

The following sub-section defines the applications where connected vehicle technology can be deployed.

- **Vehicle to Vehicle communication (V2V):** In this type of communication protocol, the connected vehicle technology can be deployed in features like crash avoidance and electronic brakes.

- **Vehicle to Infrastructure communication (V2I):** In this type of communication protocol, the connected vehicle technology can be incorporated to send
vehicle information like speed, acceleration, GPS position and heading to the infrastructure unit.

- **Infrastructure to Vehicle communication (I2V):** In this type of communication protocol, the connected vehicle technology can be deployed with features like broadcasting traffic signal timing details and sending safety alerts regarding the work zone and the weather.

**Connected Vehicle Roll-out**

U.S. National Highway Traffic Safety Administration (NHTSA) defines vehicle automation as those vehicle operations where the driver does not provide a direct input to control the vehicle functions such as steering, vehicle acceleration and braking. The operations are designed in a way such that, it is not expected from the driver to keep an eye on the road while driving in self-driving mode. Figure 1.1 gives a basic description of the five levels of the vehicle automation defined by NHSTA [8].

**Zero-Automation (Level 0):** At that level, complete vehicle control is given to the driver.

**Driver assisted function Automation (Level 1):** At that level, the automation of one or more specific vehicle controls happen such as automatic braking system to enable driver regain the control.

**Partial Function Automation (Level 2):** At that level, minimum two of the primary vehicle control functionality work together to allow the driver relieve those function’s control. Example of such functions is adaptive vehicle cruise control with feature such as lane centering.
Conditional Self-Driving Vehicle Automation (Level 3): At that level, a driver gives away full control of the main critical functions during some conditions, and the vehicle continuously monitors changes and reverts vehicle control to the driver occasionally, allowing comfortable transition time.

Fully Self-Driving Vehicle Automation (Level 4): At that level, the vehicle performs all critical vehicle driving functionality and continuously monitors the situations. Here, the driver is not expected to have any control of the automobile at all.
Vehicles with automation level 3 and above must also include connected vehicle technologies. Currently only features up-to level 2 of the connected vehicle roll-out is available to the public. For wireless communication among vehicles and infrastructure, Dedicated Short Range Communication protocol (DSRC) has been adopted [9].

1.1.3 Penetration Rates

Researchers have proposed new mobility based applications that leverage wireless communication techniques that could improve the traffic congestion and minimize fuel consumption. Several algorithms that have been proposed that utilize the location and speed of the vehicles instead of estimating vehicle movements from historical data and loop detectors. In the context of connected vehicles, penetration rates is defined as ”how many vehicles will be equipped with connected vehicle technology during a particular instant of time at any lane.” In the coming five years, only half of the total vehicle count will have the connected vehicle capabilities.

Vehicles that have connected vehicle technology are known as equipped vehicles and the vehicle that don’t have that technology are called unequipped vehicles. The equipped vehicle’s behavior often comes as a reaction with presently available unequipped vehicles and a location estimate of unequipped vehicles can be predicted with the data of these equipped vehicles.
1.2 Purpose and Scope of the Research

The purpose behind this research is to investigate possible adaptive traffic control solutions that are based on connected vehicle initiative with the possibility of implementing a platoon based vehicle control model. Specific objectives of this research are as follows:

- Design, implement and evaluate an adaptive traffic signal control algorithm which could work based on the principle of connected vehicles.
- Ensure the algorithm works on current data obtained from the connected vehicles and adhere to the traffic signal control standards.
- Ensure that the proposed algorithm minimizes the re-identification and tracking of vehicles during the platoon formation.
- Identify potential additional work that can be implemented to further improve the proposed algorithm.

The upcoming chapters are presented below:

Chapter 2 outlines a brief summary of the literature which has been proposed in the area of traffic signal management. Some of the topics which have been discussed in this chapter include early adaptive traffic signal control systems, vehicle communication protocols, and vehicle control models.

Chapter 3 outlines and describes the proposed traffic signal control algorithms based on connected vehicles. This chapter describes the various models required for the proper functioning of the proposed algorithm.
Chapter 4 describes the simulation scenarios which have been used for the evaluating the proposed algorithm. This chapter also lists out the tools and simulation parameters used for this research. It evaluates the performance of the proposed algorithm with existing systems and also discusses the results in the context of various performance measures.

Chapter 5 summarizes the key findings of the proposed research effort and discusses about the future work which can be carried out in this area of research.
Chapter 2: Literature Review

The literature review has been conducted to summarize previous research work carried on traffic signal control systems and connected vehicles. This chapter is categorized into following categories:

1. Traffic signal control,
2. Connected Vehicles, and

2.1 Traffic Intersection signal control

2.1.1 Brief History

The first traffic signal ever to be installed was in 1836 in London, England. The standardization of the traffic signals began in 1920 when National Bureau of Standards were asked to design a uniform code for traffic signal rules and signs. A common phase numbering system was also codified by the National Electrical Manufacturers Association (NEMA), with 2 and 6 being designated as main through lane movements.

Initially, the traffic signal operation were based on fixed time control where each phase has a green for fixed length of time. The pre-timed control strategies are
cyclic, in that the phases are serviced in a certain order. The introduction of loop and video detectors allowed traffic control systems to be actuated, where adjustments to the phases can be somewhat made in real-time. The adjustments included skipping phases, which do not have any waiting vehicles and another adjustment where green split value is shortened depending on whether there are approaching vehicles are not. Signals that allow progression of vehicles in the form of platoons are said to be coordinated.

2.1.2 Adaptive Control Strategies

In-order to make the traffic signal more adaptive to real world situations, several attempts have been made which rely on video and inductive loops. Adaptive control strategies are categorized into two groups:

- Cyclic systems,
- Acyclic systems.

Cyclic Adaptive Control Systems

Earlier adaptive intersection signal control models used cyclic signal timing control plans, which had adjustments modeled on real-time varying traffic volumes. One of the examples is the SCATS, implemented in Australia [10]. The system measures traffic volume from detectors which are placed at the stop-line. The system then selects the best cycle length, phase and offset from pre-defined and calculated timing plans.

Another strategy is SCOOT (Split, Cycle and Offset optimization technique) [11]. It uses upstream based detectors to predict and analyze vehicle arrivals based on
the platoon dispersion model. The algorithm optimizes signal timing plan using an objective function consisting of queue length, delay and stop frequency.

**Acyclic Adaptive Control Systems**

**Optimized Policies for Adaptive Control:** This adaptive control technology uses different control strategies depending on whether considered intersection is congested or not [12]. When traffic is not congested, the signal timings follow the pre-timed signal timing plans or the cycle lengths are calculated dynamically. The timings are based on detected data and predicted data. When the traffic is congested, the model optimizes the timing plan based on the saturation flow which is pre-calculated. The number of phase switches is limited to three.

