Co-operative Driving at Intersections using Vehicular Networks and Vehicle-Resident Sensing

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Abstract

Road intersections are considered to be serious bottlenecks of urban transportation. According to the U.S., European, and global statistics, intersection-related crashes, with fatal outcome, represent approximately 20 percent of all traffic fatalities. More than 44% of all reported crashes in the U.S. occur within intersection areas, which, in turn, lead to 8,500 fatalities and approximately 1 million injuries every year [1]. Furthermore, the impact of road intersections on traffic delays leads to enormous waste of human and natural resources. Statistics collected by FHWA in 2011 urban mobility report states that the average intersection delay endured by a commuter is 34 hours every year. The cost of this wasted time and related fuel consumption at intersection congestions is over $101 billion a year [2]. Therefore, it is critical to address these safety and throughput concerns as one of the main challenges for manual as well as autonomous driving through intersections.

This dissertation studies the problem of managing traffic through intersections, and develops new decentralized, reliable and efficient active safety methods to provide safe and efficient passage through intersections and roundabouts. Our cyber-physical framework called STIP (Spatio-Temporal Intersection Protocols) incorporates a fusion of vehicle-to-vehicle (V2V) communications, vehicle-to-infrastructure (V2I) communications and vehicle-resident sensing to enable co-operative driving of autonomous and manually-driven vehicles at intersections. The proposed system allows vehicles to traverse safely by avoiding vehicle collisions at intersections, and significantly increase traffic throughput. The STIP framework includes a family of distributed protocols and covers the following two main traffic environments, categorized based on the market penetration of autonomous vehicles: (1) *Homogeneous Traffic*: autonomous vehicles only, (2) *Heterogeneous Traffic*: mix of human-driven and autonomous vehicles.

For the homogeneous traffic category, we introduce two sets of intersection protocols: (1) *V2V-Intersection Protocols*, which rely on V2V communications and localization to avoid vehicle collisions at intersections by controlling and navigating them within the intersection area. Autonomous vehicles approaching an intersection use DSRC to periodically broadcast information such as position, heading and intersection crossing intentions to other vehicles. The vehicles then decide among themselves regarding who crosses first, who goes next and who waits. (2) *Synchronized movement-intersection protocols*, which are designed to increase the parallelism at intersections by allowing the

concurrent crossing of vehicles arriving from all directions. This method enforces synchronized and staggered arrival of vehicles at intersections. This method allows vehicles to cross the intersection without stopping or slowing down, and maximizes the capacity utilization of the intersection space. In case of the heterogeneous traffic category, in order to enable the safe co-existence of manually-driven and autonomous vehicles at intersections, we propose a set of communication-based and perception-based protocols, leveraging a fusion of V2V, V2I and on-board sensor systems such as cameras, radars and lidars.

In this dissertation, we formally prove the deadlock-freedom property of our family of intersection protocols, and study the effects of packet loss on our V2V intersection protocols and measure the reliability of these protocols in the presence of channel impairments. We also measure the impact of position inaccuracy of commonly-used GPS devices on our V2V-intersection protocols and incorporate required modifications to guarantee their safety and efficiency despite these impairments. Additionally, we study sensor inaccuracy and occlusion’s impact on our perception-based intersection protocols, and propose simple solutions to deal with these shortcomings. The functionality of our methods is evaluated using our vehicular networks emulator-simulator, called AutoSim. Our results indicate that our proposed STIPs provide both safe passage through the intersection and significantly decrease the delay at the intersection by increasing the concurrency. Specifically, one of our V2V-intersection protocols yields over 87% overall performance improvement over the common traffic light signalized intersections. Throughput increases are even more significant in the case of our synchronized movement intersection protocols, as intersection delays are reduced up to 96% compared to the common traffic light signalized intersections, and the optimal intersection capacity utilization of 100% is achieved in certain cases.

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List of Acronyms

AC-IP: Advanced Crossing Intersection Protocol

ADAS: Advanced Driver Assist Systems

AMP-IP: Advanced Maximum Progression Intersection Protocol

AP-IP: Advanced Progress Intersection Protocol

PB-IP: Perception-based Intersection Protocol

BRIP: Ballroom Intersection Protocol

CAMP: Crash Avoidance Metrics

CC-IP: Concurrent Crossing Intersection Protocol

CDAI: Collision Detection Algorithm for Intersections

CPS: Cyber Physical Systems

CR: Communication Range

CRS: Current Road Segment

DSRC: Dedicated Short Range Communication

GPS: Global Positioning System

HCP: High-Concurrency Protocols

HCP-EVD: High-Concurrency Protocols with Enhanced Vehicle Dynamics

ITS: Intelligent Transportation Systems

LCP: Low-Concurrency Protocols

LOS: Line of Sight

MP-IP: Maximum Progression Intersection Protocol

NHTSA: National Highway Traffic Safety Administration

NLOS: Non-Line of Sight

NRS: Next Road Segment

OEM: Original Equipment Manufacturers

OSM: Open Street Maps

PB-SS-IP: Perception-Based with Stop Sign Intersection Protocol

PB-TL-IP: Perception-Based with Traffic Light Intersection Protocol

RITA: Research and Innovative Technology Administration

SM-IP: Synchronized-Movement Intersection Protocol

SPaT: Signal Phase and Timing

STIP: Spatio-Temporal Intersection Protocols

TE-IP: Throughput Enhancement Intersection Protocol

TCL: Trajectory Cells List

TIC: Trajectory Intersecting Cell

USDOT: U.S. Department of Transportation

V2V: Vehicle-to-Vehicle Communications

V2I: Vehicle-to-Infrastructure Communications

V2X: Vehicular Communications

V2V-IP: V2V-Intersection Protocol

WAVE: Wireless Access in a Vehicular Environment

Chapter 1

Introduction

Road intersections are currently managed by stop signs or traffic lights. These technologies were designed to manage traffic and increase the safety at intersections, but there is a growing concern about their efficiency and safety. Each year, more than 2.8 million intersection-related crashes occur in the United States, accounting for more than 44% of all reported crashes [1]. In addition, the delays introduced by stop signs and traffic lights significantly increase trip times. This leads to a huge waste of human and natural resources. The 2011 Urban Mobility Report, published by the Texas Transportation Institute, illustrates that the amount of delay endured by the average commuter was 34 hours which costs more than $100 billion each year in the U.S. [2]. Our goal is to introduce new intersection management methods to increase safety by avoiding vehicle collisions at intersections, and also increase the throughput of the intersections and decreasing the delays faced by each vehicle.

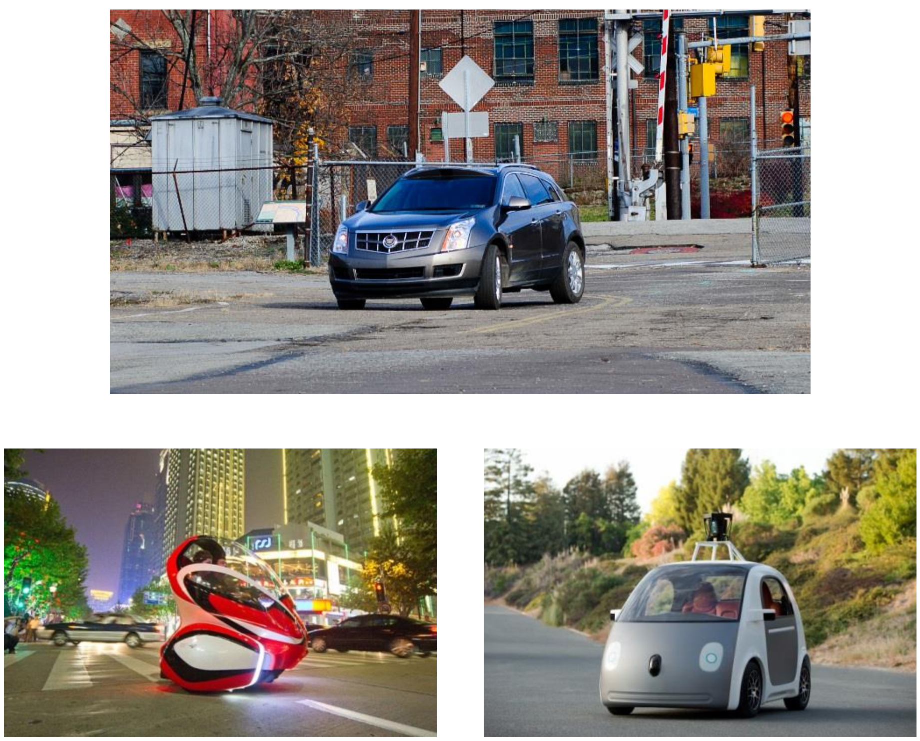

Figure 1-1: CMU's Autonomous Vehicle, GM's EN-V and Google's Car

One of the biggest recent advances in Cyber-Physical System (CPS), which aims among other challenges to increase the safety and comfort of road transportation, is the introduction of the autonomous vehicle concept. Autonomous driving is progressing rapidly and is generally expected to play a significant role in the future of automotive transportation. Various autonomous vehicles successfully demonstrated at the DARPA Urban Challenge, CMU's new self-driving vehicle, GM's EN-V and Google's car shown in Figure 1 are only some of the examples of this arising technology [6], [7], [31]. We consider this to be a major opportunity to introduce new methods which are suitable for autonomous driving at intersections and roundabouts, and thereby provide safe and efficient solutions to traffic congestion.

1.1 Thesis Statement

A fusion of vehicular networks and vehicle-resident sensing enables co-operative driving among autonomous and manual vehicles, leading to safety and high throughput at intersections.

The enabled co-operative driving technology will also be applicable and beneficial to a wide range of active safety applications for various driving scenarios such as lane-changing and highway merging. However, in this dissertation, our focus will be on driving at intersections and roundabouts which are considered to be the bottlenecks of urban transportation.

In this dissertation, we will first study the problem of managing the passage of autonomous vehicles through road intersections and roundabouts. We will then study the safe co-existence of manual and autonomous vehicles at cross-roads. To tackle these challenges, we will introduce a family of protocols called STIP (Spatio-Temporal Intersection Protocols). We develop the STIP framework which incorporates vehicular networks to enable co-operative driving. STIP safely and efficiently manages the transition of manual and autonomous vehicles through intersections and roundabouts, and guarantees deadlock-freedom of the system.

STIP enables vehicles to safely and efficiently cross the intersections in different types of traffic environments that fall into one of the following two categories:

- **Homogeneous traffic:** This type of traffic only consists of connected autonomous vehicles. The proposed approach leverages the capability of these vehicles to interact with each other through vehicular networks. Vehicles use their Dedicated Short Range Communication (DSRC) devices to broadcast and receive our proposed intersection safety messages and make decisions regarding their movement behavior in a completely distributed manner.

- **Heterogeneous traffic:** This type of traffic includes autonomous vehicles as well as human-driven cars. Our proposed approach benefits from infrastructure at the intersection, vehicular networks and on-board sensors to enable the safe co-existence of autonomous and human-driven vehicles.

1.2 Scope of the Thesis

We assume that autonomous driving at intersection cross-roads and roundabouts can be categorized into the following two traffic environments.

1.2.1 Homogeneous Traffic

This category only consists of connected autonomous vehicles and no human-driven vehicle is a part of the traffic flow. We will introduce two sets of intersection protocols for managing the homogeneous traffic through intersections and roundabouts:

- **V2V-Intersection protocols:** These completely distributed protocols rely on vehicle-to-vehicle (V2V) communications and localization to avoid vehicle collisions at intersections by controlling and navigating them within the intersection area. Autonomous vehicles approaching an intersection use Dedicated Short Range Communications (DSRC) and Wireless Access in a Vehicular Environment (WAVE) [8] to periodically broadcast information such as position, heading and intersection crossing intentions to other vehicles. The vehicles then decide among themselves regarding who crosses first, who goes next and who waits.
- **Synchronized movement-intersection protocols:** It is designed to increase the parallelism at intersections by allowing the concurrent crossing of vehicles arriving from all directions. This spatio-temporal method enforces synchronized and staggered arrival patterns of vehicles at intersections. This allows vehicles to cross the intersection without stopping or slowing down, and maximizes the capacity utilization of the intersection space.

As in any distributed system, our distributed intersection protocols can be affected by deadlock and starvation conditions. Therefore, it is important to consider these possibilities and potentially propose techniques to avoid them. We formally prove the deadlock-freedom properties of our family of intersection protocols.

Communication reliability is crucial for safety applications such as intersection collision avoidance. High packet loss will affect the approaching vehicles' communication across the intersection corners. In urban intersections, signal propagation within DSRC channels may be affected by fading. Line-of-Sight (LOS) conditions are not always available due to the presence of tall buildings and other obstacles at intersection corners [14], [15], [16]. On the other hand, when dealing with dense traffic volumes, in which all approaching vehicles are broadcasting safety messages, packet collision can become a severe problem and even lead to channel congestion. Therefore, we will consider these communication failures in designing our intersection protocols. To achieve this goal, we will make use of realistic DSRC propagation and MAC models.

Additionally, localization and positioning accuracy plays an important role in safety applications. GPS position inaccuracy affects various distance measurements and may lead to vehicle collisions inside and outside of the intersection/roundabout area. Therefore, we will study the effects of position inaccuracy on our STIP framework by using realistic GPS models.

1.2.2 Heterogeneous Traffic

In this category, we deal with a mixed traffic flow, which includes both autonomous and human-driven vehicles. In contrast to homogeneous traffic, in which all vehicles are assumed to be equipped with communication devices, not all human-driven vehicles are able to transmit and receive safety messages. Therefore, we will develop intersection management protocols which make use of vehicular networks along with on-board sensor systems such as cameras, radars and lidars.

In order to guarantee the safe crossing of autonomous and human-driven vehicles through the intersection, it is also important to consider human errors and rule violation scenarios such as red-light violation. To tackle these concerns, we will study their effects on our proposed protocols and suggest methods for violation detection and appropriate reactions to avoid consequent collisions.

In urban areas, it is critical to consider the presence of big obstacles such as tall buildings at intersection corners which decrease the effective range of the on-board sensors. This will limit an autonomous vehicle’s ability to detect the presence of human-driven vehicles at other legs of the intersection.

Therefore, we will introduce occlusion detection models and propose intersection management protocols which deal with these limitations.

1.3 Approach Overview

In this section, we describe our proposed approach. As mentioned in the previous section, our work can be grouped into one of the following two categories: (1) homogeneous traffic and (2) heterogeneous traffic.

1.3.1 Homogeneous Traffic

As mentioned in Section 1.2, in the homogeneous traffic category, we only consider connected autonomous vehicles. Each autonomous vehicle is assumed to be equipped with a digital road-map database, a DSRC radio, a navigation system and an autonomous vehicle controller. The map database stores map data with specific information about intersections, such as the number of lanes, and lane travel patterns. The map database operates in association with the navigation system to display the various maps and other information that is available, and allows a user to input, plan and display a route. Also, the map database can store the intersection-related information such as the number of entering/exiting lanes from each direction and also the allowed travel directions for each lane. The controller controls the operation of the vehicle, including steering, brake, throttle, etc. The vehicle also includes a wireless interface that allows the vehicle to wirelessly transmit information and receive information from many sources, such as the internet, satellite or a wireless infrastructure. The wireless interface also supports V2I and V2V communications.

We have designed two families of protocols to manage the safe and efficient passage of the homogeneous traffic through intersections and roundabouts: (1) V2V-Intersection Protocols (V2V-IP). (2) Synchronized Movement-Intersection Protocols (SM-IP). In both categories, our protocols can in the future replace current intersection technologies such as stop signs and traffic lights, with safer and more efficient methods.

V2V-Intersection Management at Intersections

These protocols benefit from Vehicle-to-Vehicle (V2V) communications as a part of vehicular networks to enable co-operative driving of autonomous vehicles at intersections. These fully distributed protocols will allow vehicles to interact with each other and safely cross the intersection areas while increasing the overall throughput. These protocols will be described and evaluated in Chapters 4.

We have deigned a scheme called CDAI (Collision Detection Algorithm at Intersections) which is used by each vehicle to detect any potential conflicts with other approaching vehicles along their trajectories through the intersection. CDAI runs on all vehicles, using the information obtained from received safety messages which are being broadcast by surrounding vehicles. CDAI is explained in details in Chapter 3.

All versions of our V2V-IP protocols are designed to allow simultaneous crossing of vehicles from different directions to increase the throughput of the intersection without sacrificing the safety. We have categorized our V2V-IPs based on the actions taken by *potentially conflicting* vehicles to avoid collisions. We will describe three generations of V2V-IP:

(1) Low-Concurrency Protocols (LCP): In this category, the *potentially conflicting* vehicle with higher priority can ignore the intersection safety messages from other lower-priority vehicles and cross the intersection without slowing down or stopping. However, any lower-priority vehicle is cautious and, when it loses a competition, it comes to a complete stop before entering the intersection boundaries and waits.

(2) High-Concurrency Protocols (HCP): The main goal of HCP is to increase parallelism inside the intersection area by allowing more vehicles to cross the intersection at the same time. To achieve this scheme's goal, we focus on allowing even potentially conflicting vehicles to make maximal progress inside the intersection area, without sacrificing the primary goal of safety. In contrast to LCP, in which lower-priority vehicles should stop before entering the intersection box and wait for the higher-priority vehicle to clear the intersection area, HCP plans to allow all vehicles to progress and only stop before the potential conflicting point.

(3) High-Concurrency Protocols with Enhanced Vehicle Dynamics (HCP-EVD): In both MCP and HCP categories, *potentially conflicting* vehicles with lower priority must come to a complete stop outside or inside the intersection area to allow the safe passage of higher-priority conflicting vehicle. When the vehicle comes to a complete stop inside or outside of the intersection box, it needs to start again and accelerate to reach its desired speed. The delay due to stopping and starting again depends on the vehicle's dynamics such as its acceleration parameter. This delay is not negligible, and multiple stops and moves increase the trip time of the vehicle.

We have designed the HCP-EVD scheme to decrease the delays due to complete stops, decrease air pollution and also to increase the fuel efficiency of vehicles. Additionally, avoiding numerous stops will increase the comfort of passengers. To achieve these goals, HCP-EVD protocols allow lower-priority conflicting vehicles to slow down while approaching an intersection and prior to reaching the conflicting cell, to provide the higher priority-vehicle with necessary time gap to cross. This will minimize a vehicle's need to get to a complete stop, and also the total number of stops and startups will be decreased significantly.

To choose the most suitable approach among the above V2V-IP generations, we consider various factors such as traffic load, communication reliability and available map and positioning accuracy.

V2V-Intersection Management at Roundabouts and Cascading Intersections

A roundabout is a channelized intersection with one-way traffic flow circulating around a central island. Roundabouts are also considered as "traffic-calming" devices since all traffic is slowed to the design speed of the one-way circulating roadway. In addition to slower speeds, roundabouts have fewer conflict points than traditional intersections. Therefore, it is established that roundabouts are safer than junctions [3, 4]. While statistics collected by the Insurance Institute for Highway Safety (IIHS) show that when comparing roundabouts to signalized intersections, the number of accidents is decreased by 40% and delays are reduced up to 20% [5], by using V2V communications as a part of co-operative driving, we are able to further improve the safety and significantly reduce delays. These protocols are described and evaluated in Chapter 5.

In our scheme, the roundabout area is considered to be a grid which is divided into small cells. The cell geometry and number of cells is unique for each particular roundabout and depends on the physical parameters of the roundabout area, such as the radius of the intersection and the size of its central island. The cell geometry is also determined based on the number of lanes entering the roundabout from each direction. All approaching vehicles broadcast specific safety messages, which contain information regarding their position, speed and their intent at the roundabout. A distributed algorithm then runs on all vehicles, using the information obtained from received safety messages, which are broadcast by surrounding vehicles. The algorithm determines if there is any potential collision between any two vehicles' trajectories while crossing the roundabout. Our method to be presented in Chapter 5 will to manage the behavior and movement of each vehicle depending on potential conflicts with other approaching vehicles. Our protocols will be designed to avoid collisions inside the roundabout area, as it prevents vehicles to enter the conflicting cells. Additionally, our protocols will benefit from the gaps in the traffic flow to allow more vehicles to enter the roundabout, and therefore, increase the overall traffic throughput.

In Chapter 5, we also extend our V2V-Intersection Protocols (V2V-IP) to be suitable for managing the traffic not only at a single isolated intersection, but at multiple intersections along the vehicles trajectory from its source of travel all the way to the its destination. Traffic management through intersection cascading has its own challenges that need to be addressed. For example, traffic congestion can happen at the exit lanes of intersections due to different reasons and this congestion will be propagated to previous intersections. In addition to the congestion propagation, congested exit lanes can lead to road blockage inside the intersection box and starvation of vehicles approaching from perpendicular directions. Our approach is to avoid any blockage and starvation situation at any of the intersections that constitute a cascading intersection.

V2V-Intersection Management Challenges

Our V2V-Intersection Protocols (V2V-IP) face various challenges. Our approach is to study the main challenges, evaluate the effect of these challenges and provide practical solutions. Our methods will be described and evaluated in Chapter 6.

We have looked at three different challenging aspects of our protocols:

1) **Communication Failure:** Channel impairments such as fading and packet collisions will decrease the communication reliability by increasing the packet loss ratio. Therefore, a high rate of packet loss will affect the communication as vehicles do not receive the information soon enough to avoid collisions at the intersection. We will study the impact of imperfect V2V communication on our intersection protocols and how to deal with them. When dealing with busy urban intersections in which the traffic is dense, a high number of safety messages is broadcast, and results in higher channel load and may lead to channel congestion. We will discuss how to evaluate such environments in this thesis in Chapter 6.

2) **Positioning Inaccuracy:** We will take into consideration in Chapter 6 the position information accuracy provided by on-board GPS devices. We study the impact of such errors on our intersection protocols and propose some techniques to overcome such inaccuracies. To avoid collisions outside the intersection grid, our method introduce safety buffers among following vehicles which prevents vehicles from getting very close to each other and gives them the capability to slow down without causing an accident when the leader vehicle brakes suddenly. Additionally, for inside the intersection grid, we will introduce an appropriately sized safety cell buffer as a function of the GPS error characteristics. The safety cell buffer will be designed to allow more cell space between potentially conflicting vehicles inside the intersection area when dealing with higher levels of positioning inaccuracy.

3) **Deadlock:** A deadlock situation can occur inside the intersection area, among the vehicles which are trying to cross the intersection at the same time. We will investigate possible deadlock scenarios, in which all vehicles progress inside the intersection area as much as possible without getting into a collision. Therefore, we will define a set of rules as a part of our V2V-Intersection Protocols to avoid deadlock and guarantee the liveliness of the system. Additionally, we will present mathematical proofs for the deadlock-freedom of our proposed system.

Synchronized Movement-Intersection Management

We will propose a spatio-temporal method in Chapter 7 to manage traffic at intersections by synchronizing the arrival of autonomous vehicles and allowing their efficient and continuous crossing. The goal of our approach is to enhance the capacity utilization and increase parallelism at intersections and also increases the passenger comfort, by reducing the delays faced by each vehicle due to multiple stop-and-go movements.

An arrival synchronization pattern is known or broadcast to all approaching vehicles. This includes the information regarding the turn restrictions for all traffic lanes arriving from different directions and the desired entrance speed which will be maintained throughout the intersection. It also includes the permitted synchronized and staggered time slots during which vehicles can enter the intersection area. This allows each vehicle to choose the correct lane based on its turning intentions, adjust its speed and enter the intersection box during a permitted time slot.

To deal with anomalies such as vehicle breakdowns, flat tires or other mishaps V2I and/or V2V wireless communications can be employed. Anomalies can also include passage of emergency vehicles such as police cars, ambulances and fire trucks. V2I and/or V2V wireless communications can be used for recovery and collision avoidance in case of such anomalies. Once the transient has passed, normal operation resumes.

1.3.2 Heterogeneous Traffic

As mentioned earlier in Section 1.2.2, heterogeneous traffic scenario consists of both manually-driven and autonomous vehicles. In Chapter 8, we will propose a framework to manage the heterogeneous traffic through intersections. Heterogeneous traffic consists of (1) Human-Driven Vehicles (HDV), which are controlled by human drivers and are *not* equipped with any communication devices or on-board sensors; (2) Enhanced Human-Driven Vehicles (EHDV), which are still controlled by human drivers while benefiting from ADAS. These vehicles are assumed to be equipped with a GPS receiver and a DSRC radio. Additionally a warning system is used to warn the driver to avoid dangerous road situations so that the driver can take actions in a timely manner and prevent collisions; (3) Autonomous Vehicles (AV), which are equipped with autonomous vehicle controllers and various information sources such as GPS receiver, digital road-map database, DSRC radio, and on-board sensors such as cameras, radars and lidars.

V2V-Intersection Management

First, we assume that the traffic consists of AVs (Autonomous Vehicles) and EHDVs (Enhanced Human-Driven Vehicles). Therefore, all vehicles are equipped with DSRC radios and are able to transmit and receive safety messages to and from other vehicles in their communication range. We will present a new scheme which enables the co-operative driving of AVs and EHDVS through intersections, and increases the safety and throughput of their passage. We have developed a scheme to benefit from all the available information and allow AVs to make the best and safest decision at an intersection and also provide EHDVs with a sophisticated warning system.

For both signalized intersection types, we will determine the best behavior of AVs in rule violation scenarios to avoid potential collisions with minimum possible impact on the throughput of the intersection. Additionally, EHDVS will benefit from a warning system which allows the fast reaction of the driver during potential rule violation scenarios using acoustic and visual alert messages on their safety displays.

Perception-Based Intersection Management

We study the characteristics of a mixed traffic of AVs and HDVs in Chapter 8. We have designed a method for the safe co-existence of AVs with HDVs at the intersection area. In contrast to the previous set of protocols, since HDVs are not equipped with DSRC radios, they are not capable of transmitting or receiving any messages including BSM (basic safety messages). This means that AVs cannot use V2V communications to gain information regarding the neighboring HDVs and should rely on other sources of information. In this thesis, we introduce a method in which, AVs will mainly use their on-board sensors such as cameras, radars and lidars to detect the presence of HDVs at the intersection area. Our protocol benefits from a distributed intersection management algorithm which runs on each autonomous vehicle and controls their behavior at the intersection.

Human errors play a significant role in car accidents. Therefore, we will propose various methods for autonomous vehicles to detect scenarios such as red-light violations by manually-driven vehicles. These schemes will benefit from AV's on-board sensors as well as the received information from intersection RSUs. To obtain the traffic light cycle durations, we suggest using smart traffic lights which are equipped with DSRC radios and periodically broadcast their status via SPaT (signal phase and timing) messages to all approaching vehicles [107], [108], [109]. The SPaT message format has been standardized by SAE J2735 [8].

Since these protocols mainly rely on perception and information obtained through on-board sensors, their coverage range and precision play an important role in the efficiency of this method. Another important aspect would be dealing with occlusion at intersection areas. The presence of tall buildings at the corners of urban intersections prevents the detection of approaching HDVs from occluded legs of the intersections. In Chapter 8, we propose to detect the occlusions using on-board sensors and digital road-map databases and propose the appropriate behavior of autonomous vehicles in the presence of occlusion.

Chapter 2

Literature Review

This chapter describes some existing work related to this dissertation.

2.1 Autonomous Driving

Autonomous driving is introduced as the future of road transportation in order to increase the safety and comfort of passengers. With the recent advances in Cyber-Physical Systems (CPS), autonomous driving technology is progressing rapidly and its goals look more achievable than ever. Towards a fully autonomous vehicle, various Advanced Driving Assist Systems (ADAS) have been developed by car manufacturers. ADAS technologies such as adaptive cruise control and lane centering assist technology has also been developed to enhance freeway driving safety [32], [33], [54].

Since 1980s, multiple autonomous driving experimental platforms have been built which are able to deal with various driving scenarios, including distance keeping, lane changing and intersection handling [35], [36], [37], [38]. Google has also released its autonomous driving platform [39]. The main sensors are radars and a rotational multi-beam laser scanner installed on a customized roof-rack. The autonomous driving system has logged over 300,000 miles on public roads. The VisLab vehicle from Parma University crossed Europe and Asia autonomously in 2010 [40]. Vision technology is heavily used in this system and shows great potential. Another Parma University vehicle, BRAiVE, has improved sensor integration and user interface design [41].

Carnegie Mellon University (CMU) has built a series of experimental platforms since the 1990s which are able to run autonomously on freeways [42], but they can only drive within a single lane. In 2005-2007, the DARPA Grand Challenge and Urban Challenge provided researchers a practical scenario in which to test the latest sensors, computer technologies and artificial intelligence algorithms [43], [44]. A new, highly integrated autonomous vehicle has been developed and tested by CMU in a closed test field and public road for over a year. Experiments show that the platform design proposed in this paper is robust and easy for developers and end-users to operate. The vehicle is equipped with redundant sensors and has the ability to perform everyday driving while maintaining an appealing appearance. The system also has reliability and fault-tolerance features [31], [45].

2.2 Safety Systems

Regardless of the level of autonomy in vehicles, safety has always been the biggest concern and the highest priority goal for urban transportation. Passive Safety systems such as seat-belts and air-bags were introduced to avoid fatalities and injuries after vehicle collisions. In order to eliminate the source of these fatalities and injuries, active safety and advanced driver assist systems such as blind spot detection and adaptive cruise control were designed to avoid vehicle collisions in the first place [52], [53], [55].

2.2.1 Vehicle-resident Sensing

To enable various active safety applications, car manufacturers have introduced driver assist systems which mainly rely on on-board sensors. The vehicle-resident sensing system can include multiple components such as cameras, radars and lidars.

Radar is an object-detection system that uses radio waves to determine the range, altitude, direction, or speed of objects. The radar dish (or antenna) transmits pulses of radio waves or microwaves that bounce off any object in their path. The object returns a tiny part of the wave's energy to a dish or antenna that is usually located at the same site as the transmitter. Radar has been widely used in automotive applications for decades. It has the ability to detect obstacles' positions and speeds directly. However, radar outputs are usually not informative enough to estimate obstacle shape [49].

Lidar (also written LIDAR, LiDAR or LADAR) is a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light. The term lidar was actually created as a portmanteau of light and radar [50], [51]. Lidar is popularly used as a technology to make high-resolution maps. Autonomous vehicles use lidar for obstacle detection and avoidance to navigate safely through environments. Cost map or point cloud outputs from the lidar sensor provide the necessary data for robot software determine where potential obstacles exist in the environment and where the robot is in relation to those potential obstacles. The data provided by LIDAR are usually a cloud of 3D points dense enough for the shape of cars, pedestrians, curbs, non-drivable areas and more information to be extracted. However, LIDAR's cost, sensing range, robustness to weather conditions and velocity measurement accuracy are not as good as radar's.

Cameras are the most cost-effective sensor for automotive applications. Camera data are very informative, especially for detecting lane markings, signs and traffic lights with texture and color features. There are various camera-based active safety systems which are growing rapidly such as Back-up Camera, Lane Departure and Forward Collision Warning and Blind Spot Detection. However, false-positive and recognition failure rates are much higher for vision than for LIDAR and radar.

Vehicle-resident sensing systems present some limitations as mentioned earlier. Additionally, their effective ranges comparing to the human-driver's vision cannot be easily extended without compromising their accuracy and reliability. Additionally, their performances suffer from various conditions such as reflective surfaces in surrounding vehicles and occlusion from various road obstructions. To overcome these limitations, the concept of Vehicle-to-Vehicle and Vehicle-to-Infrastructure communications was introduced and considered as the natural extension to sensor-based active safety systems. V2X communications could provide vehicles with high-quality data and deliver important information beyond on-board sensors' field of view or range [9], [10], [11].

In this thesis, we propose intersection management methods that use the sensor fusion of all the components of the perception system to achieve the goal of safe and efficient co-existence of autonomous and manually-driven vehicles at road intersections.

2.2.2 V2X Safety Applications

CAMP (Crash Avoidance Metrics Partnership) was formed to accelerate the implementation of crash avoidance countermeasures in passenger cars to improve traffic safety [27], [28]. CAMP was the collaboration of OEMs (Original Equipment Manufacturers) and NHTSA (National Highway Traffic Safety Administration). Their main focus was in identifying high risk road transportation scenarios and how to save lives by introducing safety application solutions. Vehicle-to-vehicle (V2V) as well as Vehicle-to-Infrastructure (V2I) has been used for collision avoidance on the road in CAMP project but managing the traffic intersections using V2V or V2I has not been in their focus. Figure 2.1 illustrates the 8 high-priority co-operative vehicular safety applications defined by CAMP.

Safety Application	**Type**	**Freq.**	**Data Transmitted**	**Function**
Traffic Signal Violation	V2I	10 Hz	Signal phase-timing, position, direction, road geometry	Warns the driver when violating a red light seems imminent.
Curve Speed Warning	V2I	1 Hz	Curve location, curvature, slope, speed limit, surface	Warns the driver when approaching a curve beyond current safe limits of the road and vehicle.
Emergency Brake Lights	V2V	10 Hz	Position, heading, velocity, acceleration	Alerts the driver when a preceding vehicle performs a severe braking maneuver.
Pre-Crash Sensing	V2V	50 Hz	Vehicle type, position, heading, velocity, acceleration, yaw rate	Collects information regarding an impending collision and communicates this information to the vehicle's occupant protection system.
Forward Collision	V2V	10 Hz	Vehicle type, position, heading, velocity, acceleration, yaw rate	Aids the driver in avoiding or mitigating collisions with rear-end of vehicles in the forward path of travel through driver notification or warning of the impending collision.
Lane Change Warning	V2V	10 Hz	position, heading, velocity, acceleration, turn signal status	Provides a warning to the driver if an intended lane change may cause a collision with a nearby vehicle.
Left Turn Assist	V2I or V2V	10 Hz	Signal phase, timing, position, direction, road geometry	Provides information to drivers about oncoming traffic to help them make a left turn at a signalized intersection without a phasing left turn arrow.
Stop Sign Assist	V2I or V2V	10 Hz	Position, heading, velocity	Provides a warning to a vehicle that is about to cross through an intersection after having stopped at a stop sign.