**InSync:** This signal control system is one of the current systems deployed on a number of corridors in USA [13]. This system uses cameras having high resolutions and an image processing software to optimize the traffic network at both the corridor-level and the local-level. The cycle lengths are calculated by the amount of time required to clear the side street traffic queues, and the intersections provide feedback data by sending the information regarding queue clearance for the current cycle.

InSync, when tested using a software-in-the-loop simulation on a calibrated model of an arterial road, had improvements of 2-20% depending on the test scenarios. As the system integrates well with the control hardware of different manufacturers, it performs better on corridors where signal control systems had not been previously co-ordinated.
2.2 Connected Vehicles

Nowadays, most aspects of a vehicle have been computerized in some way. Vehicles are now able to collect more detailed information about their surroundings as compared to what they used to do in the past decades or so. A recent initiative has come up to allow wireless communication to be feasible between vehicles and the vehicular infrastructure. This initiative has been coined the term as **connected vehicles**.

All the major automotive companies and technology companies have stated corporate goals to invest in the connected vehicle technology. The connected vehicle technology has a variety of benefits:

- Connected vehicles can help in reducing maintenance costs and reducing the requirement of building new infrastructure.

- Connected vehicles can help in crash-free driving and it could improve the overall safety of the vehicles.

- This initiative can help reduce uncertainty in the vehicle travel time and can provide a better predictive assessment of average travel time using different routes.

- Improved energy efficiency in terms of efficient driving, more fuel-efficient vehicles can be achieved.

The connected vehicle technology is an initiative to enable safe, interoperable communication between vehicles (V2V), the road-side infrastructure (V2I) and personal...
devices (V2X). The connected vehicle technologies use advanced wireless communication protocols, on-board processing unit, vehicle sensors, Internet and GPS navigation systems to provide a network based environment. So, instead of depending upon the point detectors such as loop and video detectors, the signal control systems would be getting the data from sensors inside the vehicle through wireless communication protocols. Data such as vehicle speed, position, acceleration and deceleration rate, queue length will be accessible to the signal controller.

The information exchange can occur using various communication protocols:

- Dedicated short range communication protocol (DSRC),
- Cellular service,
- Wi-Fi,
- 4G/5G technology, and
- Bluetooth.

The United States department of transportation (US-DOT) has selected DSRC as a major research priority and the best suitable medium for V2V and V2I communications. DSRC is basically defined as medium range or a two-way wireless communication protocol, which has very low latency of less than one second and it allows high data transmission in critical safety applications. DSRC is the only wireless alliterative to Wi-Fi which has the following the specific properties:

- It has a very low latency rate. It can support very high data transmission at a latency less than one second.
- It operates in (75 MHz of spectrum) licensed frequency band.
• DSRC has been allocated for vehicular safety applications.

• It provides privacy and safety message authentication.

• It supports both V2V and V2I communication standards.

• DSRC can work in situations where high reliability is required. It also works in vehicles with high speed conditions as well.

• DSRC has fast network acquisition capability.

• Delivers high performance during extreme weather conditions.

The types of data and communication protocols used by connected vehicles is outlined by SAE J2735 DSRC message set dictionary [9, 14]. It defines specific information that may be communicated between vehicles and the road-side infrastructure termed as data elements, which are further grouped as data fields and then finally into message sets. The message used is the Basic Safety Message (BSM). It transmits at a 10Hz frequency and it is used for safety applications. The data fields that are transmitted include:

**MsgCount:** Specific ID of the message,

**TemporaryID:** ID that is assigned to the vehicle, which is periodically change to protect the vehicle privacy,

**DSecond:** Timestamp,

**PositionLocal3D:** vehicle position parameters such as latitude, longitude, elevation and accuracy estimate,

**Motion:** It gives the vehicle’s transmission status such as speed, heading, steering wheel angle,
Control: Gives the status of vehicle control components, and

VehicleBasic: Provides the vehicle’s type and size.

The DSRC latency is observed at between 10 to 20 milliseconds, and has accepted communication range of 300 meters. When considering safety applications, each vehicle sends a basic safety message that transmits above mentioned data fields.

The potential DSRC applications based on public and vehicle safety and traffic management are mentioned below:

- Blind spot warnings,
- Collision warnings,
- Electronic parking and toll payment systems,
- Emergency vehicle movement priority
- Safety inspection of the vehicle
- Travel and traffic condition monitoring, and
- Co-operative Adaptive Cruise Control (CACC).

2.3 Traffic Signal Control Using V2I Communication

Traffic signal management is one of the areas which will be benefited with wireless V2I and V2V communication and connected vehicle technologies. Vehicle can send a basic safety message through DSRC and the traffic controller can determine a vehicle’s location and speed within a specified range. One of the main aspect of connected vehicle strategy is that it allows direct measurement if queue length, vehicle speed
and platoon size. This section discusses key concepts of traffic signal control using V2I.

### 2.3.1 Over-saturated Conditions Based Algorithms

One of the first algorithms that was designed, worked on the principle of connected vehicles assisting in over-saturated situations by predicting queue length and blockages [15]. Whenever a blockage is detected by the controller at downstream intersection, then the green phase of the upstream intersection is modified and then the cross street traffic is allowed to progress. The over-saturated condition algorithm is only useful in special circumstances where there is a par of two-phase intersections.

### 2.3.2 Gap-out Algorithms

When an actuated traffic signal control is implemented, a minimum green phase time is provided to a traffic lane. If no vehicles are present during the gap time, the green phase is terminated. Usually, the gap-out time is of three seconds. The flaw in the actuated system is that the signal shortens the green-time only when there are no vehicles detected during the gap-out time. An algorithm was developed by Agbolosu-Amison and Park [16], which used connected vehicle technology to detect the vehicle arrival time over that particular gap-out time. The algorithm can terminate the signal phase at the starting of gap-out time instead of doing at the end. This resulted in saving several seconds per signal cycle.

### 2.3.3 Cumulative Travel Responsive Algorithms

Cumulative Travel Time Responsive (CTR) algorithm was proposed by Lee [17]. This algorithm is based on connected vehicle technology and it works by determining
the time amount that a vehicle has taken to travel towards the intersections within the DSRC range of 300 meters. The travel time consists of both parameters, the time when vehicle is moving, and also when it is stopped. The travel times for each movement combination is summed up and the phase combination with highest travel time is chosen as the next phase to be implemented. The algorithm uses a Kalman filtering technique to estimate actual travel time when the connected vehicle penetration is less than 100%. This technique when tested on an isolated intersection performed better than the actuated traffic signal control and showed improvement of 34% in travel time. The disadvantage of this algorithm is poor performance on corridors with low vehicle arrival volume side roads.

2.3.4 Rolling Horizon based Algorithms

Priemer et al. [18] proposed an algorithm which is based on rolling horizon and V2I wireless communication technique. The algorithm’s main idea is to reduce the queue length value by optimizing the phase signals over a 20-second rolling horizon and in a five-second interval. The algorithm also employs dynamic programming. The algorithm can predict queue lengths at low penetrations by calculating the distance from the last stopped equipped vehicle to the stop bar. The algorithm performs much better than the pre-timed timing plan at 100% penetration rate. The algorithm reduces delay by 23% and improves the vehicle speed by 5%. When the penetration rate is above 33%, then the algorithm performs better than pre-timed timing plan.