Figure 2-1: 8 High-priority V2X Safety Applications

Vehicle-to-Vehicle Communications (V2V) for Safety is the dynamic wireless exchange of data between nearby vehicles that offers the opportunity for significant safety improvements. By exchanging anonymous, vehicle-based data regarding position, speed, and location, V2V communications enables a vehicle to: sense threats and hazards with a 360 degree awareness of the position of other vehicles and the threat or hazard they present; calculate risk; issue driver advisories or warnings; or take pre-emptive actions to avoid and mitigate crashes. At the heart of V2V communications is a basic application known as the *Here I Am* data message. This message can be derived using non-vehicle-based technologies such as GPS to identify location and speed of a vehicle, or vehicle-based sensor data wherein the location and speed data is derived from the vehicle's computer and is combined with other data such as latitude, longitude, or angle to produce a richer, more detailed situational awareness of the position of other vehicles. Because the *Here I Am* data message can be derived from non-vehicle-based technologies that are ubiquitous within the marketplace, the ITS Program may leverage an opportunity to accelerate V2V capability and deployment in the near-term and produce safety benefits through reduced crashes sooner than through OEM embedded systems only [62], [63].

The vision for V2V is that eventually, each vehicle on the roadway (inclusive of automobiles, trucks, buses, motor coaches, and motorcycles) will be able to communicate with other vehicles and that this rich set of data and communications will support a new generation of active safety applications and safety systems. V2V communications will enable active safety systems that can assist drivers in preventing 76 percent of the crashes on the roadway, thereby reducing fatalities and injuries that occur each year.

V2V communications for safety is a key component of the connected vehicle research program within the Intelligent Transportation Systems Joint Program Office (ITS JPO) of the U.S. Department of Transportation (USDOT) Research and Innovative Technology Administration (RITA).

The four major objectives of the V2V communications for safety program are:

- Develop V2V active safety applications that address the most critical crash scenarios.
- Develop a rigorous estimation of safety benefits that will contribute to the assessment of a 2013 National Highway Traffic Safety Administration (NHTSA) agency decision.
- Work with industry and enable market factors that will accelerate V2V benefits through in-vehicle V2V technologies and through the use of aftermarket and/or retrofit options to ensure that the first V2V-equipped vehicle owners find value in their investment.
- Building from the results of the VII program's proof-of-concept tests, complete the development and testing of the V2V communications technologies and standards.

Since 2002, the USDOT has been conducting research with automotive manufacturers in order to assess the feasibility of developing effective crash avoidance systems that utilize vehicle-to-vehicle communications. Engineering prototypes have been developed and demonstrated with applications that address the most critical crash scenarios which are:

- Emergency Brake Light Warning
- Forward Collision Warning
- Intersection Movement Assist
- Blind Spot and Lane Change Warning
- Do not pass Warning
- Control Loss Warning

The development of these applications was critical to understanding the functional and performance requirements for the underlying technologies such as positioning and communications. However, additional work needs to be done to address more complex crash scenarios for head-on collision avoidance, intersection collision avoidance, pedestrian crash warning and extending the capabilities to prevent motorcycle crashes. It is important to note that these capabilities could be achieved by providing V2V communication capabilities that complement other vehicle-based safety technologies.

The concept of V2V active safety applications requires each vehicle to periodically broadcast safety messages to its surrounding vehicles. This includes information such as vehicle's speed, heading, position and its physical characteristics such as the vehicle size and break status. The idea is that one type of safety message would be used in various safety applications. To standardize the format of the safety messages, the Basic Safety Message (BSM) was specified as part of the DSRC Message Set standard, SAE J2735 [8].

2.2.3 Intersection Management

Road intersections are currently managed by infrastructures such as stop signs [87], [88] and traffic lights [89], [90]. They main goal was to provide a safe passage of approaching vehicles through the intersection area. However with the high number of accidents and therefore fatalities and injuries around the intersection areas, there is a growing concern regarding the safety and the suitability of these techniques for the current urban transportation [86], [91].

Additionally, various methods have been proposed and implemented specially for the traffic light intersections in order to increase the efficiency and throughput of the traffic. A green wave occurs when a series of traffic lights are coordinated to allow continuous traffic flow over several intersections in one main direction. Any vehicle travelling along with the green wave will see a progressive cascade of green lights, and not have to stop at intersections. This allows higher traffic loads, and reduces noise and energy use. In practical use, only a group of cars can use the green wave before the time band is interrupted to give way to other traffic flows. The coordination of the signals is sometimes done dynamically, according to sensor data of currently existing traffic flows - otherwise it is done statically, by the use of timers. Under certain circumstances, green waves can be interwoven with each other, but this increases their complexity and reduces usability, so in conventional set-ups only the roads and directions with the heaviest loads get this preferential treatment [76], [77].

Most existing traffic control systems are based on complex mathematical models that determine the above variables in order to optimize traffic flow in specific settings. Two well-known systems, SCATS (Sydney Coordinated Adaptive Traffic System) [84] and SCOOT (Split, Cycle and Offset Optimization Technique) [85], follow this methodology. These systems have detectors placed on every approach to an intersection, usually at a single point of the road or at two points for calculating the size of the queue. Thus, they cannot get accurate data when this queue grows beyond the length between detectors, or the link is oversaturated. Since they use a model based especially on occupancy, they also have difficulties in differentiating between high flows or intersection stoppage. A further optimization of adaptive traffic lights was proposed in [86], where an adaptive traffic light system based on wireless communication between vehicles and a wireless controller node placed at the intersection. As compared to the approaches mentioned previously, the adaptive traffic light system includes more information (e.g., vehicles' positions and speeds) in the signal decision process. As a result, this approach overcomes the shortcomings of traditional systems that can result from the fixed location of the detectors.

A pilot project to incorporate traffic signal technology with artificial intelligence is currently being developed by Traffic21, a research program affiliated with Carnegie Mellon University. The new technology functions similarly to adaptive signal control, a system of fiber optic video receivers that allow controllers to monitor and change traffic signals in real time to account for situational changes in traffic patterns. However, in the case of this study, the series of signals relay information to each other, changing the lights without the need for human operators. Traffic21 researchers use the city of

Pittsburgh, Pennsylvania, to test their fully integrated traffic strategies and designs. In the case of their adaptive traffic control system, the smart signals were installed at nine intersections in the city's congested East Liberty section to try to cut down on air pollution. The results, the AP reported, were significant: motorists spent less time idling and more time moving, time spent stopped at the lights was reduced by 40 percent, and overall travel time was also decreased by 26 percent. This marked drop in wait time and decrease of wasted fossil fuels had a projected 21 percent reduction in the motor vehicular emissions that were tested [78], [83].

Ferreira et al. [79], [80] have proposed a method to replace the current traffic light infrastructure by the migration of traffic lights as roadside-based infrastructures to in-vehicle virtual signs supported only by vehicle-to-vehicle communications. They have design a virtual traffic light protocol that can dynamically optimize the flow of traffic in road intersections without requiring any roadside infrastructure. Elected vehicles act as temporary road junction infrastructures and broadcast traffic light messages that are shown to drivers through in-vehicle displays. Distributed car control has been proposed repeatedly as a solution to safety and efficiency problems in ground transportation.

With the recent advances in autonomous driving technology it is crucial to focus on the difficulties faced by these vehicles on the roads. As mentioned earlier, road intersections are considered the bottlenecks of urban transportation and will be one of the most challenging missions for the future autonomous vehicles. Therefore, intersection crossing by autonomous vehicles has become a focus of many researches in the CPS community.

Dresner et al. [19], [20], [21] proposed the use of Vehicle-to-Infrastructure (V2I) communications for managing the traffic at intersections. As the word infrastructure implies, the system mainly consists of an intersection manager, which is an intelligent and powerful computational and communicational unit which would be installed at each intersection. All vehicles approaching an intersection communicate with the intersection manager. Intersection manager reserves a safe time-space passage through the intersection for each vehicle, and communicates the reservation parameters back to vehicles. Installing such a powerful centralized infrastructure at every intersection is somewhat impractical due to the prohibitively high total system costs. Another drawback is that as in all centralized systems, the intersection manager is a single point of failure. Therefore, if the intersection manager fails, vehicles must somehow coordinate on their own. In this situation crossing the intersection could be chaotic and dangerous, similar to signal breakdown at a busy intersection.

More recent works in managing the intersections using V2I focus mainly on solving the potential trajectory conflicts by a smart intersection infrastructure entity and make reservations for each vehicle's traversal [22][29][30], [93], [94]. Although each of these approaches has its own benefits, they suffer from the mentioned limitations and drawbacks.

To address these shortcomings, in this thesis we propose that Vehicle-to-Vehicle (V2V) communications can be used as a part of a distributed system in which all the approaching autonomous vehicles are interacting with each other. Therefore, each car can make decisions about when to cross the intersection safely and efficiently. These protocols are also suitable for managing the traffic through roundabouts. Our V2V-safety systems can also be beneficial for manually-driven vehicles equipped with DSRC devices to receive and transmit the safety messages, and a warning system to display safety messages and warn the human driver in case of danger situations at the intersection to prevent potential collisions.

We have also designed intersection management methods which are suitable for heterogeneous traffic, in which not all manually-driven vehicles are equipped with DSRC devices. Therefore, pure V2V or V2I cannot replace the need for infrastructure to manage the intersection area. In this case, in addition to benefiting from V2X communications, we leverage the use of vehicle's perception system and the current infrastructure to provide the safe co-existence of autonomous and manually-driven vehicles, while significantly increasing the throughput.

2.2.4 Dedicated Short Range Communication (DSRC)

To pursue the goals of V2X active safety, Dedicated Short Range Communication (DSRC) was introduced and FCC allocated 75MHz of spectrum in the 5.9GHz band to be used only for Intelligent Transportation Services (ITS). Comparing to on-board sensors, DSRC devices are expected to be less costly, which increases the feasibility and affordability of the related active safety applications [8], [9]. In Europe, a 30 MHz wide frequency spectrum was allocated by the Electronic Communications Committee (ECC) in August 2008, with a possible extension to 50 MHz [34].

In the physical layer, like 802.11a, 802.11p leverages OFDM to compensate for both time and frequency-selective fading. Unlike 802.11a, however, 802.11p will be used in drastically different environments. In contrast to IEEE 802.11a which is intended for short range, low mobility and indoor use, 802.11p will encounter medium ranges, extremely high mobility, and rapidly changing channel conditions [46].

There are two major changes in the physical layer specifications of 802.11a to deal with the requirements of 802.11p's environment characteristics. Firstly, DSRC will operate at a slightly higher frequency band than 802.11a. Its allocated bandwidth of 75 MHz spans 5.850 GHz to 5.925 GHZ, while 802.11a operates in the 5.170–5.230 GHz and 5.735–5.835 GHz bands. The DSRC band is largely free of interference from competing wireless devices, as it is not designated for ISM (industrial, scientific, medical) usage. Because the primary motivator behind DSRC is safety-related communications, regulators wished to minimize extraneous interference as much as possible. Secondly, the DSRC standard reduces channel widths to 10 MHz from the 20 MHz width of 802.11a. This has a number of cascading side effects, some of which aid in compensating for vehicular wireless channels. By using narrower channelization while keeping the number of occupied subcarriers constant at 52, the spacing between subcarriers has been halved to 156.25 kHz. This new spacing, in turn, results in a longer fast Fourier transform (FFT) interval (6.4 µs) and guard interval (1.6 µs). Consequently, the length of OFDM symbols doubles from4 µs at 20 MHz to 8 µs at 10 MHz.

For the medium access layer, the main difference between IEEE 802.11 compared to other IEEE 802.11 networks is the ability to communicate outside the context of a basic service set to enable communication in an ad-hoc manner in a highly mobile network. The IEEE 802.11 authentication and association processes preceding a first frame exchange would last too long, e.g. in the situation of communication between two vehicles with opposing driving direction. Consequently, authentication and association are not provided by the IEEE 802.11p PHY/MAC, but have to be supported by the station management entity (SME) or a higher layer protocol. IEEE 802.11p adds the mode of communication outside a BSS into the standard as this way of operation was not foreseen. The communication outside of a BSS reduces the functionality of MAC to the basic needs.

An important aspect for vehicular communications concerning safety will be the prioritization of important safety and time-critical messages over the ones that do not directly concern safety. IEEE 802.11p therefore specifically adapts enhanced distributed channel access (EDCA) that was originally proposed in the IEEE 802.11e amendment of the standard, introducing quality of service (QoS) support. The medium access rules defined by the DCF are replaced by the ones of EDCA, where four different access categories (AC) are defined. Each frame is assigned one of the four access categories by the application creating the message, depending on importance and urgency of its content.

Our V2V-Intersection Protocols leverage Vehicle-to-Vehicle (V2V) communications to enable the co-operative driving of autonomous vehicles and allow their safe passage through intersections. Communication failure affects the reliability of the V2V-based safety applications. Impairments such as packet loss due to fading, packet collisions and channel congestion in vehicular environments have been extensively studied by researchers and there is a wealth of literature in this domain [14], [15], [16], [17], [18]. Empirical models have been proposed to be used for simulation purposes to get more realistic and accurate results for DSRC related applications [56], [57], [58], [59], [61]. We have used various empirical models and different methods to study the impact of the communication failure on our V2V-safety applications and measure their reliability levels.

2.2.5 Simulation Platforms

There is a number of Vehicular Ad-hoc Network (VANET) simulators used in this research community. Simulations are commonly used as a first step in the protocol development for VANET research. Several networking simulation tools exist to provide a platform to test and evaluate network protocols, such as ns-2 [48], [60][66], OPNET [67]and Qualnet [68]. However, these tools are designed to provide generic simulation scenarios without being particularly tailored for applications in the transportation environment. On the other hand, in the transportation arena, simulations have also played an important role. A variety of simulation tools such as PARAMICS [69], CORSIM [70], VISSIM [71], MOVE [73], [73] and etc. have been developed to analyze transportation scenarios.

Geographical Routing of Vehicular Networks (GrooveNet) [25], [26] is a sophisticated hybrid vehicular network simulator that enables communication among simulated vehicles, real vehicles and among real and simulated vehicles. By modeling inter-vehicular communication within a real street map-based topography, GrooveNet facilitates protocol design and also in-vehicle deployment. GrooveNet's modular architecture incorporates multiple mobility models, trip models and message broadcast models over a variety of links and physical layer communication models. It is easy to run simulations of thousands of vehicles in any US city and to add new models for networking, security, applications and vehicle interaction. GrooveNet supports multiple network interfaces, GPS and events triggered from the vehicle's on-board computer. Through simulation, message latencies and coverage under various traffic conditions can be studied.

New models can easily be added to GrooveNet without concern of conflicts with existing models as dependencies are resolved automatically. Three types of simulated nodes are supported: (i) vehicles which are capable of multi-hopping data over one or more DSRC channels, (ii) fixed infrastructure nodes and (iii) mobile gateways capable of vehicle-to-vehicle and vehicle-to-infrastructure communication. GrooveNet map database is based on the US Census Bureau's TIGER/Line 2000+ database format [47]. Multiple message types such as GPS messages, which are broadcast periodically to inform neighbors of a vehicle's current position, are supported. On-road tests over 400 miles within GrooveNet have lent insight to market penetration required to make V2V practical in the real world.

We have built the next generation of GrooveNet, called AutoSim. AutoSim is a hybrid simulator-emulator which enables interaction of simulated and real vehicles and benefits from various mobility, control, communication, GPS, perception and many more models [Chapter 9].

Chapter 3

Co-operative Driving

We believe that the co-operative driving of vehicles would be beneficial in various road transportation scenarios. These scenarios are not limited to intersection crossings, and the co-operative driving can provide safety and efficiency in various critical driving scenarios.

We will first look at an important driving behavior outside of the intersection area, where vehicles have to keep a safe distance while following a vehicle right in front of them. In the first subsection, we describe our distance keeping algorithm incorporating V2V communications. Secondly, another common behavior of vehicles is lane merging. This action is required in various traffic scenarios such as the time that a lane is ending or blocked due to various reasons, and therefore, vehicles must change lanes to continue their trajectories. Finally this chapter includes our distributed collision detection algorithm which runs on each vehicle to determine any potential collisions inside the intersection boundaries with other approaching vehicles.

3.1 V2V Distance-Keeping

In order to ensure a safe distance between cars before arriving at and after leaving the intersection area, a distance-keeping protocol known as the Car-Following Model is used. This model is designed to control the mobility of vehicles while moving towards, or after exiting the intersection. A safety message of type GENERIC is broadcast at a regular interval to all surrounding vehicles. This message contains information about a vehicle's position, velocity, current road and lane.

The following rules define the behavior of the receiving vehicle B on-reception of GENERIC safety messages from a neighboring vehicle A.

<u>Algorithm 3.1:</u> <u>Distance-Keeping Receiver Vehicle</u>

Input: GENERIC message from a vehicle A

Output: Set the *Desired Speed*

1. **If** $(Leader_B = A \text{ and } Dist_{B,A} < SafeDistance)$ **then**
2. $DesiredSpeed_B = CurrentSpeed_A$

, where $Leader_B$ is the leader of vehicle B, meaning the immediate vehicle in front of it. And $Dist_{B,A}$ is the distance between vehicles A and B.

As shown in Figure 3.1, vehicle B must first determine if vehicle A is its leader. The leader-vehicle is the first vehicle in front of it on the same road segment and the same lane. Therefore, on receiving the GENERIC message, each vehicle checks if it is on the same road segment and the same lane as the sender. If this is the case, then by comparing its current GPS position with the sender's position, the vehicle determines if the sender is in front or behind it. If multiple vehicles satisfy these conditions, only the vehicle with the shortest distance from the receiving vehicle, meaning the immediate vehicle in front of it, is its leader.

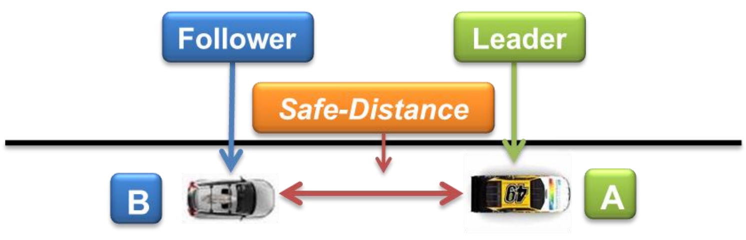

Figure 3-1: An example scenario of Distance-Keeping

In case of being behind the sender's vehicle, the vehicle adjusts its current velocity to the speed of the vehicle in front to maintain a safe distance and prevent any collisions. The vehicle does not need to have the same speed as the leader vehicle unless the distance between them is less than a threshold *Safe Distance*. Otherwise, it can maintain its current velocity which is enforced by the road's speed limit. The process of achieving the *Desired Speed* is fulfilled through the vehicle’s controller model which is unique to each vehicle based on its physical characteristics such as the acceleration and deceleration capabilities.

3.2 V2V Lane-Merging

Lane changing is inevitable when vehicle's current traveling lane is blocked due to various reasons such as lane ending, construction or parked vehicles. In these cases, the vehicle must change its current lane by merging into the adjacent lane. To perform a safe lane change and in order to merge into the adjacent lane without causing any accidents, vehicles must be aware of the other vehicles that are already traveling on the adjacent lane.

To avoid any potential collisions among vehicles while performing a lane change, we have designed a simplistic *V2V lane-merging* algorithm. This protocol incorporates the use of GENERIC safety messages and *V2V distance-keeping*, and allows the safe lane changing when necessary.

Figure 3.2 shows an example in which vehicle A has to change its current lane due to a lane blockage along its trajectory. Vehicle A's current lane is $L_1$and is intending to switch lanes and move to the adjacent lane L_2. Each vehicle broadcasts its velocity, position and current lane information within the periodic GENERIC message to all its neighboring vehicles in its communication range. Vehicle A must update its current lane information before performing the lane-change to indicate and inform other vehicles about its intentions. Therefore, with an updated current lane, now vehicle A should perform car-following to the leader of the new lane L_2, which is the vehicle B. Therefore, vehicle A adjusts its speed by performing the *V2V Distance-Keeping* to keep a safe distance to the leader vehicle B before entering the adjacent lane. On-reception of the updated GENERIC safety messages from vehicle A, Vehicle C will also run the *V2V Distance-Keeping* algorithm and slow down to allow a safe distance between itself and vehicle A. Therefore, Vehicle A would be able to safely change its current lane and merge into the adjacent lane, positioning itself between vehicles B and C.

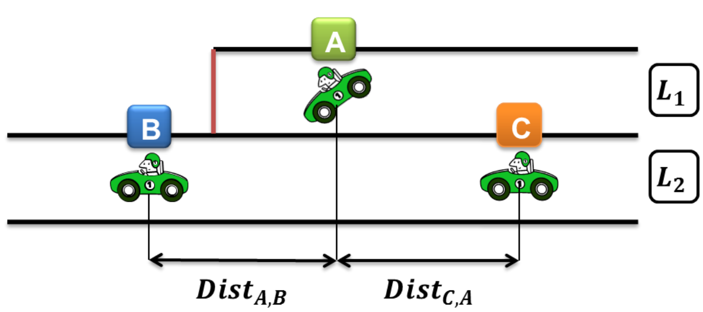

Figure 3-2: An example scenario for lane-merging

Video clips from AutoSim of an example scenario for V2V lane merging:

- https://youtu.be/l-UanzeCjcM
- https://youtu.be/y5ft4caJ1NE
- https://youtu.be/q4S5pInRiUo

3.3 Distributed Collision Detection

In this section we will introduce a method used by each vehicle to detect potential collisions with other vehicles approaching to the same intersection. We will first define a simplistic intersection model that will be considered to describe our intersection protocols in the following chapters. We will then describe our Collision Detection Algorithm for Intersections (CDAI), and provide definitions on how intersection state is calculated based on the vehicles distance to and from an approaching intersection [113], [114]. We finally describe the intersection safety messages, their format and content as a part of the Basic Safety Messages (BSM).

3.3.1 Intersection Model

We consider an intersection to be a big grid which is divided into smaller uniformly sized cells[1]. Figure 3.3 shows an example of an intersection grid with two entering lanes per direction. Each cell in the intersection grid is associated with a unique identifier.

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[1] In practice, road intersections have different shapes and sometimes irregular geometries with different number of lanes entering an intersection. In these cases, cell size and geometry will depend on each intersection's unique physical characteristics such as size and number of entering/exiting lanes. For the purposes of this thesis, without loss of generality, we only consider regular and uniform cell geometries for an intersection which is based on the lane width of each entering lane and can fit one vehicle inside it. When dealing with longer vehicles, intersection cells can be virtually merged to fit these vehicles inside them. As a future research direction, it would be interesting to use a dynamic notion of intersection cells, where the cell size and geometry is dependent on the crossing vehicles shapes as well as the traffic volume. In the case of heavy traffic, multiple cells can be virtually merged in order to fit more back-to-back vehicles in one intersection cell and enable platooning of these vehicles through the intersection area. As will be explained in Chapter 4 of this thesis, regardless of the intersection cell

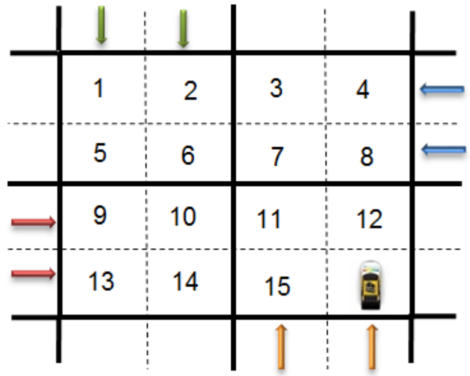

Figure 3-3: Intersection Grid

In the context of an intersection, we define the *current road segment (CRS)* as the road segment that a vehicle is on before the intersection, and the *next road segment (NRS)* represents the road segment that the vehicle will be on after crossing the intersection. We use an offline table, which we refer to as the *Trajectory Cells Table (TCT)* to determine the cells which will be occupied by the vehicle while crossing the intersection area. TCT uses the CRS, NRS and the lane number as inputs, and returns a list of cell numbers, which will be referred to as *Trajectory Cells List (TCL).* Therefore vehicle's TCL is defined as the ordered list of the cell numbers which will be occupied by that vehicle along its trajectory inside the intersection box.

Figure 3.4 shows an intersection with two lanes entering the intersection grid from all four directions. In this example scenario, vehicle A's TCL includes cell numbers {15, 11, 7, 3}.

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geometry and its static or dynamic nature, our proposed intersection protocol rules still hold and provide safe and efficient passage of vehicles through the intersection area.

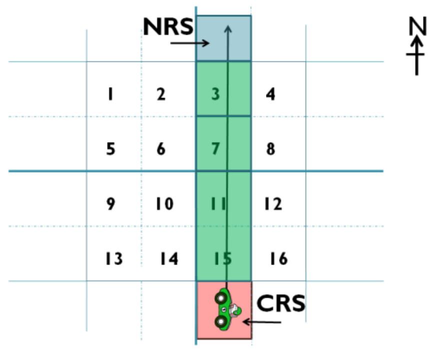


Figure 3-4: Intersection Grid, Current Road Segment (CRS) and Next Road Segment (NRS)

In order to update the Trajectory Cells List (TCL) accurately, each vehicle should be aware of the current cell it is occupying inside the intersection grid. As we mentioned before, all vehicles are equipped with GPS devices and have access to the digital map database as well as the intersection's coordinates. Therefore, each vehicle is able to use this information to map the current GPS coordinates to its current cell number. The current cell number will be then used to update the TCL and will be broadcast to surrounding vehicles as part of the basic safety message (BSM) [8].

If the vehicle detects that it has not entered the intersection box, it does not modify the TCL. In this case, the TCL contains the full list of cell numbers which will be occupied by the vehicle while crossing the intersection area. If the vehicle is inside the intersection box, then it uses the current cell number and modifies the TCL as follows. As the trajectory cells list is sorted, using the current cell number, the vehicle can tell which cells have already been crossed and what the next cells along its trajectory are. Thus, the vehicle updates the TCL by removing cell numbers that have been completely passed and the new TCL contains the current cell number and the remaining cells of the trajectory. Figure 3.5 shows an example, wherein a vehicle is crossing the intersection, and updating the TCL based on its location outside or inside the intersection grid.

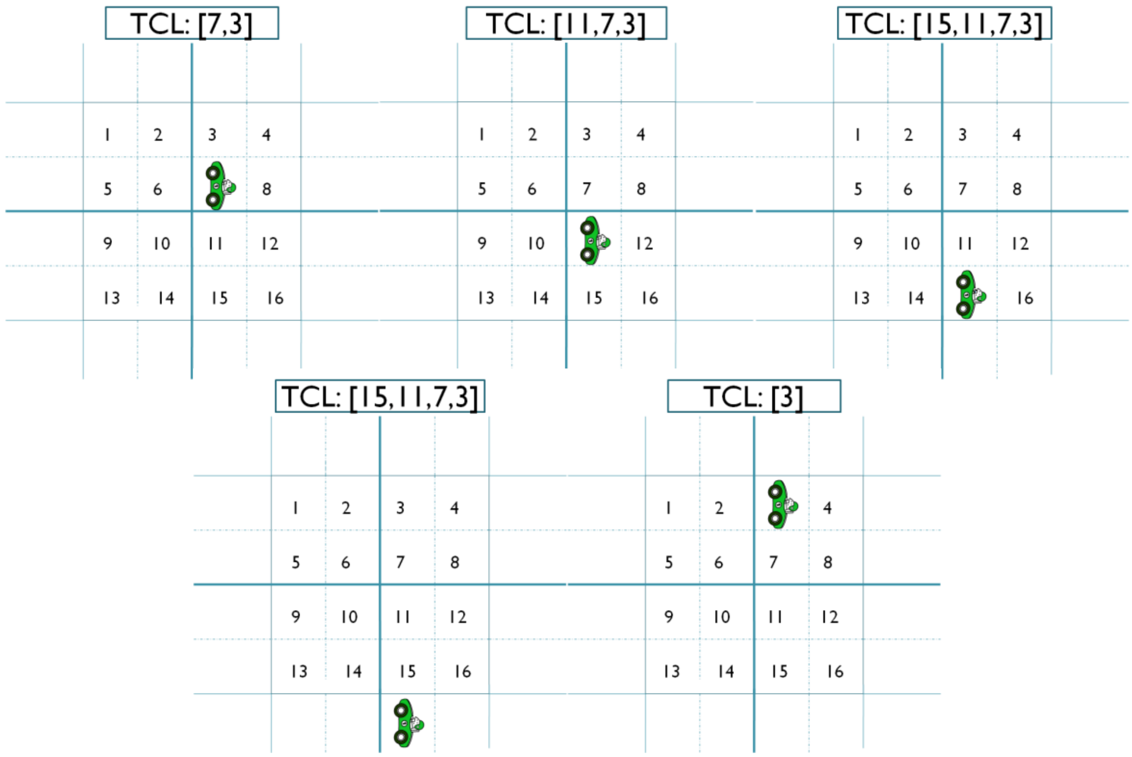


Figure 3-5: Sequence of updating the TCL

3.3.2 Collision Detection Algorithm for Intersections (CDAI)

A collision occurs inside the intersection area if two or more vehicles have time and space conflicts. In other words, vehicles get to a potential collision if they have overlapping (Arrival-Time, Exit-Time) intervals and they occupy at least one common cell along their trajectories through the intersection. If any of these conditions is false, then there will be no conflicts and vehicles can continue along their trajectories safely.

Our proposed V2V-Intersection protocols make use of our Collision Detection Algorithm for Intersections (CDAI). CDAI runs on all vehicles, using the information obtained from received safety messages broadcast by surrounding vehicles. The algorithm uses the TCLs of the sender and the receiver of the safety messages and by comparing the two lists, it determines if there is any common cell along their trajectories while crossing the intersection. If a potential collision is detected by CDAI, the algorithm returns the *first* conflicting cell number which we refer to as *Trajectory Intersecting Cell (TIC)*. For example in Figure 3.6, vehicle A's TCL is {15, 11, 7, 3} and vehicle B's TCL is {8, 7, 6, 5}. Therefore cell number 7 is the TIC between vehicles A and B.

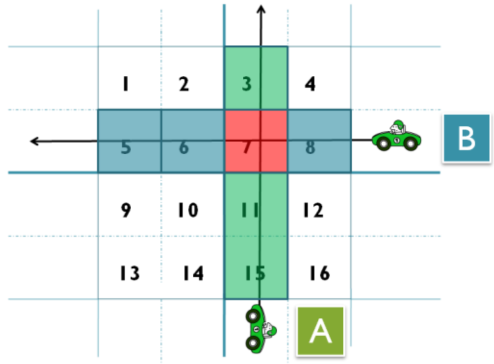


Figure 3-6: An Intersection Scenario

When no potential collision is detected among the sender and the receiver(s) of intersection safety messages, they can safely cross the intersection concurrently without stopping or slowing down. This behavior increases the throughput of the intersection by decreasing any unnecessary delays faced by approaching vehicles. But if a potential collision is detected, vehicles identify the common cell(s) among their TCLs. In this case, each vehicle uses a pre-designed priority policy and follows the assigned V2V-Intersection Protocol (V2V-IP) rules, which will be described in Chapter 4, to cross the intersection area.

Various priority policies can be assigned to the approaching vehicles in case of potential collision scenarios. First-Come, First-Served (FCFS) is one of these priority policies which provides fairness while benefits from simplicity. In this approach, priorities are assigned to vehicles based on vehicles' arrival times to the intersection box. This means that the vehicle which arrives at the intersection earlier has a higher priority than the vehicle that arrives later on. In the case that two or more vehicles arrive at the intersection almost at the same time, ties can also be broken in favor of vehicles on a main road. If there is still a tie, it is broken by Vehicle Identification Number (VIN), which is uniquely assigned to each vehicle. Emergency vehicles such as police cars, ambulances and fire-trucks should be assigned with the highest-priority to be able to cross the intersection without any stops behind the intersection boundaries.

3.3.3 Intersection state

Every vehicle uses its own GPS coordinates, speed and also the map database to compute the distance to the approaching intersection and the distance passed from the previous intersection. We consider four *intersection states* for each vehicle based on its relative location to the intersection area.

1) *Intersection-Approach*: when vehicle's distance to the approaching intersection is less than a threshold parameter D_{ENTER}.

2) *Intersection-Enter*: when the vehicle is inside the intersection grid's boundaries.

3) *Intersection-Exit*: when the vehicle exits the intersection, until it travels farther than a threshold value D_{EXIT} from the exit point of the intersection.

4) *Intersection*-Idle: when the vehicle's distance to the next intersection is more than D_{ENTER} or when the vehicle's distance from the previous intersection is more than D_{EXIT}.

Figure 3.7 illustrates an example of intersection state determination based on the vehicle's distance to and from an intersection. It also shows a diagram which includes the four possible intersection states and the transition among them based on the described distance thresholds.

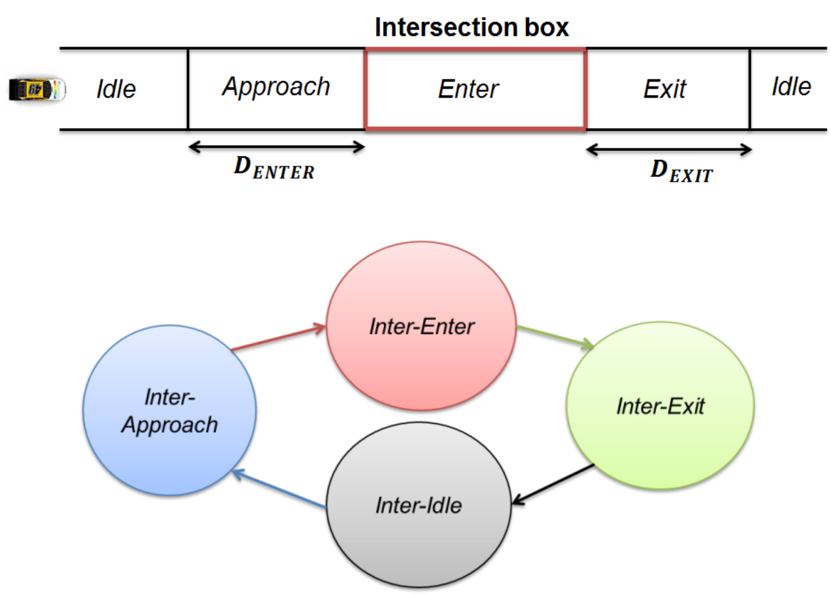


Figure 3-7: Intersection State Diagram

3.3.4 Intersection Safety Messages

Vehicles use V2V communications using DSRC/WAVE to broadcast intersection safety messages to other vehicles in their communication range. These protocols enable co-operative driving among approaching vehicles to ensure their safe passage through the intersection. Our assumption is that all the vehicles are equipped with Global Positioning System (GPS) devices and have access to a digital map database, which provide them with critical information such as position, heading, speed, and road and lane details. Intersection safety messages are broadcast at 10Hz and they contain the trajectory details of the sender along the intersection area. The format of these safety messages is defined by SAE's J2735 standard \cite{DSRC} and while information such as vehicle's position coordinates, heading and velocity are parts of the first/mandatory part of the Basic Safety Messages (BSM), we use the second part of the BSM for the extra information in our intersection safety messages.