An intersection signal control system algorithm proposed by the University of Arizona, PAMSCOD, determines optimized signal timing plan over short horizon using
mixed-integer linear programming [19]. The algorithm uses information from the vehicle communication protocols and then mixed-integer linear programming calculates the phasing and signal timing for four cycles in the future at a rolling horizon of 30 seconds. The algorithm performs better in terms of vehicle and bus delay at saturation rates greater than 0.8, but lags in the performance at saturation rate lower than the value of 0.6.

Liu and Di [20] at the University of Minnesota developed a travel-time based traffic control algorithm. The algorithm uses connected vehicle information at partial penetration rates to calculate the densities of the vehicle. A Markov model is combined with a Kalman filter to integrate fixed-point and trajectory motion into the model. The algorithm’s simulation results showed that only 10% penetration rate for vehicles is needed in-order to estimate the density accurately.

2.3.5 Swarm based traffic signal control algorithms

Swarm based intersection signal control algorithms are one of the most researched approaches to improve the performance of the current traffic light controllers. These nature-based algorithms can be replaced with vehicles behaving as the swarm and the signal phase as the objective.

Wen and Wu [21] developed algorithm for optimizing traffic signal timings and phase selection using swarm algorithms for corridors. The algorithm is similar to optimizing signal plans for corridors using genetic algorithms. Instead of using genetic string of bits, solution set is presented as a set of nodes. The algorithm also uses virtual ants to search for paths. The algorithm reduces delay by 8-13% as compared to the local traffic responsive signal control.
Hoar, et al. developed a swarm based traffic signal control algorithm called SuRHJE (Swarms under R and J Evolution) [22]. The algorithm uses cumulative stopped delay divided by the total vehicle travel time for minimization. Vehicles can vote whether they want more green time or not and the votes are based on the vehicle’s experienced stopped delay. Signal timing plan changes are not known immediately because the votes do not change the phasing deterministically in real-time, but instead, influences the behavior and probability of phase getting or losing green time. The performance of the timing plan is compared to a random generated signal plan instead of a baseline signal timing plan.

2.3.6 Summary for Traffic Intersection Signal Control

The traffic intersection signal algorithms related to connected vehicles and wireless V2I communication discussed on this particular chapter has some following disadvantages:

- The algorithms are tested on idealized network or they are using a basic vehicle control model.
- The algorithms re-identifies the vehicles traveling in the simulations; which can cause issues regarding the driver privacy.
- The vehicle control logic limits are applicable to a given specific scenarios only.
Chapter 3: Connected Vehicle based Proposed Methodology

In this chapter, a connected vehicle based algorithm is proposed for an adaptive signal controller that addresses the issues and disadvantages of the already proposed or implemented traffic intersection signal control model algorithms discussed in the previous chapter. This algorithm will try to provide a simple but understandable vehicle and traffic control logic based on information collected from connected vehicles, with no re-identification of the vehicles at the intersection.

3.1 Algorithm Description

The traffic signal algorithm developed has the following objectives:

1. The algorithm tries to significantly improve the control logic performance of the current deployed fixed timed signal control and actuated traffic signal control systems.

2. The algorithm will respond to real-time traffic demands through connected vehicle technology and thus can eliminate the requirement of setting manual signal phase timing plans based on changes to the traffic conditions.

3. Protect driver privacy by not re-identifying or tracking records of the vehicles movements for any period of time.
To achieve these objectives, the algorithm is modeled on the concept of multi-agent system. The multi-agent system contains multiple autonomous entities that coordinate with each other in an environment. For an isolated intersection, two types of agent systems are considered. The agent type is called the Intersection management agent (IMA) and the second is called the Vehicle agent (VA). The functioning of this algorithm is dependent on two major models, namely:

- Vehicle control model, and
- Optimized traffic signal controller.

The vehicle control model basically implements a connected vehicles based maneuvering technique called platooning. The algorithm separately implements both platooning based vehicle control model and a non-platoon based control model. Both the models combined with optimized traffic signal controller are compared with existing traffic signal control systems. The optimized traffic controller uses a nature-inspired algorithm called Multi-objective Bat-inspired algorithm (MOBA) and it works on the principle of echolocation behavior of bats. The vehicle control model and the optimized traffic signal controller works simultaneously, sending information to each other through V2I communication protocol. The next two subsections will explain the two models in detail:

### 3.1.1 Vehicle Control Model

This section explains about the vehicle control model called the vehicle platooning in detail. A platoon is defined as a group of different vehicles which maintain equal vehicle speed and acceleration characteristics and the same moment maintain a fixed bumper-to-bumper spacing. One of the main objectives of vehicle platooning is to
increase the current road capacity. The concept of vehicle platooning is originally researched, designed and is being tested for highways and freeways. Recently, six brands of automated trucks participated in the European truck platoon challenge, where they were testing the concept of truck platooning on public roads of European countries. One such example of the platoon based driving for highways is SARTRE [23]. The idea of the above mentioned concept is to develop systems which aid in developing the concept of platooning on public roadways and also interacting with traffic which are following a non-platoon based pattern. The objective of this project is to reduce journey times, congestion and cut fuel consumption. This platooning system links vehicles electronically, with the first vehicle being driven by a driver, and rest following the turn as slave vehicles. Several platooning implementation concepts have been proposed recently. This paragraph discusses about two of the mechanisms, namely: Adaptive Cruise Control (ACC) and other to be known as Cooperative Cruise Control (CACC).

**Adaptive Cruise Control:** It is a system that is currently available as a feature in upscale cars. It is similar to the conventional cruise control model available in the vehicles in conditions where a vehicle does not follow another vehicle. In these conditions, ACC maintains a pre-set value of speed. If a vehicle is detected in the front, then it adjusts the vehicle’s speed in-order to keep a constant time-gap with the vehicle just in front of it. There is no driver intervention involved to carry out this functionality. To detect the vehicles in the front, ACC equipped vehicles have radar or camera systems. The system helps calculates the car’s speed and the distance of the vehicle which is preceding it, and then the ACC controls the vehicle speed. The
task is automated but the driver can overrule the system. Figure 3.1 illustrates a vehicle platoon working with ACC.

![Figure 3.1: Illustration of ACC control model](image)

Cooperative Adaptive Cruise Control: The issue with ACC is that, the radar can only detect the vehicles in line of sight. So, it is difficult to determine the distance and the speed of the vehicles which are behind the ACC equipped vehicle or a vehicle driving in another lane. This results in the information flowing through the platoon with increased values of delays. To overcome this issue, CACC concept has been proposed. The CACC brings in the concept of wireless communication, GPS and new control logic with the features of ACC. The information can travel to vehicles through wireless communication and can get to know about the behavior of the leading vehicle. The wireless communication helps in extending the view beyond the radar’s line of sight. Figure 3.2 illustrates a vehicle platoon working with CACC.