In our intersection protocol, each vehicle depending on its *intersection state* information uses 3 different types of intersection safety messages to interact with other vehicles within its communication range.

1) *ENTER*: An ENTER message is used to inform the neighboring vehicles that the vehicle is approaching the intersection area with specific crossing intentions. The ENTER message contains 9 parameters: *Vehicle ID, Current Road Segment, Current Lane, Next Road Segment, Next Vertex, Arrival-Time, Exit-Time, Trajectory Cells List, Cells Arrival Time List, Message Sequence Number and Message Type*, which is ENTER in this case.

2) *CROSS*: A CROSS message is to inform that the vehicle is inside the intersection grid, this message contains the sender's identification and trajectory details, identifying the space that will be occupied by the vehicle while crossing the intersection. The CROSS message contains the same parameters as the ENTER message. Its Trajectory Cells List contains the updated list of trajectory cells and their related arrival times for the current cell and remaining cells along the vehicle's trajectory through the intersection area, and the *CROSS Message Type*.

3) *EXIT*: An EXIT message indicates that the vehicle has exited the intersection boundaries. The EXIT message contains 3 parameters: *Vehicle ID, Message Sequence Number, and EXIT Message Type*.

In addition to these intersection safety messages, when the vehicle's *intersection state* is *Intersection-Idle*, it broadcasts the GENERIC message to the surrounding vehicles in its communication range. As mentioned earlier this message type includes vehicle's current position, velocity, road and lane information. The GENERIC message is useful for various active safety applications outside of the intersection box, such as the V2V-Distance Keeping and the V2V-Lane Merging.

3.4 Summary

Co-operative driving of vehicles using Vehicle-to-Vehicle (V2V) communications enables a wide range of active safety applications. In this Chapter, we proposed three V2V-based methods which are applicable to various critical driving scenarios and can provide collision avoidance and higher road efficiency.

1. *V2V Distance-Keeping*: In order to ensure a safe distance between cars before arriving at and after leaving the intersection area, we have designed a V2V-based distance-keeping method. This model is designed to control the mobility of vehicles while moving towards, or after exiting the intersection. To enable this car-following model, vehicles broadcast a safety message of type GENERIC at a regular interval which contains information about a vehicle's position, velocity, current road and lane. A receiving vehicle uses these safety messages to detect the presence of a leader vehicle in front of it and keep the safe distance by adjusting its velocity.
2. *V2V Lane-Merging*: To avoid any potential collisions among vehicles while performing a lane change, we have designed a *V2V lane-merging* algorithm. This protocol incorporates the use of GENERIC safety messages and *V2V distance-keeping*, and allows the safe lane changing into an adjacent lane when necessary.
3. *Distributed Collision Detection*: We have defined a simplistic intersection model in which the intersection is considered as a big grid which is divided in to smaller cells. We define the intersection state based on vehicle’s position comparing to the intersection grid. A set of intersection safety messages are designed to enable our distributed collision detection method. Using the information obtained via intersection safety messages, each vehicle runs our Collision Detection Algorithm for Intersections (CDAI) to detect potential collisions with other vehicles approaching to the same intersection.

Chapter 4

Homogeneous V2V-Intersection Management

To manage the homogeneous traffic which only consists of autonomous vehicles, we have designed a family of protocols which mainly relies on Vehicle-to-Vehicle (V2V) communications. V2V is used as a part of vehicular networks to enable co-operative driving of autonomous vehicles at intersections. These fully distributed protocols will allow vehicles to interact with each other and safely cross the intersection areas while increasing the overall throughput. Our V2V-Intersection protocols are designed to increase the throughput at intersections while avoiding collisions. These protocols are designed to manage intersection crossings by pure V2V communication without using any infrastructure such as stop-signs, traffic lights, sensors and cameras.

Vehicles use V2V communications through DSRC/WAVE to broadcast intersection safety messages described in Chapter 3, to other vehicles in their communication range. Our assumption is that positioning and time synchronization is provided by high accuracy Global Positioning System (GPS) devices and vehicles have access to a digital map database.

The relationship between any two vehicles is determined using the Collision Detection Algorithm for Intersections (CDAI) which runs on each vehicle as explained in the previous chapter. This relationship is considered to be one of the following:

- *Non-Conflicting*: Vehicles with no conflict between their trajectories along the intersection area. Therefore no potential collision will happen if they cross at the same time.
- *Potentially Conflicting*: Vehicles which have trajectory conflicts with one another through the intersection area and may get into a potential collision.

All versions of our V2V-IP protocols will allow *non-conflicting* vehicles to cross the intersection at the same time. This will significantly increase the throughput of the intersection. To resolve the issue between *potentially conflicting* vehicles, a unique priority will be assigned to each vehicle based on a pre-defined priority assignment policy. We propose the categorization of the V2V-IPs based on the actions taken by *potentially conflicting* vehicles to avoid collisions. We have developed three generations of V2V-IPs: Low-Concurrency Protocols (LCP), High-Concurrency Protocols (HCP), and High-Concurrency Protocols with Enhanced Vehicle Dynamics (HCP-EVD), which are respectively based on the cautious, aggressive and efficient behavior of the *potentially conflicting* vehicles. Figure 4.1 shows the categorization of all V2V-IP protocols.

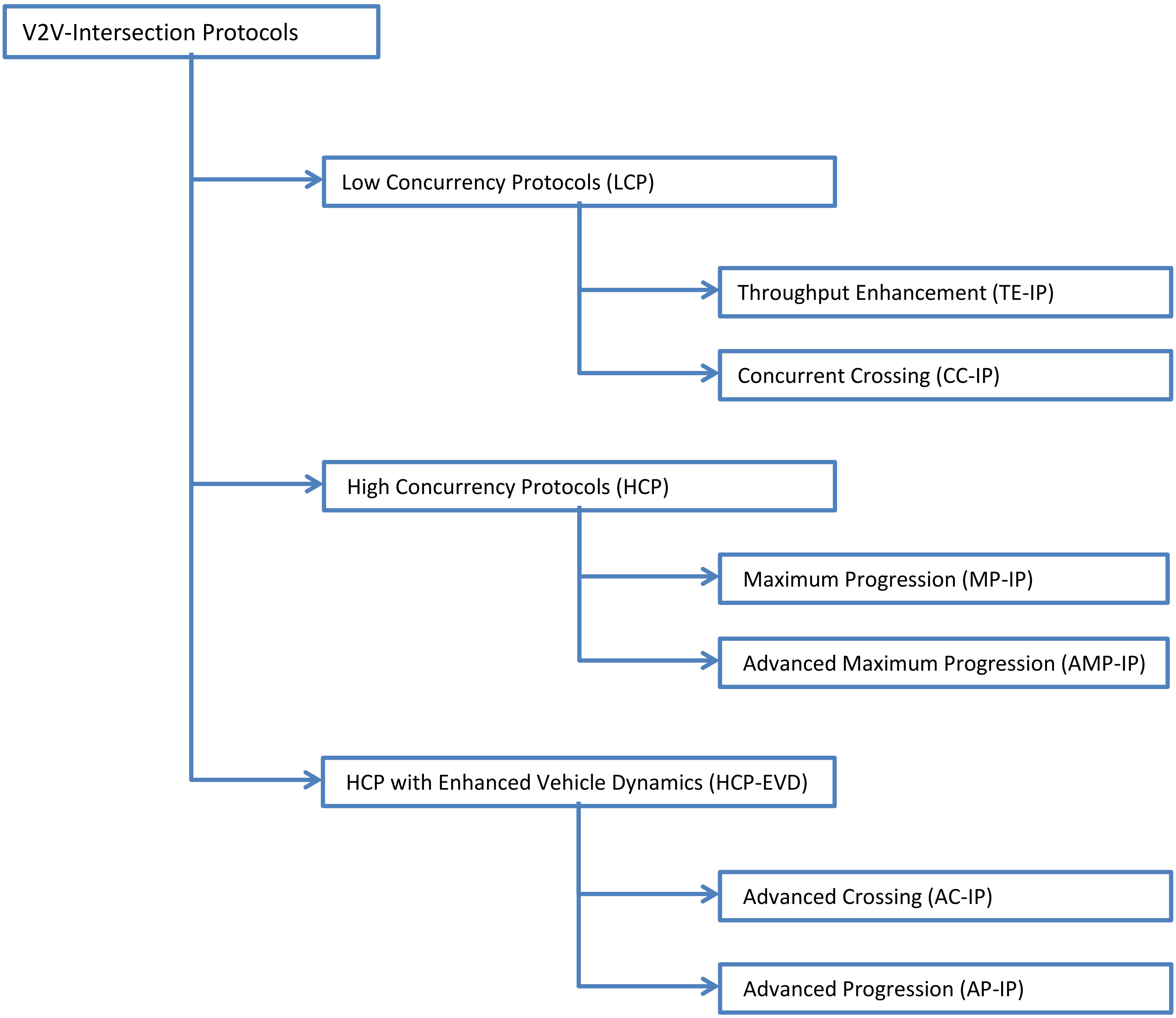


Figure 4-1: V2V-Intersection Protocols (V2V-IP) Generations

The rest of this chapter is organized as follows. In Sections 4.1, 4.2 and 4.3, we will describe and provide the evaluation results for the Low-Concurrency Protocols (LCP), High-Concurrency Protocols (HCP) and High-Concurrency Protocols with Enhanced Vehicle Dynamics (HCP-EVD) respectively. Finally, we describe each category's pros and cons for various types of environmental characteristics and provide our concluding remarks in chapter 4.4.

4.1 Low-Concurrency Protocols (LCP)

The first generation of STIP protocols is called Low-Concurrency Protocols (LCP). In this category, the *potentially conflicting* vehicle with higher priority can ignore the intersection safety messages from other lower-priority vehicles and cross the intersection without slowing down or stopping. However, any lower-priority vehicle is cautious and when it loses a competition, it comes to a complete stop before entering the intersection boundaries, and waits till it receives an EXIT message, from the higher-priority vehicle. This message informs the lower-priority vehicle that the higher-priority vehicle has crossed the intersection and now the intersection area is safe for its passage. This protocol is applied across all priority levels. LCP includes Throughput Enhancement Intersection Protocol (TE-IP) and Concurrent Crossing-Intersection Protocol (CC-IP) [113], [114], [115].

4.1.1 Throughput Enhancement-Intersection Protocol (TE-IP)

This protocol is designed to enhance the throughput at intersections without causing collisions. Vehicles use, *ENTER* and *EXIT* safety messages to interact with other vehicles. We define the throughput of an intersection based on the delay of all vehicles trying to cross the intersection. The following rules are applicable to each vehicle. The following *send* rules are applicable to all vehicles under TE-IP:

Algorithm 4.1: TE-IP Sender Vehicle

Input: Vehicle's STATE based on its distance to the intersection

Output: Broadcasting the appropriate intersection safety message

1. **If** ($STATE = INTERSECTION_{APPROACH}\ \ or$
$STATE = INTERSECTION\_ENTER$) **then**

2. Broadcast *ENTER* message

3. **Else if (** $STATE = INTERSECTION\_EXIT$) **then**

4. Broadcast *EXIT* message

The following *receive* rules are applicable to all vehicles under TE-IP:

Algorithm 4.2: TE-IP Receiver Vehicle

Input: Received intersection safety message

Output: Vehicle's movement at the intersection

1. **If** $(received\ message\ =\ ENTER)$, **then**

2. Run CDAI to detect trajectory conflicts with the sender

3. **If (**no potential collision is detected) **then**

4. Cross the intersection

5. Else

6. Use FCFS priority policy to determine the priority based on vehicles' arrival times

7. **If** (higher priority than the sender) **then**

8. Cross the intersection

9. Else

10. Stop and wait to receive the EXIT message from the same sender

11. **Else if** $(received\ message\ =\ EXIT)$ **then**

12. **If** (the sender is the same sender of the last processed ENTER message) **then**

13. Cross the intersection

Figures 4.2(a) and 4.2(b) show two situations in which vehicle A has the highest priority and crosses the intersection without slowing down or stopping. Vehicle A is broadcasting the ENTER message. Vehicles B and C are receiving these safety messages and run the CDAI algorithm. Both vehicles get to the same decision that they do not have a potential collision with vehicle A. As can be seen in Figure 4.2(a), vehicle B and C may collide as they have a conflicting trajectory along the intersection. Therefore, only one of them can safely cross through the intersection box while vehicle A is cross. The other vehicle can come to a complete stop before entering the intersection box. Vehicles B and C should get to a decision using the priorities assigned to them by the priority policy so that the vehicle with the higher priority can cross, while the other one is waiting outside of the intersection till it receives the EXIT message from the higher-priority vehicle.

Assume that the following priorities are assigned based on the priority policy: $P_C < P_B < P_A$. Therefore, vehicles A and B safely cross the intersection at the same time. Vehicle C will come to a complete stop and wait till it receives the *EXIT* safety message from vehicle B, indicating that it is now safe for vehicle C to complete its trajectory through the intersection grid.

In Figure 4.2(b), vehicles B and C can cross the intersection at the same time as the higher-priority vehicle A, since none of them has a space conflict with the other two. Therefore, all three vehicles cross the intersection simultaneously without slowing down or stopping at the intersection.

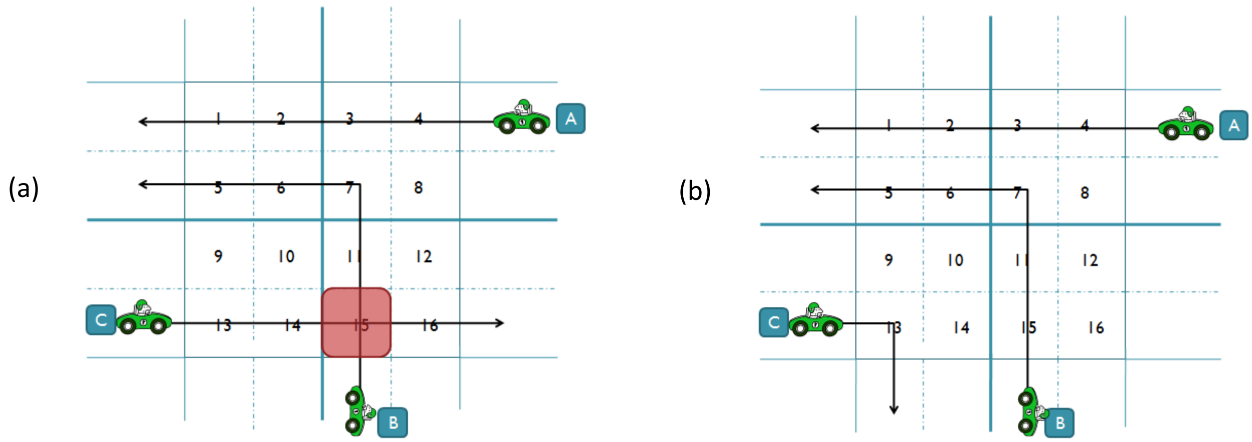


Figure 4-2: Two example scenarios for TE-IP

Using TE-IP, vehicles stop at the intersection if and only if the collision detection algorithm predicts a collision and assigns a lower priority to them based on the messages it receives from all vehicles at the intersection. If no collision potential is detected or the highest priority is determined among contending vehicles, a vehicle can ignore other STOP messages, broadcast its own STOP messages to notify other vehicles, and cross the intersection safely.

Multiple vehicles can be inside the intersection area at the same time if no space conflict occurs based on the collision detection policy's results. These rules increase the throughput of the intersection by decreasing the average delay time relative to the situation that vehicles should stop at the intersection.

4.1.2 Concurrent Crossing-Intersection Protocol (CC-IP)

This protocol is designed to increase the throughput at intersections while avoiding collisions. This intersection management protocol is based on pure V2V communications. Each vehicle uses *ENTER*, *CROSS* and *EXIT* safety messages to interact with other vehicles in its communication range.

The following *send* rules are applicable to all sender vehicles:

Algorithm 4.3: CC-IP Sender Vehicle

Input: Vehicle's STATE based on its distance to the intersection

Output: Broadcasting the appropriate intersection safety message

1. **If** ($STATE = INTERSECTION\_APPROACH$) **then**
2. Broadcast *ENTER* message
3. **Else if (** $STATE = INTERSECTION\_ENTER$) **then**
4. Broadcast *CROSS* message
5. **Else if (** $STATE = INTERSECTION\_EXIT$) **then**
6. Broadcast *EXIT* message

And here are the rules applied to a vehicle B when it receives intersection messages from a vehicle A (A $\neq$ B).

Algorithm 4.4: CC-IP Receiver Vehicle

Input: Safety message received from vehicle A, *Received Message (RM)*

Output: Vehicle B's movement at the intersection

1. **If** (RM = ENTER) **then**
2. Run CDAI to detect trajectory conflicts with vehicle A and find $TIC_{A,B}$
3. **If** ($TIC_{A,B} = NULL$) **then**
4. Cross the intersection
5. **Else**
6. Run FCFS priority policy
7. **If** ($P_B > P_A$) **then**
8. Cross the intersection
9. **Else**
10. Stop at the intersection

Else if (RM = CROSS) **then**
Run CDAI to detect trajectory conflicts with vehicle A and find $TIC_{A,B}$
If ($TIC_{A,B} \neq NULL$) **then**
Stop at the intersection
Else
Compete with other vehicles in the same situation*
Else if (RM = EXIT) **then**
If ($TIC_{A,B}$ is cleared) **then**
Cross the intersection

---

*: When a vehicle receives a CROSS safety message, it uses the CDAI to detect any potential trajectory conflict with the sender of the CROSS message. If no potential collision has been detected by CDAI, with the sender of the CROSS message, the receiver may still not be allowed to cross the intersection area, as there might be more than one vehicle which has no conflict with the crossing vehicle. In this situation, these vehicles may attempt to cross the intersection area without being aware that they may collide with each other.

Figures 4.3(a) and 4.3(b) show two situations in which vehicle A is crossing the intersection box and is broadcasting the CROSS message. Vehicles B and C are receiving these safety messages and run the CDAI algorithm.

Both vehicles get to the same decision that they do not have a potential collision with vehicle A. As can be seen in Figure 4.3(a), vehicle B and C may collide as they have a conflicting trajectory along the intersection. So only one of them can safely cross through the intersection box while vehicle A is crossing, and the other vehicle can come to a complete stop before entering the intersection box. Vehicles B and C should get to a decision using the priorities assigned to them by the priority policy so that the vehicle with the higher priority can cross, while the other one is waiting outside of the intersection till it receives the EXIT message from the higher priority vehicle.

In Figure 4.3(b), vehicles B and C can cross the intersection at the same time as vehicle A, since none of them has a space conflict with the other two.

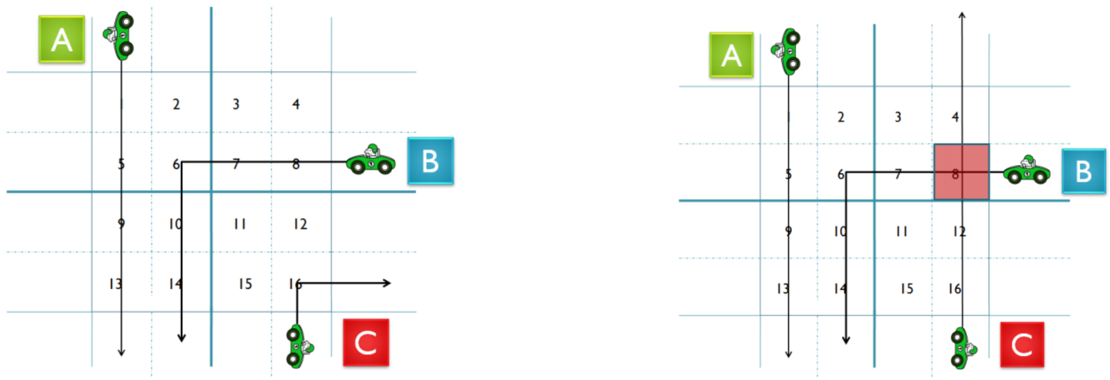


Figure 4-3: Two example scenarios for CC-IP

Each receiving vehicle makes sure that it does not have trajectory conflicts with other receiving vehicles before entering the intersection area. As discussed before, the receiving vehicle uses the received ENTER messages to detect any potential collisions with other receivers of the CROSS message, which are waiting to enter the intersection box. If no potential collision is detected with all other leader vehicles or if it has the highest priority among them, the receiver can cross the intersection safely while broadcasting the CROSS message.

In TEP, when vehicles approach an intersection and while crossing through it, till they exit the intersection box, they broadcast STOP safety message to all surrounding vehicles. To increase the throughput of the intersection, in CC-IP, we added the CROSS safety messages, which are sent by vehicles inside the intersection area. This allows more parallelism as receiving vehicles detecting no trajectory conflict with the sender of the CROSS message can cross through the intersection at the same time. This concurrency occurs regardless of their arrival time at the intersection. In the case that the vehicle detects no potential collision with the vehicle already crossing the intersection, it can simultaneously pass through the intersection box, even though the vehicle has arrived later than some others. This decreases the intersection delay when compared to the FCFS policy.

4.1.3 Evaluation

In this section, we evaluate our Low-Concurrency Protocols (LCP): Throughput Enhancement Intersection Protocol (TE-IP) and Concurrent Crossing Intersection Protocol (CC-IP), using various mobility models that we have designed and simulated in AutoSim [Chapter 9]. AutoSim is a hybrid emulation environment for vehicular communications that enables the interaction between real and simulated vehicles, and provides modeling of different aspects of mobility protocols.

We compare our V2V-interaction models to the following mobility models:

- **Stop-Sign Model:** When a simulated vehicle approaches an intersection managed by stop-signs at each entrance, it comes to a complete stop regardless of the situation of any other vehicle at the intersection. In other words, the velocity of the vehicle becomes zero even if there is no other car trying to cross the intersection. In discussions, police recommend 3 seconds of complete stopping even at an empty intersection. This stop delay will increase in proportion to the number of cars that arrived earlier at the intersection.
- **Traffic-Light Model:** The traffic-light model follows the same basic logic as the stop sign model except that stop signs are now replaced by traffic lights. The Green-Light Time of the traffic light has a default value that can be changed by the user.

Both the Stop-Sign and Traffic-Light models have been designed to simulate the behavior of vehicles at intersections equipped with stop-signs or traffic-lights. In these two models, vehicles do not communicate with each other.

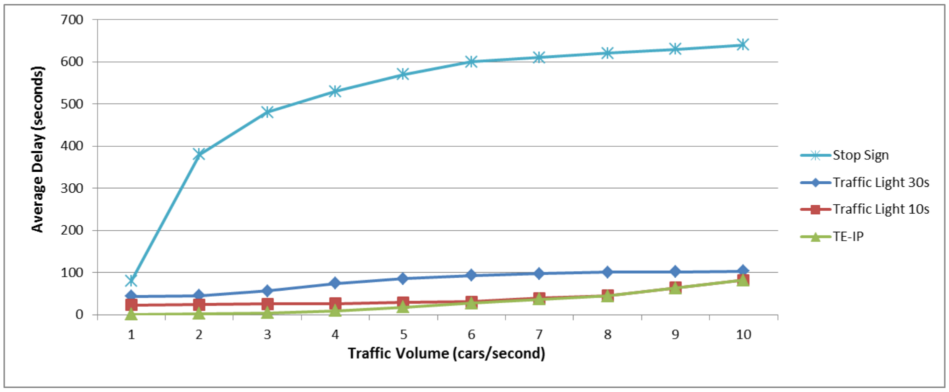
We define the *Trip Time* for a vehicle as the time taken by that vehicle to go from a fixed starting point before the intersection to a fixed end point after the intersection. We calculate the trip time for each simulated car under each model and compare that against the trip time taken by the car assuming that it stays at a constant street speed and does not stop at the intersection. The difference between these two trip times is considered to be the *Trip Delay* due to the intersection. We take the *average trip delays* across all cars in a simulation sequence as our metric of comparison.

Since there is a large variation in intersection types, we restrict our attention to *Four-Way Perfect-Cross* Intersections, in which the intersection legs are at perfect right angles to the neighboring leg. We prioritize each leg of the intersection and characterize them as Primary and Secondary roads based on the priorities assigned to them. Traffic volume is also specified on a per intersection-leg basis, allowing intersection legs to have different traffic levels. We study how assigning higher priorities to the roads with higher traffic volume affects the overall trip delay of vehicles. Additionally, we have looked at *T-junction* intersection, in which two roads are perpendicular to each other, and one of the roads ends at the intersection.

We run all our simulations on 4-lane roads, with 2 lanes in each direction. The intersection type, vehicle-birthing sequence, vehicle routes and turn-types are generated offline. Each vehicle is removed from simulation when it reaches its destination. This file is then fed into AutoSim to invoke the intersection protocols. Each simulation run uses 1000 vehicles, and each run is terminated when the last vehicle reaches its destination. The simulation model in AutoSim has been designed to prevent a vehicle from becoming active if vehicles with earlier start times are already present within 10 meters ahead of its starting position in its lane. This simulation parameter prevents cars from starting if the lane is already completely backed up.

In our first experiment, we compare different protocols for a perfect-cross intersection with an equal amount of traffic volume in every lane and an equal amount of turn ratios (that is, a vehicle has equal odds of going straight or making a turn at an intersection). The results are presented in Figure 4.4. As can be expected, the Stop-Sign model results in higher average delays than the other protocols. As the traffic volume increases above 0.1 vehicles per second, the performance of the Stop-Sign model drops dramatically and significant traffic backlog results. In contrast, both Traffic-Light models behave at a near-constant level until the traffic volume reaches 0.25 cars per second for the Traffic-Light model with a green-light time of 10 seconds and 0.3 cars per second for the Traffic-Light model with a green-light time of 30 seconds. After that, the average delay jumps until it settles down at a higher near-constant level at about 0.35 cars per second. Beyond this traffic volume, the Traffic-Light models behave the same regardless of the green-light duration as all the lanes are completely saturated and traffic is backed up significantly.

The V2V-Intersection model TE-IP performs the best, doing very well at low traffic volumes up to 0.2 vehicles per second resulting in very negligible delay. As traffic volume increases, the average delay increases and beyond 0.3 cars per second, it performs very similar to the Traffic-Light model with a green-light time of 10 seconds. However, the overall performance improvement is about 26% as compared to the latter Traffic-Light model. Figure 4.4(b) zooms into the plot of Figure 4.4(a) to show a detailed comparison between the Traffic-Light models and the Intersection model, by not showing the poorly performing Stop-Sign model.



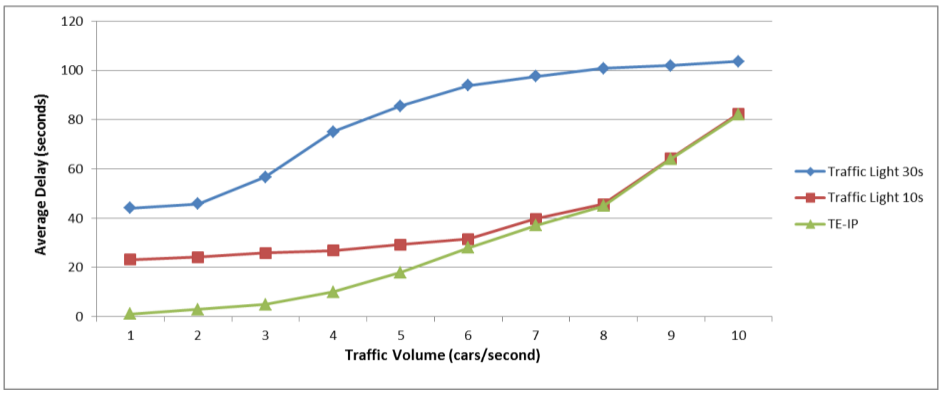


Figure 4-4: Delays for Perfect-Cross Intersection. Figure (a) shows all protocols. Figure (b) shows more detail w/o the Stop-Sign Protocol.

According to classical queueing theory, the average delay will asymptotically become very high when the arrival rate (i.e. traffic intensity) exceeds the service rate (throughput) at the intersection. This delay, however, occurs under steady-state conditions only after a considerable amount of time. Due to practical considerations, our simulations are run for finite durations, and hence capture only transient delay behaviors after overload conditions have been reached. Nevertheless, our results clearly indicate that before overload conditions are reached, the service rate (i.e. throughput) with the V2V-Intersection protocol is noticeably better than the Traffic-Light models.

We then repeated the above experiment for a T-junction and the corresponding results are shown in Figure 4.5. For the T-junction, the V2V-Intersection protocol has an 83% overall performance improvement over the Traffic-Light model with a 10-second green-light time, and a 94% overall performance improvement over the Traffic-Light model with a 30-second green-light time. The T-junction has fewer conflicts to deal with than at a perfect-cross intersection, resulting in less stopping at the intersection for the V2V-Intersection model leading to its much better performance than before.

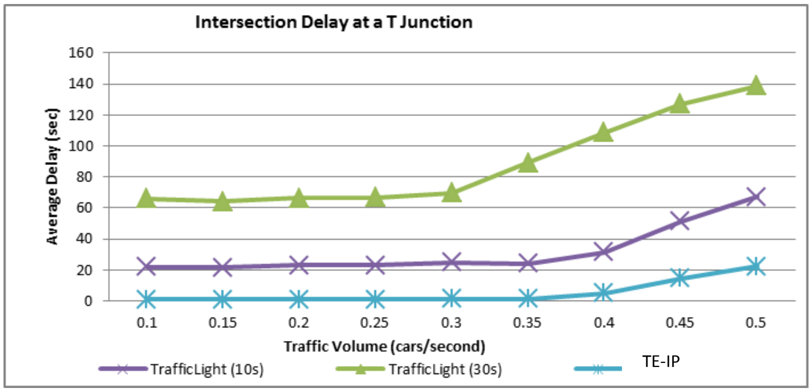


Figure 4-5: Delays at a T-Junction

Next, we studied the scenario where traffic varies along different intersecting roads. That is, when two roads intersect, one road has more traffic than the other. However, we still assume that both roads have the same type and hence one does not have priority over the other. The corresponding results are given in Figure 4.6(a) for the Traffic-Light Model and Figure 4.6(b) for the V2V-Intersection Model. Again, the V2V-Intersection Model performs better than the Traffic-Light Model.

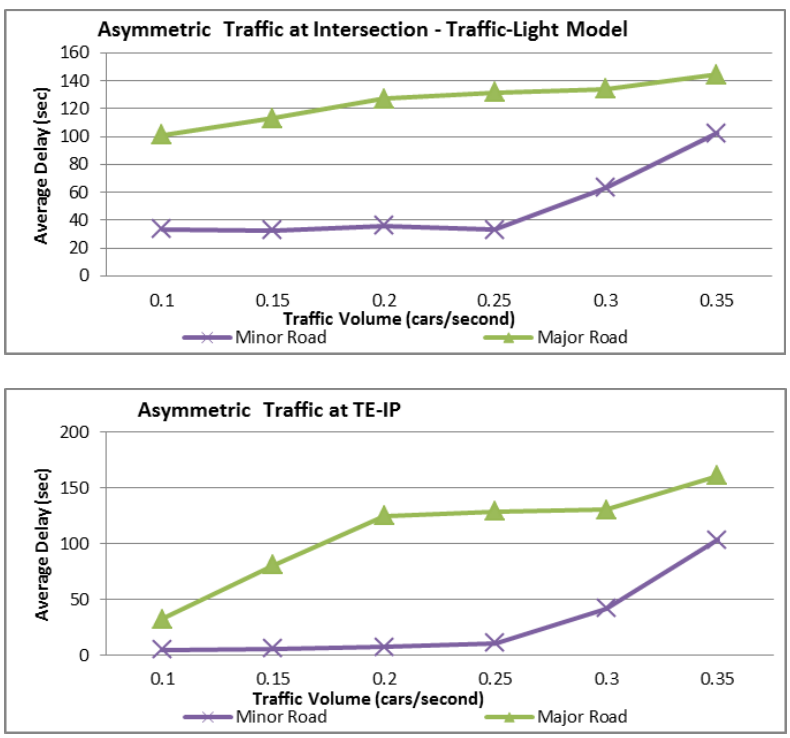


Figure 4-6: Delays with Asymmetric Traffic: (a) Traffic-Light Model (b) TE-IP

We have next compared the traffic light model to our CC-IP for a perfect-cross intersection. Figure 4.7 shows this comparison. Each experiment includes an equal amount of traffic volume in every direction and an equal amount of turn ratios (that is, a vehicle has equal odds of going straight or making a turn at an intersection). All roads are considered as primary roads and hence they have the same priority. The X-axis is the traffic volume determined as cars per second and the Y-axis is the delay in seconds.

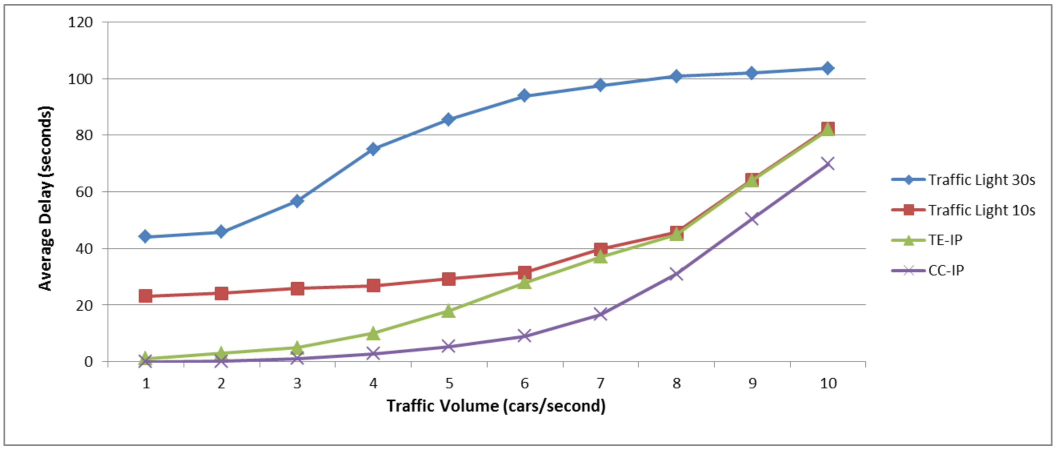


Figure 4-7: Delay comparison between Traffic light models and V2V-Intersection models.