![Figure 3.2: Illustration of CACC control model](image)
Control functions of vehicle platoons

This sub-section describes the control functions that the connected vehicles or the autonomous vehicles perform during vehicle platooning.

Longitudinal Control: It is a type of functionality which controls the distance and the vehicles speed to the vehicle in the front using brakes and powertrain. The two objectives of longitudinal control are to provide a comfortable journey for the passengers and to have high accuracy which can guarantee safety. There are two types of longitudinal control mechanisms:

- The controllers that adjust the vehicle speed and distance based on the sensors available in the vehicle are called as autonomous controllers. These type of controllers maintain a good string stability, which means the headway errors are not passed down to the entire the platoon.

- The other type of controllers are the cooperative controllers. The controllers combine the features of radar and image processing sensors with the wireless communication systems to collect data of vehicles driving close by. These controllers are able to maintain a good string stability under constant distance and time-gaps. The distance-gap are not effected by vehicle speeds, so these controllers are capable to keep the headway small at high speeds.

Lateral Control: This type of controller tries to keep the automobile at the center of the specific lane and human driver is responsible for steering a vehicle. It sometimes helps in coordinating with lane changing feature. It uses magnetic markers and sensors to calculate the vehicle position with respect to the center of the road. The data is sent to the on-board unit which commands the steering wheel actuators
to maintain a constant distance to the center of the road. In-case of vehicles being autonomous and platooning envisioned, the lateral control functionality (Automated Highway System) is also automated.

**Benefits of Vehicle Platooning**

The vehicle platooning has a lot of benefits. The benefits include improving road capacity, improved safety, reduced air drag and improved passenger comfort. Understanding the impact and benefits of vehicle platooning on the traffic conditions are very important, as they serve as a justification parameter for the implementation of vehicle platoons.

**Increased Road Capacity**

One of the benefits of vehicle platooning is to increase road capacity. The key to achieve high road capacity is that the vehicles travel as close as possible to each other. A vehicle platoon system has not been deployed in real-time situations on a large scale. On highways, it is estimated that a fixed distance-gap of 21 feet between the vehicles moving at a speed of 65 miles per hour, the traffic lane capacity is increased to 5700 vehicles per lane per hour (vplph) from 2000 vplph. This results in the value of road capacity getting more than doubled. Thus, more vehicles are able to use the highways at that time without the effect of traffic congestion.

**Reduced Air Drag**

The transportation industry is one of the largest contributor to the green house gases emissions. The transpiration industry is studying different solutions to reduce fuel consumption factors. Air drag experienced by each vehicle is also significantly reduced when vehicle platooning is implemented. Reduction to air drag in-turn results in reduction of pollution, less fuel consumption and better vehicle fuel efficiency. The
air drag reduction is most effective when the distance between the travelling vehicles is half the car length value. At this distance-gap, the drag can be reduced to about 50% and about 25% reduction in fuel consumption.

**Improved Safety**

One of the major cause for traffic accidents is human error. Some of human error reasons included speeding, fatigue, drunk driving and distractions. Combination of technologies such as vehicle platooning with wireless communications can improve the driver’s line of sight and also help in reacting quickly to dangerous conditions and situations. Constant monitoring and information updates between the vehicle platoons also results in improved safety of the vehicle and the passengers.

**Improved Driver Comfort**

The vehicle platooning concept can also help improve the driver’s comfort. The driver tasks can be delegated to the vehicle based on the level of automated functionalities. On long journeys, this helps in reducing the driver’s stress. The comfort of the driver is further improved by smoothing of the traffic flow by having automated speed changes. These speed changes are less jerky as compared to the vehicles driven under human control.

**Vehicle Platooning Algorithm**

The features and benefits of vehicle platooning discussed in the previous sections justified to propose a platooning control model for an isolated signalized intersection. This section describes how a platoon of vehicle is formed and some related terms to it. The concept of vehicle platooning here is used to increase the road capacity, calculate the estimated time of arrival (ETA) and intersection departure time from the intersection for the platoon using the connected vehicle technology. The first part
of the algorithm is to decide how many vehicles can be there in a platoon at maximum. According to [24], increase in road capacity can be achieved by implementing intra-platoon vehicle control model.

The formulation to calculate the road capacity is given as:

\[ C = \frac{vn}{ns + (n - 1)d + D} \]

where \( d \) is the gap between vehicles in the same platooning system, \( D \) is the gap between two different platooning systems, \( v \) is the steady-state speed, \( s \) is the length of the vehicle and \( n \) is the vehicle count to be kept in the platoon. The above equation is taken into consideration and the table below gives a generic idea about the vehicle count in a platoon.

Table 3.1: Road capacity with vehicle platooning concept

<table>
<thead>
<tr>
<th>( v ) (mph)</th>
<th>( n )</th>
<th>( d ) (m)</th>
<th>( D ) (m)</th>
<th>( C ) (veh/h)</th>
<th>Improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>45</td>
<td>1</td>
<td>-</td>
<td>30</td>
<td>2182</td>
<td>-</td>
</tr>
<tr>
<td>45</td>
<td>5</td>
<td>1</td>
<td>30</td>
<td>7347</td>
<td>3.4</td>
</tr>
<tr>
<td>45</td>
<td>8</td>
<td>1</td>
<td>30</td>
<td>9443</td>
<td>4.3</td>
</tr>
<tr>
<td>45</td>
<td>15</td>
<td>1</td>
<td>30</td>
<td>12135</td>
<td>5.6</td>
</tr>
<tr>
<td>45</td>
<td>20</td>
<td>1</td>
<td>30</td>
<td>13211</td>
<td>6.1</td>
</tr>
</tbody>
</table>

In Table 3.1, when the speed of the vehicle is set as 45 mph and the number of vehicles per platoon is kept at 8, the road capacity is tripled as compared to a case at \( n=1 \). In all the cases, the value of intra-platoon gap is kept as 1 meter and the gap between two different platoons is set at 30 meters. The number of vehicles per platoon is kept as eight vehicles at maximum, considering the length of the traffic lane of an isolated signalized intersection.
A vehicle platoon has two types of vehicle agents (VA) namely:

- Platoon leader VA, and

- Follower VA.

The maximum wireless communication range for formation of a platoon is about 150 meters. A basic procedure for platoon formation has been illustrated through a flowchart.
diagram in Figure 3.3. The proposed multi-agent system labels all the vehicles as either platoon leader VA or the follower VA.

The platoon formation procedure illustrated above is described in the following steps:

- When an untagged vehicle agent (VA) enters the simulation traffic network, the first step is to check for any other VA’s within the V2V communication range.

- The untagged vehicle agent checks whether there is a platoon leader VA within the range and sends a request to join the existing platoon of that leader VA. If the platoon’s threshold vehicle count is not reached, it becomes a follower VA of that platoon.

- If the threshold value is reached, the untagged VA is tagged as a new platoon leader VA.