Both V2V-based models perform better than the traffic light model. The *Concurrent Crossing-Intersection Protocol (CC-IP)* has respectively 48.78% overall performance improvements over the traffic light model with a 10-second green light time.

The average delay is very negligible for lower traffic volumes in both V2V-based models. In the case of *CC-IP*, as the traffic volume increases, the delay also increases and at beyond a traffic volume of 0.8 cars per second, its performance gets closer to the traffic light model but still outperforming it.

Next, we looked at the case where roads have the same traffic volumes but different types, i.e. the north-bound and the south-bound lanes of the intersection are primary roads and the south-bound and the west-bound lanes, are secondary roads. Hence, the vehicles on primary roads have higher priority over vehicles coming from secondary roads to cross the intersection. As we can see in Figure 4.8, CC-IP V2V-Intersection model performs almost the same as its performance in the scenario that all the roads have the same type (same priority), for low and medium traffic volumes. And it performs slightly better in the case of high traffic densities.

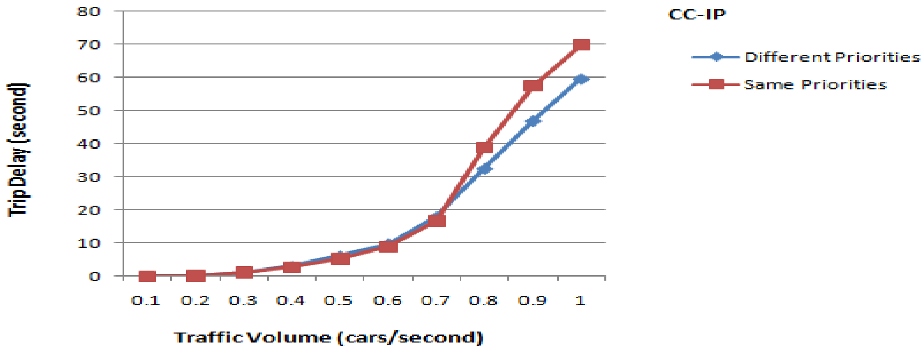
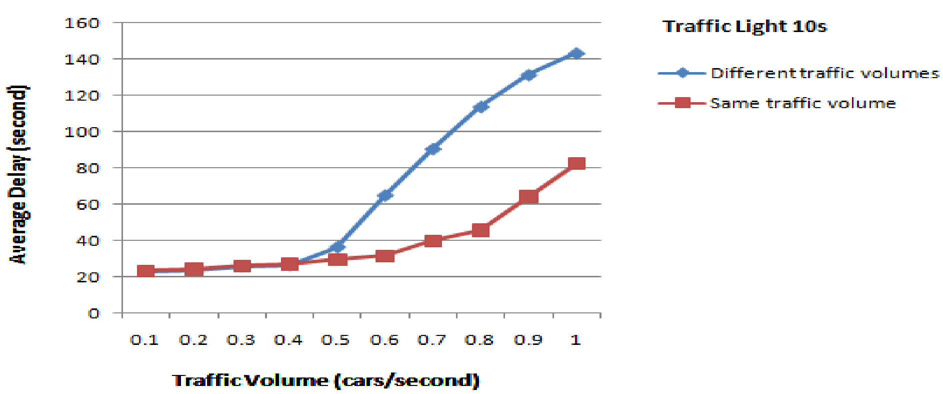


Figure 4-8: Delay comparison between the normal intersection and when the intersection roads have same traffic volume but different types (priorities) in CC-IP model

We next studied the case that the traffic volume is significantly different on the intersection roads. We assume that the roads coming to the intersection from the North and the South have higher traffic densities than the roads on the East and the West. However, the roads have the same type and priority to cross the intersection. Figure 4.9 illustrates the performance comparisons between the asymmetric traffic (various traffic volumes among the intersection roads) and the symmetric traffic, for each intersection model, including the traffic light model and our two V2V-Intersection models. As we expect, the vehicles arriving on the higher traffic density roads face higher delays which increases the overall average delay. Using the *CROSS* safety messages permits more vehicles from the higher traffic volume legs of the intersection, which are situated in opposite directions (i.e. north and south legs), to cross the intersection area at the same time. The reason is that there are fewer space conflict cases between the vehicles arriving at intersection from opposite directions than the vehicles coming from the other directions.



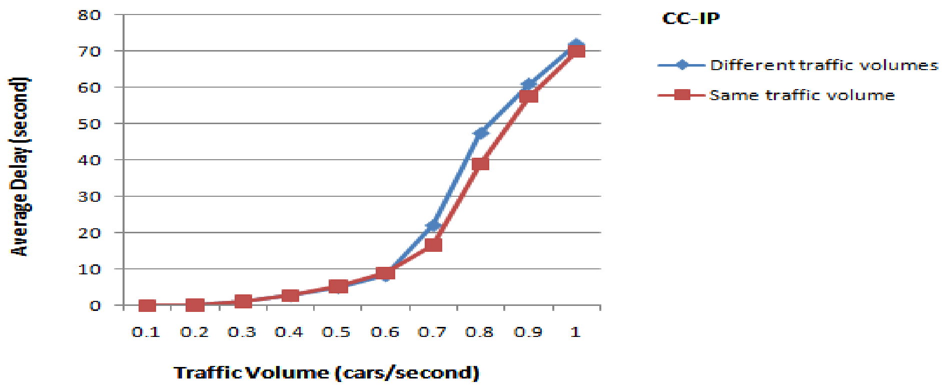


Figure 4-9: Delay comparisons between the symmetric and asymmetric intersections, managed by (a) Traffic Lights, (b) CC-IP

We finally studied the scenario in which higher priorities have been assigned to high-traffic-volume roads, in order to allow more vehicles to cross the intersection coming from the higher density roads. This reduces the backed-up traffic and accordingly increases the overall throughput of the intersection. Figure 4.10 shows the comparisons between two different scenarios using the Concurrent *Crossing-Intersection Protocol (CC-IP)*. Both scenarios look at asymmetric intersections, in which the traffic volume is not the same among all legs of the intersection. In both V2V-Intersection models, assigning higher priorities to higher traffic volume roads outperforms the scenario that all legs of the intersection have the same priority. The improvement is small at low volume traffic but it increases significantly as the traffic density increases. These results highlight the importance of priority policy and how assigning higher priorities to vehicles on the high volume traffic roads can decrease the overall delay and increase the throughput of the intersection significantly while dealing with large number of vehicles at the intersection.

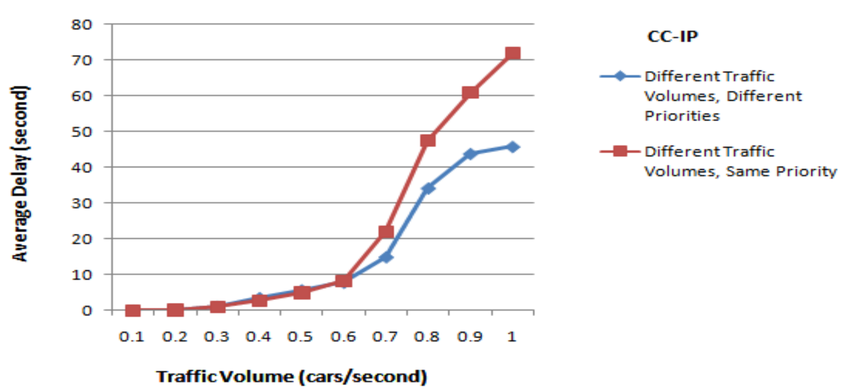


Figure 0-10: Delays at asymmetric intersections. Comparison of same priority assignment, with assigning higher priorities to higher traffic volumes, managed by V2V-intersection protocol: CC-IP

4.2 High-Concurrency Protocols (HCP)

The main goal of proposed HCP family of intersection protocols is to increase parallelism inside the intersection area by allowing more vehicles to cross the intersection at the same time. To achieve this scheme's goal, we focus on allowing even *potentially conflicting* vehicles to make maximal progress inside the intersection area, without sacrificing the primary goal of safety. In contrast to LCP, in which lower-priority vehicles should stop before entering the intersection box and wait for the higher-priority vehicle to clear the intersection area, HCP plans to allow all vehicles to progress and only stop before the potential conflicting point. HCP includes the Maximum Progression Intersection Protocol (MP-IP) and the Advanced Maximum Progression Intersection Protocol (AMP-IP) [119]. We explain these protocols in this section.

4.2.1 Maximum Progression Intersection Protocol (MP-IP)

MP-IP is designed to increase the intersection throughput by allowing even *potentially conflicting* vehicles to progress inside the intersection area, when the primary goal of safe passage of all vehicles across the intersection can be satisfied.

Here we define the terms that will be used in our theorems.

- P_V: Priority of vehicle *V*. This is determined by the priority policy.
- S_V: Set of cells required for vehicle *V* to cross the intersection. It consists of the current cell and next cells that will be occupied by vehicle *V*.
- C_V: Current cell occupied by vehicle *V*.
- N_V: Next cell that will be occupied by vehicle *V*.
- $TIC_{V,W}$: Trajectory Intersecting Cell between the higher-priority vehicle *V* and lower-priority vehicle *W*.

Based on the above definitions, one can derive the following logical relations:

$$C_V \neq N_V \quad and \quad C_V \in N_V \quad and \quad N_V \in S_V$$

The same rules as in Algorithm 4.3, apply to all sender vehicles. The following rules are applied to a vehicle B when it receives intersection messages from a vehicle A, where (A ≠ B).

Algorithm 4.5: MP-IP Receiver Vehicle

Input: Safety message received from vehicle A, *RM*

Output: Vehicle B's movement at the intersection

1. **If** (RM = ENTER or RM = CROSS) **then**
2. Run CDAI to detect trajectory conflicts with vehicle A and find $TIC_{A,B}$
3. **If** ($TIC_{A,B}$ = NULL) **then**
4. Cross the intersection
5. **Else**
6. Run FCFS priority policy
7. **If** ($P_B > P_A$) **then**
8. Cross the intersection
9. **Else**
10. Progress and stop before entering $TIC_{A,B}$
11. **Else if** (RM = EXIT) then
12. **If** ($TIC_{A,B}$is cleared) **then**
13. Cross the intersection

We now illustrate MP-IP with an example. Figure 4.11 shows two vehicles A and B, approaching an intersection. We assume that vehicle A has higher priority than vehicle B. In this case, vehicle A gets to cross the intersection without stopping or even slowing down. Vehicle B shall progress inside the intersection grid and stop before entering the TIC with vehicle A, which is cell number 6. As vehicle A leaves cell number 6, it updates its TCL to {10, 14} and sends a CROSS message. This informs vehicle B that the TIC is now clear and it can continue its trajectory through the intersection by proceeding to cell number 6.

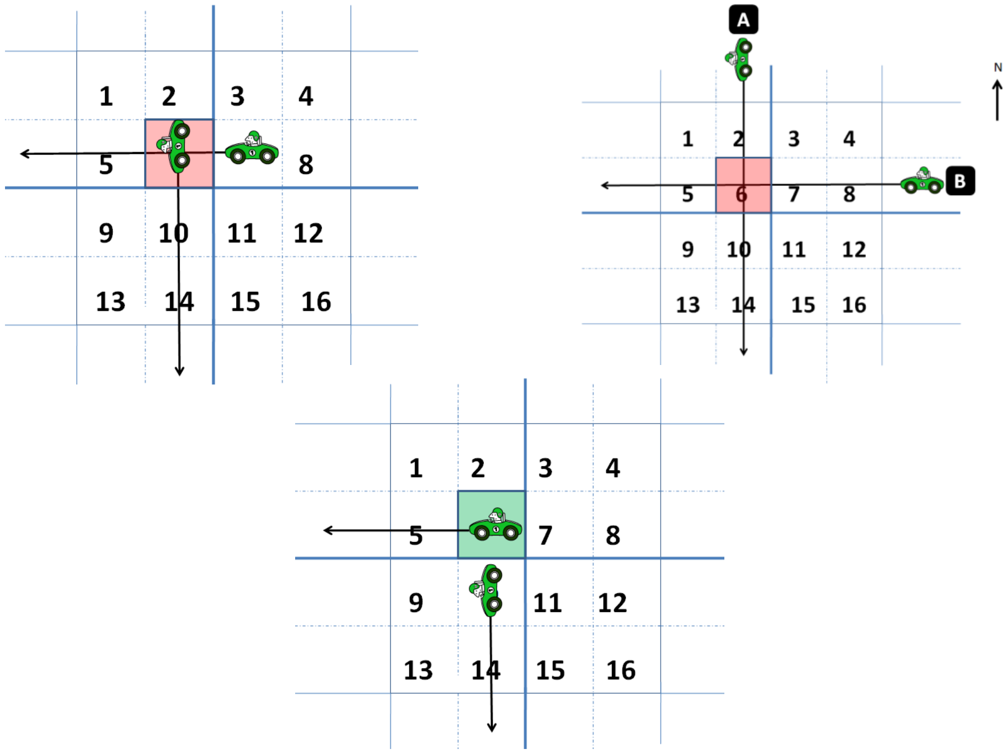


Figure 4-11: An example scenario for MP-IP

Video clips of MP-IP from AutoSim:

- https://youtu.be/kkIBU2MncUU
- https://youtu.be/4UDjBE4RCRw

4.2.2 Advanced Maximum Progression Intersection Protocol (AMP-IP)

This protocol is built based on MP-IP's key idea that conflicting vehicles can make concurrent progress inside the intersection grid when collisions can still be avoided. Additionally, AMP-IP has the advantage of allowing the lower-priority vehicles to cross the conflicting point and clear the conflicting cell before the arrival of the higher-priority vehicle to that cell.

Each vehicle uses its GPS coordinates, controller model parameters and digital map information to calculate its current position, velocity and distance to any point at the intersection grid. All this information is used as inputs to measure the exact arrival time of the vehicle to each cell along its trajectory while crossing the intersection area. When a vehicle detects a potential collision with a higher-priority vehicle, it compares its own arrival time at the conflicting cell with the exit time of the higher-priority vehicle from the same cell. If its arrival time is sufficiently earlier than higher-priority vehicle's exit time, then it can go ahead and cross the conflicting cell without stopping at the intersection.

To ensure the safe passage of both the *potentially conflicting* vehicles, we use a *Safety Time Interval* to increase the safety and make sure that the lower-priority vehicle has enough time to leave and clear the conflicting cell completely, before the arrival of the higher-priority vehicle to that cell.

Based on the Newtonian equations of motion, we set the *Safety Time Interval* as follows:

$$D(t) = D_0 + V_0 . t + \frac{1}{2} . a . t^2$$

$$t = \frac{-V_0 + \sqrt[2]{{V_0}^2 + 2.a.\Delta D}}{2.a} \tag{4.1}$$

As of year 2010, the amount of time that an average vehicle takes to accelerate from 0 miles per hour (mph) to 60 mph is about 8.95 seconds. This value has been calculated by averaging the acceleration parameter of 1,807 car records [95]. Using this value, we calculate the maximum acceleration to be approximately 2.9969 $m/_{s^2}$. The width of each cell is assumed to be 5 meters. The worst-case scenario is when the initial speed of the vehicle is 0 $m/_{s}$ and the time to cross the cell is the maximum possible. By replacing these values in Equation (4.1), the *Safety Time Interval* is calculated as 1.8266s, which has been rounded up to 2s for our protocol.

We now define the terms that will be used in our proof.

- $AT_{V,c}$: Arrival Time of vehicle *V* to cell *c.*
- $ET_{V,c}$: Exit Time of vehicle *V* from cell *c.*
- θ: The *Safety Time Interval*.

Similar to MP-IP, vehicles make use of the intersection safety messages to inform their neighbors about their intentions to enter, cross and finally exit the intersection area. In AMP-IP, the ENTER and CROSS safety messages contain additional information about the cells that will be occupied by the vehicle while crossing the intersection grid. This information includes the estimated arrival time of the vehicle to each of the cells in its TCL through the intersection grid. The same rules as in Algorithm 4.3, apply to all sender vehicles.

The following rules are applied to a vehicle B when it receives intersection messages from a vehicle A, where (A $\neq$ B).