The next sub-section describes how a maneuver is implemented during a vehicle platoon formation. The platoon leader VA begin in “leading” and the follower VA begin in “idle” states. The follower VA sends a request to the platoon leader VA to join the platoon with the “send request” message, and its state updates from “idle” to “wait_reply” condition state. The platoon leader VA replies with the message join request, which sends the details of platoon such as joining position, speed and lane. The leader vehicle’s state is changed to ”wait” state. The information sent by the platoon leader VA is used by the follower VA to adjust its vehicle parameters to join at the tail-end of the platoon. The follower VA also sends a message that it has reached in joining a position. The platoon leader VA confirms and the follower VA uses CACC vehicle control functionality to close the distance and maintain the
intra-distance-gap. When the joining procedure is completed, the leader VA changes state to "leading" state and follower VA changes state to "follow" state.

When the platoon leader VA communicates with the IMA within the 300 meter range, an estimated time of arrival (ETA) and estimated time for departures is calculated. The ETA values is somewhat dependent on the critical performance of the platoon. The formula for ETA is expressed as:

$$\text{max}_i \left[ t_i - \sum_{k=1}^{i-1} h_k \right].$$

The estimated time for departure for a platoon is expressed as:

$$\text{max}_i \left[ t_i + \sum_{k=i}^{n-1} h_k + t_n \right],$$

where $h_k$ is defined as headway of a single vehicle $i$; $t_i$ is the ETA time for the $i^{th}$ VA and $t_n$ is the estimated departure time for vehicle $i$. The platoon leader VA has a start-up delay of 1.5 seconds. The arrival time and the departure are reported to the intersection management agent (IMA) and then the IMA processes a detailed calculation in order to process the next best phase sequence and the required green split duration.

Non-platoon based vehicle maneuvering system is also proposed to compare it with the performance of platoon based systems. The non-platoon system collects information from individual vehicles and each vehicle sends their information to IMA for further processing. The non-platoon based system also use the V2I range of 300 meters to communicate between them and the IMA. The concept of CACC is not implemented for this kind of system. The information is sent separately to all
individual vehicles regarding the change in cycle length, phase signals or green splits by the IMA. The non-platoon based system is also compared with the pre-timed and the actuated traffic signal timing controls.

3.1.2 Signal Timing Optimization

The previous section covers how the vehicle platoon formation is carried out. It also describes the parameters the platoons take as input and process those data and send an output parameter to the intersection management agent (IMA). The second phase of the proposed multi-modal intelligent traffic intersection signal control is the optimization of the signal controller. The information received from the vehicle platoons or individual vehicles are taken as input and process using an optimization algorithm to output the next phase and the green split of that phase. These two output parameters are notified to the vehicles. The IMA sends and receives information from vehicles which are within the DSRC range of 300 meters. The proposed algorithm tries to improve the current performance of a pre-timed or a actuated traffic control by considering real-time traffic demands and also by protecting vehicle's privacy by never tacking any vehicle ID details.

Figure 3.4 illustrates how the optimization formulation of traffic signal works. The traffic signal optimization formulation has the following parameters:

- **Objective function**: First parameter required for the optimization is an objective function. In this problem, average vehicle delay and stop frequency are used as the two objectives, making them as a multi-objective function.
Multi-heuristic Bat Algorithm (MOBA): The proposed system uses a nature-inspired algorithm to optimize the functioning of the traffic signal controller. This algorithm is based on the concept of bat’s echolocation behavior.

Constraints: It is one of the parameters through which the optimization algorithm provides the output parameter within the given conditions and bounds. For this problem, cycle length, saturation flow and green split are chosen as the constraint parameters.

Decision Variables: It is the output parameter which is processed by the optimization formulation algorithm. Here, the output values are the next signal phase that is to be implemented and its corresponding green split time.
Traffic Signal Control Finite State Machine

This section gives an idea about how the currently implemented dual-ring traffic controller and the proposed adaptive and flexible traffic controller differ. National Electrical Manufacturing Association (NEMA) based dual-ring controller is one of the most popular controllers used in the United States[4]. Each of the four cardinal directions in the intersection consist of a left turn lane and a through lane. Figure 3.5 gives an illustration of the dual ring controller and the lane numbering of an signalized intersection based on the dual-ring controller.

![Dual-ring controller labelling](image)

Figure 3.5: Dual-ring controller labelling

The rings in the controller consists of two sets of signal phases namely, Ring 1 and Ring 2, where Ring 1 consists of phases numbered as [1, 2, 3, 4] and Ring 2 consists
of phases numbered as $[5, 6, 7, 8]$. Two signal phase numbers from each ring can be active for any instant of time. The barrier decides which two phases can be active at a given time. The signal phase numbers should be from the same side of the barrier. In case of a dual-ring controller, the main street has the following phase signal numbers, $[1, 2, 5, 6]$ and the side street has $[3, 4, 7, 8]$ as signal phases. When the signal timing plan starts, the phase cycle starts from 1 and 5, which is followed by 2 and 6, then signal phases 3 and 7 are implemented, and at last signal phases 4 and 8 are implemented. Then the whole signal phase cycle is repeated.

Figure 3.6 gives a finite state machine representation of the NEMA dual-ring controller. This illustration explains the limitations of a pre-timed traffic signal timing plan for a dual-ring controller. The figure includes all the phases, namely yellow, red and green phases. For the dual-ring controller, there are 9 unique signal phase states, where All-red signal phase state is repeated during the transition from one phase to another.

Figure 4.1 gives a finite state machine interpretation of the proposed adaptive and optimized traffic signal controller. The illustration is shown for the main street only. A adaptive traffic signal control considers optimizing both the signal phase sequences and the signal phase duration. In the adaptive signal paradigm, there is no strict coupling among different phase sequences as in the case of fixed manual phase signal timing of a dual ring controller. This indicates that the phase 1 can couple with both phase 5 and phase 6. This allows the two rings of the dual-ring controller to operate separately and independently. The ”All red” signal state represents as a barrier and common connection between the two perpendicular streets. The finite state has four green states for the phase coupling $[1, 5], [2, 5], [1, 6], [2, 6]$. Including all
the combination of the red and yellow states for the four phases of the main street, there are 25 unique states. The side street has a similar kind of a finite state diagram, so the total unique states for the whole traffic controller becomes 49.

Features of the Intelligent Traffic Signal Control

This section describes about the features to be implemented in an intelligent traffic signal control. The traffic controller uses microscopic traffic simulation techniques to implement the vehicle behavior. The information snapshot collected by the traffic signal controller agent for calculation of the signal phase and the green split for that phase includes:
When a platoon based connected vehicle system is implemented; the estimated time of arrival, estimated time for departure, speed of the platoon, position and the platoon ID of the equipped vehicles is sent to the IMA.

When non-platoon based connected vehicle system; the speed, position, estimated time of arrival, estimated time for departure and vehicle ID is sent to the IMA.

The decision zone for the intersection agent is within the range of 300 meters. The information exchange occurs between the connected vehicles and the IMA within this
range only. Two parameters, queue length and the ratio of the vehicle actual speed and the desired vehicle speed are the main factors for the IMA to decide what next signal phase sequence should be. The ratio is expressed as follows:

\[
\frac{\sum_{k=1}^{n} \frac{s_k}{v_k}}{n} > 0.95,
\]

where \(s_k\) is defined as actual vehicle speed, \(v_k\) is equal to the desired vehicle speed and \(n\) is equal to the vehicle count. Queued vehicles or queued platoons are defined as the vehicles having a speed below a pre-defined threshold value, i.e., 10 miles per hour (mph) and the vehicles are approaching the intersection.

The intersection traffic signal controller also implements the basic amber and the red phase states. The amber phase is timed for a four seconds value and the red phase is timed for two seconds value. The amount of green signal time allocated to a signal phase sequence being serviced is defined as the green split duration. In the proposed algorithm, the green split duration is kept within the range of 5 to 15 seconds. The exact amount of green signal time is calculated through the optimization algorithm by optimizing the two objective functions, which are going to be discussed later in this chapter. The algorithm uses a nature inspired optimization algorithm known as multi-objective Bat algorithm (MOBA). The algorithm has been used in optimization of parameters in the manufacturing processes. This is the first time, it is being implemented for the field of intelligent transportation systems. The algorithm will also be discussed later in detail.

There are several constraints placed on the behavior of the optimized intelligent traffic signal controller. One of the constraint is that each signal phase sequence will have a maximum red time of 120 seconds. If the signal phase sequence is not
selected within the 120 second cycle length time, that signal phase sequence is added as the immediate signal phase transition, once the current signal phase duration is over. These phase transitions may have a 5 second or more of green split duration depending on the values of queue length and the ratio of vehicle actual speed to the desired vehicle speed. The saturation traffic flow rate is the flow rate value when a lane is termed to be fully congested at that value or above. For this research, the saturation traffic flow rate value is kept at 1700 vehicles per lane per hour (vplph).

One of the new features of the intelligent traffic signal controllers are:

- **Green Split Extension:** This feature is enabled when the current signal phase being serviced continues to have the lowest and the optimized objective function values as compared to other signal phase sequences. The green split duration extension is extended again for a minimum of 5 second duration and a maximum of 15 second duration, again depending on the traffic parameter values.

- **Green Split Squeezing:** This feature is enabled when a signal phase sequence which is not being serviced has the lowest and the optimized objective function value as compared to the phase signal sequence being serviced currently. The proposed algorithm makes sures that the current phase signal is serviced for a minimum of 5 seconds of green split duration before transitioning to the other signal phase sequence.

- The proposed algorithm also avoids an incomplete queue discharge, which occurs when the intersection management agent does transitions between phases because of the queue length of the signal phase sequence being served decreases and another signal phase sequence has a higher value of queue length [4].
Multi-Objective functions

For problems related to intelligent transportation systems, average control delay is one of the most important objective function for evaluating traffic intersection signal control. The objective functions can directly relate to LOS, which is a measure which is used to relate to the quality of traffic being serviced. There are six levels to define LOS, where A is the best and F is the worst. This research problem, two objective functions have been chosen namely:

- **Average Control Delay**: It is defined as the travel time loss experienced due to the traffic resistance and friction. The function is related to traffic parameters such as green split duration, cycle length and traffic level. It is expressed as:

\[
\frac{\sum_{k=1}^{n} d_k}{ntd_{max}},
\]

where \(d_k\) is the individual vehicle delay per single time interval, \(n\) is equal to the total vehicles present at that moment and \(t\) is equal to the total time [25].

- **Stop Frequency**: It is defined as the stop count value when a vehicle passes through the signalized intersection. The stop frequency is directly related to the actual traffic rate flow and the saturation rate flow. It is expressed as:

\[
\frac{\sum_{k=1}^{n} sf_k}{n},
\]

where \(sf_k\) is the individual stop frequency per single time interval and \(n\) is the vehicle count [25].
This problem uses multiple objective objective functions instead of a single objective function. When two objective functions are being optimized simultaneously, a collection of possible solutions exist instead of a single optimal and valid solution. The key idea here is to generate the valid pareto solutions from the feasible boundary value ranges and then select the best possible solution. This kind of multi-objective functions can be optimized using a multi-heuristic optimization algorithm. The algorithm used is known as Meta-heuristic Bat algorithm. The optimization algorithm used here is described in the section below.

**Meta-heuristic Bat-Inspired algorithm**

Meta-heuristic algorithms including particle swarm based optimization, ant colony optimization and fire-fly inspired algorithm are some of the most powerful methods to solve many complex optimization problems. One of the algorithms is called as meta-heuristic Bat Algorithm. This algorithm was first proposed and published by Xin-She Yang [26]. The rules implemented for the Bat algorithm are:

- The bats use echolocation for sensing distance. The bats also know the difference between different barriers present and the prey they are looking for.

- The flying parameters for the bats are given by, velocity $v_i$ present at position $x_i$ and having a frequency $f_{min}$. They have a varying value of wavelength $\lambda$ and value of loudness, $A_0$, for their prey search.

- The loudness of the bats can differ from range of a positive large $A_0$ value to a value $A_{min}$.

The above mentioned algorithm performs much better than the other algorithms such as genetic based algorithms, particle swarm based optimization algorithms for
different standard benchmarks. For this research, as there are two objective functions, the multi-objective version of bat algorithm is adopted [27].

\[ f = \sum_{k=1}^{K} w_k f_k, \quad \sum_{k=1}^{K} w_k = 1, \]

where \( w_k \) is the random weights and \( f_k \) is an individual objective function. The input variables for the optimization algorithm are the queue length, actual traffic flow, and the range of the green split duration. The other parameters required for the functioning of the algorithm are in Table 3.2:

**Table 3.2: Input parameter required for multi-objective bat algorithm**

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension (d)</td>
<td>8</td>
</tr>
<tr>
<td>Population size (n)</td>
<td>25</td>
</tr>
<tr>
<td>Generations</td>
<td>1000</td>
</tr>
<tr>
<td>Loudness (A)</td>
<td>0.5</td>
</tr>
<tr>
<td>Pulse rate (r)</td>
<td>0.5</td>
</tr>
<tr>
<td>Frequency (minimum)</td>
<td>0.0</td>
</tr>
<tr>
<td>Frequency (maximum)</td>
<td>2.0</td>
</tr>
<tr>
<td>Lower bound of green split</td>
<td>5</td>
</tr>
<tr>
<td>Upper bound of green split</td>
<td>15</td>
</tr>
</tbody>
</table>

In MOBA, each population is represented as a signal timing value for the current traffic signal phase being serviced. The dimension \( d \) mentioned in the above table is number of phases in the phase signal timing model. In this research, an isolated signalized intersection is considered, so the value of \( d \) is set as 8. The minimum frequency \( f_{min} \) and the maximum frequency \( f_{max} \) corresponds to a range of wavelengths \([\lambda_{min}, \lambda_{max}]\). The lower and the upper bounds are based on the proposed range of
green split duration. The output for the algorithm is the next phase sequence and
the green split duration for that phase sequence.
Chapter 4: Experimentation and Results

This chapter discusses simulation parameters and the scenarios implemented to test the proposed algorithm and then discuss the performance results obtained from the simulation scenarios.

To build the whole traffic network and to evaluate the functioning of it, python based traffic control interface (TraCI) is used with SUMO (version 0.24) [28]. Emission model based on HBEFA v3.1 [29] is implemented to study the fuel consumption and CO₂ emissions details.

4.1 Simulation Traffic Parameter Setup

The parameters required for the traffic network model to be generated are:

- An isolated intersection is considered with two lanes in all four cardinal directions, namely left-turn only lane and a through lane.
- The packet loss and latency factors are considered to be almost zero.
- The length for all lane approaches is 1000 meters.
- Vehicles considered for the simulation study are assumed to be passenger sedan cars with vehicle-length of 3.5 meters.
• Initial speed of the vehicles is set at a value of 15 meters per second (m/s).

• The maximum acceleration value is set to be $2.5 \, m/s^2$ and deceleration value is set to be $-2.5 \, m/s^2$.

• The speed limit for lanes in all the cardinal directions is 20 m/s or 45 miles per hour.

• The saturation flow for all cardinal direction is set at 1700 vehicle per hour per lane (vphpl).

• The vehicle arrival rates are modeled according to a function of Poisson distribution having a rate of $\lambda$. Arrival rates for the vehicles are distributed exponentially, by the given parameter, $r = \lambda^{-1}$.

• Vehicle arrival rates have been classified into three divisions: heavy traffic ($\lambda = 1700 \, vphpl$), medium traffic ($\lambda = 850 \, vphpl$) and light traffic ($\lambda = 400 \, vphpl$).

• Vehicles have 20% chance of entering the left-turn lane on all the cardinal directions.

• V2V range value is 150 meters and V2I range value is set at 300 meters.

4.2 Traffic Demand Profile

The traffic demand profile based on vehicle arrival rates for the simulation scenarios is indicated in Figure 4.1.

4.3 Simulation Scenarios

The following scenarios have been utilized for the simulation comparisons:
Figure 4.1: Hourly traffic demand profile

- **Scenario I:** Equal vehicle arrival rate is assumed for all the cardinal directions based on the hourly demand profile.

- **Scenario II:** Vehicle arrival rates vary based on the hourly demand profile for the east-west cardinal direction and a constant vehicle arrival rate for the north-south cardinal direction ($\lambda = 100$ vehicle/hr).

- **Scenario III:** The ratio of vehicle arrival rates is set to 2:1, for the east-west direction to the north-south direction.

### 4.4 Results

The proposed platoon-based and non-platoon based multi-agent systems will be compared with actuated control systems and pre-timed signal systems. The green
splits and cycle lengths for pre-timed and actuated systems were computed using the Quick Estimation Method [30, 31] and the HCM method [32] respectively.

The simulation scenarios are simulated for two hours based on real time traffic data. The measure of effectiveness (MOE) used for measuring the performance of the traffic model are: the average waiting time per vehicle and the fuel consumption. Average waiting time is one of the most commonly used measure for evaluating the effectiveness of a traffic signal control at any signalized intersection. To study the environmental implications of the proposed signal control model, CO$_2$ emission parameter and fuel consumption parameter are also considered.

### 4.4.1 Average Waiting Time

Scenario I: Figure 4.2 shows a comparison between platoon-based, non-platoon based, actuated and pre-timed control systems for scenario I. The platoon based systems perform much better than the other three systems. The system reduces approximately 7%, 26% and 31% in average waiting time as compared to non-platoon based, actuated control and pre-timed control systems respectively.

Scenario II: Figure 4.3 shows a comparison between platoon-based, non-platoon based, actuated and pre-timed control systems. As shown in the plot, platoon based systems perform much better than the other three systems. The system reduces approximately 3%, 12% and 19% in average waiting time as compared to non-platoon based, actuated control and pre-timed control systems respectively.

Scenario III: Figure 4.4 shows a comparison between platoon-based, non-platoon based, actuated and pre-timed control systems for Scenario II. The plot shows that platoon based systems perform much better than the other three systems. The system
Figure 4.2: Average waiting time plot for Scenario I

reduces approximately 6%, 23% and 27% in average waiting time as compared to non-platoon based, actuated control and pre-timed control systems respectively.

4.4.2 Fuel Consumption and CO₂ Emissions

Scenario I: Table 4.1 shows a comparison between platoon-based, non-platoon based, actuated and pre-timed control systems for fuel consumption. As reflected by the table, platoon based systems perform better than the other three systems. The system reduces approximately 5%, 9% and 11% in fuel consumption as compared to non-platoon based, actuated control and pre-timed control systems respectively. Similarly, the system reduces approximately 5%, 7% and 9% in CO₂ emissions as compared to non-platoon based, actuated control and pre-timed control systems respectively.

Scenario II: Table 4.2 shows a comparison between platoon-based, non-platoon based, actuated and pre-timed control systems for fuel consumption. As indicated
by the table, platoon based systems perform better than the other three systems. The system reduces approximately 2%, 5% and 6% in fuel consumption as compared to non-platoon based, actuated control and pre-timed control systems respectively. Similarly, the system reduces approximately 1%, 3% and 4% less in CO$_2$ emissions as compared to non-platoon based, actuated control and pre-timed control systems respectively.

Table 4.1: Fuel consumption and CO$_2$ emission comparison for scenario I

<table>
<thead>
<tr>
<th>MOE</th>
<th>Platoon based MOBA vs</th>
<th>Relative reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumption</td>
<td>Non-Platoon based</td>
<td>5.31%</td>
</tr>
<tr>
<td></td>
<td>Actuated Control</td>
<td>9.23%</td>
</tr>
<tr>
<td></td>
<td>Pre-timed Control</td>
<td>10.80%</td>
</tr>
<tr>
<td>CO$_2$ Emission</td>
<td>Non-Platoon based</td>
<td>4.89%</td>
</tr>
<tr>
<td></td>
<td>Actuated Control</td>
<td>7.58%</td>
</tr>
<tr>
<td></td>
<td>Pre-timed Control</td>
<td>9.29%</td>
</tr>
</tbody>
</table>
Scenario III: Table 4.3 shows a comparison between platoon-based, non-platoon based, actuated and pre-timed control systems for fuel consumption. As observed in the Table 4.3, platoon based systems perform better than the other three systems. The system reduces approximately 3%, 6% and 8% in fuel consumption as compared to non-platoon based, actuated control and pre-timed control systems respectively. Similarly, the system reduces approximately 3%, 5% and 6% in CO₂ emissions as compared to non-platoon based, actuated control and pre-timed control systems respectively.

4.4.3 Effect of Penetration Rates

Penetration rate is the ratio of vehicles equipped with the connected car technology to the vehicles not equipped. The proposed algorithm uses vehicle parameters in order to form platoons and calculate the optimized output parameters. If some of the VA’s are not detected by the IMA or other VA’s, this results in decrease in performance of
Table 4.2: Fuel consumption and CO₂ emission comparison for scenario II

<table>
<thead>
<tr>
<th>MOE</th>
<th>Platoon based MOBA vs</th>
<th>Relative reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumption</td>
<td>Non-Platoon based</td>
<td>2.12%</td>
</tr>
<tr>
<td></td>
<td>Actuated Control</td>
<td>5.44%</td>
</tr>
<tr>
<td></td>
<td>Pre-timed Control</td>
<td>6.00%</td>
</tr>
<tr>
<td>CO₂ Emission</td>
<td>Non-Platoon based</td>
<td>1.27%</td>
</tr>
<tr>
<td></td>
<td>Actuated Control</td>
<td>2.55%</td>
</tr>
<tr>
<td></td>
<td>Pre-timed Control</td>
<td>3.59%</td>
</tr>
</tbody>
</table>

Table 4.3: Fuel consumption and CO₂ emission comparison for scenario III

<table>
<thead>
<tr>
<th>MOE</th>
<th>Platoon based MOBA vs</th>
<th>Relative reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumption</td>
<td>Non-Platoon based</td>
<td>3.25%</td>
</tr>
<tr>
<td></td>
<td>Actuated Control</td>
<td>6.30%</td>
</tr>
<tr>
<td></td>
<td>Pre-timed Control</td>
<td>8.19%</td>
</tr>
<tr>
<td>CO₂ Emission</td>
<td>Non-Platoon based</td>
<td>2.78%</td>
</tr>
<tr>
<td></td>
<td>Actuated Control</td>
<td>5.09%</td>
</tr>
<tr>
<td></td>
<td>Pre-timed Control</td>
<td>6.23%</td>
</tr>
</tbody>
</table>

the signal model as a whole. To quantify the performance effectiveness of the model, simulation at various penetration rates are performed. The different penetration rates are set at 75%, 50%, 30% and 25%. For these simulations, non-platoon based MOBA systems are also considered. Average waiting time has been selected as the measure of effectiveness for these simulation studies.

Scenario I: Figure 4.5 shows a comparison between non-platoon based at different penetration rates, actuated and pre-timed control systems. In the plot, it can be noticed that the non-platoon based systems at 100%, 75% and 50% perform much better than the other two conventional systems. The non-platoon based system at
30% penetration rate reduces just about 3% in average waiting time as compared to actuated control. The system at 25% penetration rate performs poorly as compared to an actuated control, and even when compared with the pre-timed control system, it shows an improvement of about 2.5%.

Figure 4.5: Effect of penetration rate for Scenario I

Scenario II: Figure 4.6 shows a comparison the between non-platoon based at different penetration rates, actuated and pre-timed control systems. In the plot, it can be noticed that the non-platoon based systems at 100%, 75% and 50% perform much better than the other two conventional systems. The non-platoon based system at 30% penetration rate performs poorly as compared to an actuated control. There
is -0.19% change in values. The system at 25% penetration rate performs poorly as compared to an actuated control, and even when compared with the pre-timed control system, it performs almost equally (0.29% improvement).

Figure 4.6: Effect of penetration rate for Scenario II

Scenario III: Figure 4.7 shows the comparison a between non-platoon based at different penetration rates, actuated and pre-timed control systems. In the plot, it can be noticed that the non-platoon based systems at 100%, 75% and 50% perform much better than the other two conventional systems. The non-platoon based system at 30% penetration rate reduces just about 2% more of average waiting time than actuated control. The system with 25% rate performs poorly as compared to an
actuated signal control, but performs slightly better than the pre-timed control system (around 1%).

![Bar chart showing the effect of penetration rate for Scenario III](image)

Figure 4.7: Effect of penetration rate for Scenario III
5.1 Conclusion

The proposed multi-modal traffic signal control algorithm has several benefits. First are the improvements in average waiting time, fuel consumption and CO$_2$ along the isolated intersection when compared to a pre-timed and an actuated signal timing plan. This improvement has been achieved at 100% connected vehicle penetration rate. Secondly, the algorithm shows a great improvement over the current timing plans when the effect of penetration rate of connected vehicles is taken into consideration. The penetration rates are varied from 25% to 75%. Third, the algorithm indicates that a minimum of 25% connected vehicle penetration rate is needed for the algorithm to perform better than the pre-timed signal plan system.

The vehicle control model based on platooning, which is primarily used as a concept in highways has been implemented in an isolated intersection environment. The platooning system is achieved using the V2V communication protocol and the concept of co-operative adaptive cruise control. According to the simulation results, the platooning vehicle control model shows better improvement than the non-platoon based system in all the three performance measures.
The algorithm used Multi-objective bat algorithm, a type of nature-inspired algorithm for optimization of the green signal splits and phase calculation. This is the first instance of this algorithm being used in optimizing traffic signal control problems. Although it relies on average delay and the stop frequency as its objective functions, the algorithm can be quickly altered to try different performance measures in order to optimize the discussed problem. However, preliminary simulations shows that the above two mentioned objective functions are best for minimizing waiting time and fuel consumption. This algorithm also makes the traffic signal more adaptive by considering 49 unique finite states as compared to the fixed 9 unique finite states of a dual ring controller. Finally, the algorithm relies solely on the connected vehicle methodology, i.e., wireless V2I communications, it eliminates the need for loop and video detectors.

5.2 Future Work

The algorithm provides a solution for homogeneous set of road traffic such as cars (sedans). This experimentation may be extended to a more heterogeneous set of traffic which includes transit buses and emergency vehicles. The algorithm can be modified to include a feature where phase switching is given to that lane where there is an emergency vehicle as soon as the vehicle data from the emergency vehicle is received.

Currently, the simulations are considered on an isolated intersection with three different scenarios of vehicles arrival rates taken into consideration. The future work may be that, the simulations can be performed on a grid of intersections and arterial intersections in order to improve the green wave methodology. The arterial and the
grid intersections are considered to be coordinated intersections, whereas, isolated intersection is considered as a non-coordinated intersection. When a series of traffic signal control systems are managed in such a way that, it allows a continuous flow of traffic through several intersections in one direction, that event is termed as green wave. The vehicles travelling through these intersections will see a cascade of green signal lights without stopping at any of the intersections.

Because of the simulations being carried out on an isolated intersection, the platoon characteristics are limited. Another study can be done, is the implementation of more platoon characteristics such as platoon leaving and a vehicle from a platoon changing the lane on arterial and grid intersections. The algorithm can also be compared to the other proposed adaptive traffic signal algorithms and also try to improve algorithm performance at lower rate of connected vehicle penetrations (10%-25%).
Bibliography