Algorithm 4.6: AMP-IP Receiver Vehicle

Input: Safety message received from vehicle A, *RM*

Output: Vehicle B's movement at the intersection

1. **If** (RM = ENTER or RM = CROSS) **then**
2.   Run CDAI to detect trajectory conflicts with vehicle A and find $TIC_{A,B}$
3.   **If** ($TIC_{A,B}$ = NULL) **then**
4.   Cross the intersection
5.   **Else**
6.   Run FCFS priority policy
7.   **If** ($P_B > P_A$) **then**
8.   Cross the intersection
9.   **Else**
10. $c = TIC_{A,B}$
11.   **If** ($[ET_{B,c} + \theta] < AT_{A,c}$) **then**
12.   Cross the intersection
13.   **Else**
14.   Progress and stop before entering $TIC_{A,B}$
14. **Else if** (RM = EXIT) then
15.   **If** ($TIC_{A,B}$ is cleared) **then**
16.   Cross the intersection

Figure 4.12 shows the same scenario as Figure 4.11 but, with vehicles following AMP-IP rules. As before, since vehicle A has a higher-priority than vehicle B, it gets to cross the intersection without stopping or even slowing down. Vehicle B compares its own arrival time to the TIC, which is cell number 3 with the arrival time of vehicle A to the exact same cell. In the case that vehicle B arrives there earlier, and has enough time to clear the cell before the arrival of vehicle A, then instead of progressing only up to the TIC, it can progress into and clear the conflicting cell number 3.

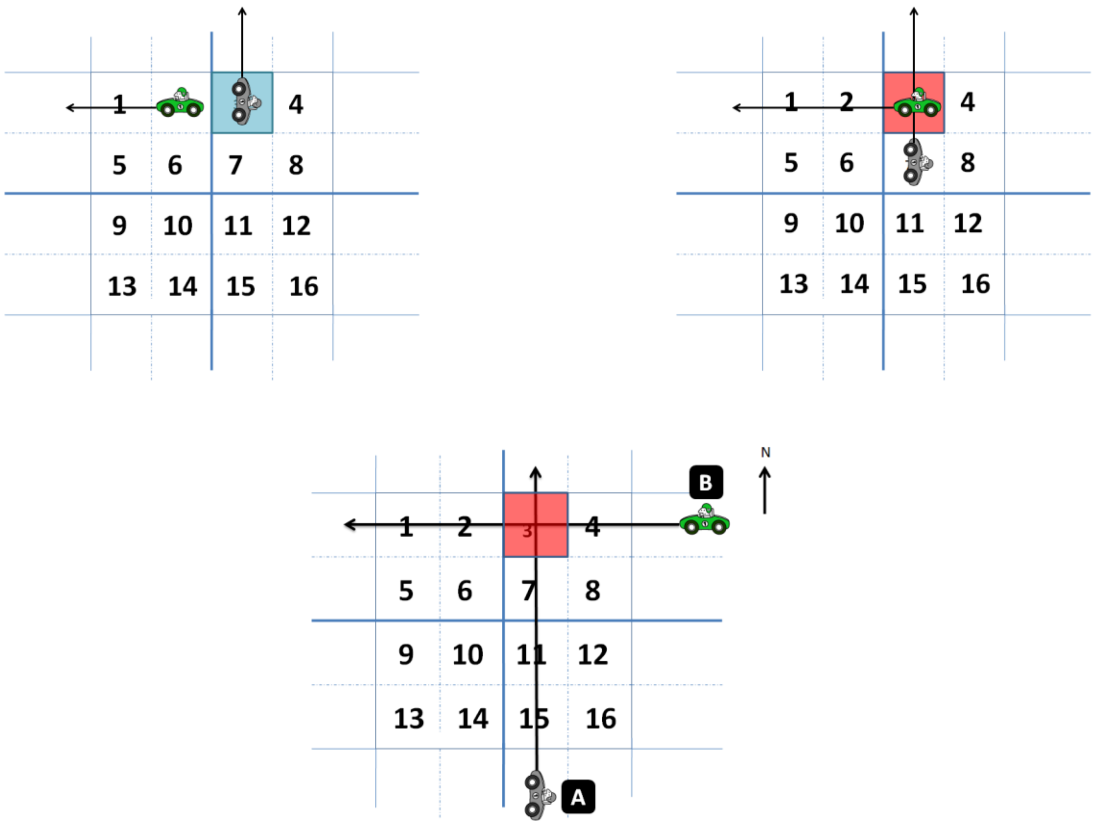


Figure 4-12: An example scenario for AMP-IP

So, by using AMP-IP, we allow the lower-priority vehicle to go ahead and cross the conflicting cell before the arrival of the higher-priority vehicle. This action decreases the delay time faced by this vehicle and increases the total throughput of the intersection.

Video Clip of AMP-IP from AutoSim:

- https://youtu.be/D2GDDZ0-nVU

4.2.3 Evaluation

We first look at the case where roads have the same traffic volumes but different types, i.e. the north-bound and the south-bound lanes of the intersection are primary roads and the south-bound and the west-bound lanes, are secondary roads. Hence, the vehicles on primary roads have higher priority over vehicles coming from secondary roads to cross the intersection. As we can see in Figure 4.13, both V2V-Intersection models perform almost the same as their performance in the scenario that all the roads have the same type (same priority), for low and medium traffic volumes. And they perform slightly better in the case of high traffic densities.

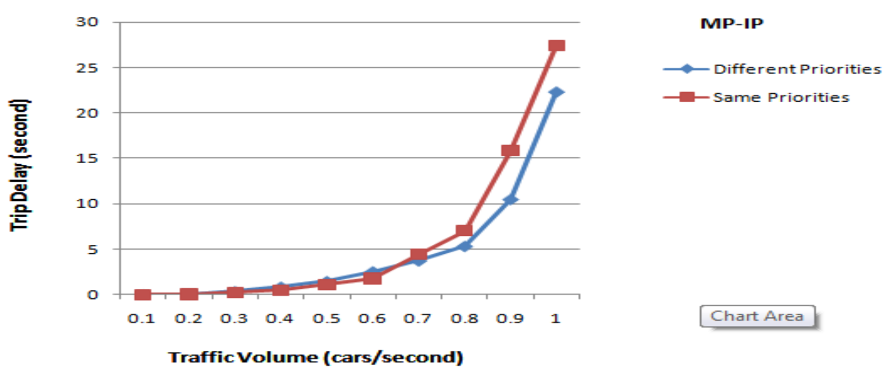


Figure 4-13: Delay comparison between the normal intersection and when the intersection roads have same traffic volume but different types (priorities) in MP-IP model

We next studied the case that the traffic volume is significantly different on the intersection roads. We assume that the roads coming to the intersection from the North and the South have higher traffic densities than the roads on the East and the West. However, the roads have the same type and priority to cross the intersection. Figure 4.14 shows that the *Maximum Progression-Intersection Protocol (MP-IP)* performs better than *the Concurrent Crossing-Intersection Protocol (CC-IP)* and both V2V-based models outperform the traffic light model significantly. Figure 4.15 illustrates the performance comparisons between the asymmetric traffic (various traffic volumes among the intersection roads) and the symmetric traffic, for each intersection model, including the traffic light model and our V2V-Intersection model MP-IP. As we expect, the vehicles arriving on the higher traffic density roads face higher delays which increases the overall average delay.

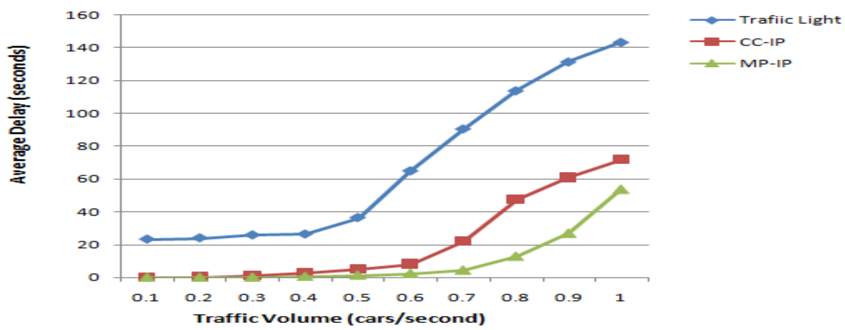


Figure 4-14: Delays when the traffic is asymmetric and some intersection roads have higher traffic volumes

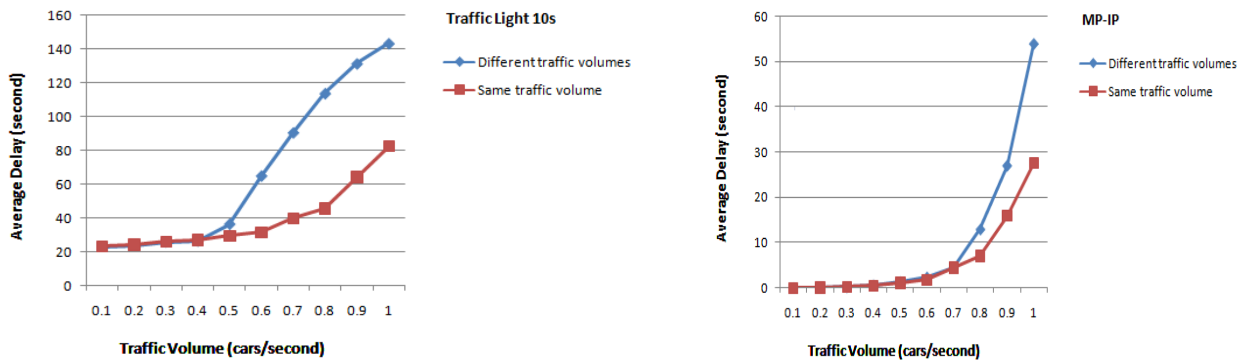


Figure 4-15: Delay comparisons between the symmetric and asymmetric intersections, managed by (a) Traffic Lights and (b) MP-IP

We then studied the scenario in which higher priorities have been assigned to high-traffic-volume roads, in order to allow more vehicles to cross the intersection coming from the higher density roads. This reduces the backed-up traffic and accordingly increases the overall throughput of the intersection. Figure 4.16 shows the comparisons between two different scenarios using the *Maximum Progression-Intersection Protocol (MP-IP)*. Both scenarios look at asymmetric intersections, in which the traffic volume is not the same among all legs of the intersection. In V2V-Intersection model, assigning higher priorities to higher traffic volume roads outperforms the scenario that all legs of the intersection have the same priority. The improvement is small at low volume traffic but it increases significantly as the traffic density increases. These results highlight the importance of priority policy and how assigning higher priorities to vehicles on the high volume traffic roads can decrease the overall delay and increase the throughput of the intersection significantly while dealing with large number of vehicles at the intersection.

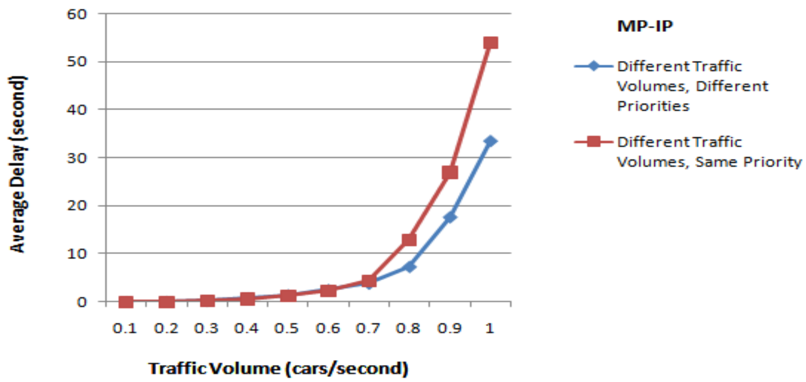


Figure 4-16: Delays at asymmetric intersections. Comparison of same priority assignment, with assigning higher priorities to higher traffic volumes, managed by V2V-intersection protocol MP-IP

We have compared the traffic light model to the best Low-Concurrency Protocol: the Concurrent Crossing-Intersection Protocol (CC-IP), and the two High-Concurrency Protocols: the Maximum Progression-Intersection Protocol (MP-IP) and the Advanced Maximum Progression-Intersection Protocol (AMP-IP). Figure 4.17 shows this comparison for a perfect-cross intersection. The traffic is assumed to be symmetric, meaning equal amount of traffic volume in every direction and an equal amount of turn ratios. The X-axis is the traffic volume determined as cars per second and the Y-axis is the delay in seconds.

All our V2V-based models outperform the traffic light models. CC-IP, MP-IP and AMP-IP have respectively 48.78% and 70.82% and 85.75% overall performance improvements over the traffic light model with a 10-second green light time. The average delay is very negligible for lower traffic volumes in MP-IP and AMP-IP V2V-based models. Under MP-IP and AMP-IP, the delays stay very low even with higher traffic volumes. AMP-IP outperforms CC-IP and MP-IP respectively by 69.94% and 51.15%. Based on our results under AMP-IP, the average delay faced by vehicles at the intersection, even in very high traffic densities, is as low as 22 seconds. Note that this traffic volume is significantly higher than the traffic density in Manhattan area during rush hour.

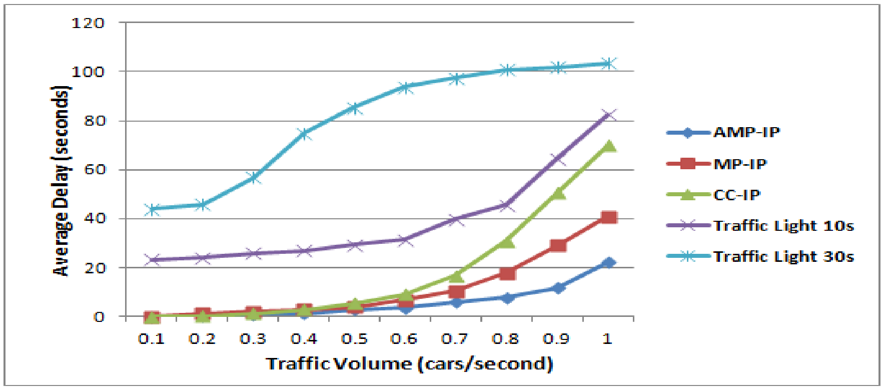


Figure 4-17: Delay comparison among different mobility models

We next studied the case where the traffic volume is significantly different on the intersection roads. We assume that the North-South directions of the intersection have higher traffic density and the intersecting East-West directions have the roads with lower traffic on them. However, the roads have the same type and priority to cross the intersection. Figure 4.18 shows that the Advanced Maximum Progression-Intersection Protocol (AMP-IP) performs better than other V2V-based models and also outperforms the traffic light model significantly. Figure 4.19 illustrates the performance comparisons between the asymmetric traffic (various traffic volumes among the intersection roads) and the symmetric traffic under the rule of AMP-IP and the traffic light model. As we expect, the vehicles arriving on the higher traffic density roads face higher delays which increases the overall average delay. In the case of the traffic light model, this difference is huge and unfair, since vehicles arriving from the higher volume traffic direction are forced to face much higher delays. However, AMP-IP results in more fair passage of vehicles through the intersection.

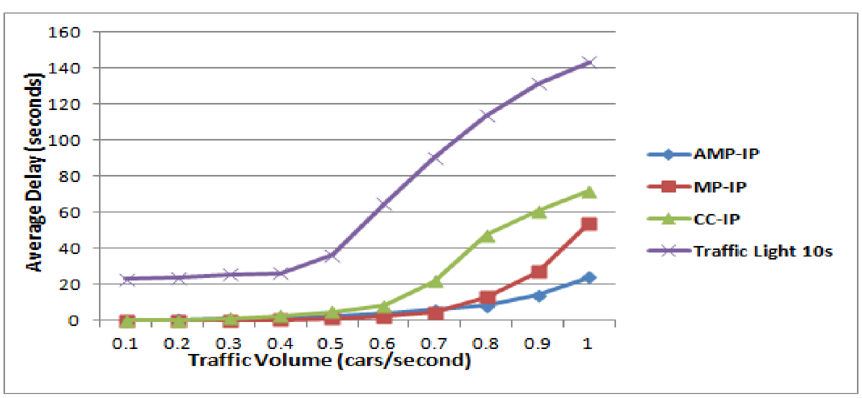


Figure 4-18: Delay comparison for asymmetric traffic.

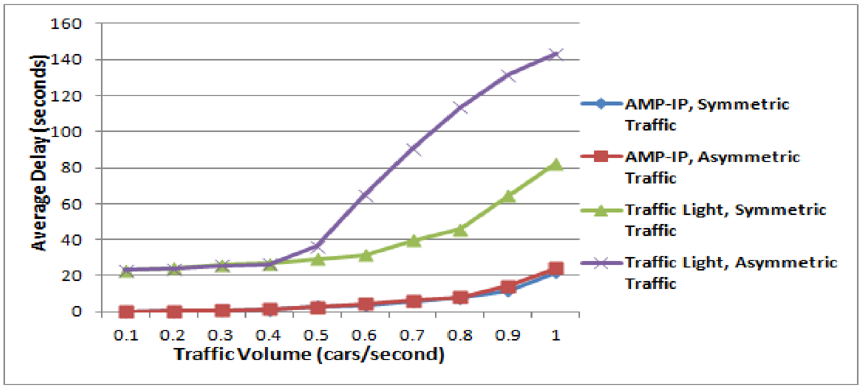


Figure 4-19: Delay comparison between traffic light and AMP-IP in symmetric and asymmetric traffic.

We finally studied the scenario in which higher priorities have been assigned to high-traffic-volume roads, in order to allow more vehicles to cross the intersection coming from the higher-density roads. This reduces the backed-up traffic and accordingly increases the overall throughput of the intersection. Figure 4.20 shows the comparisons between two different scenarios using AMP-IP. Note that assigning higher priorities to higher traffic volume roads outperforms the scenario that all legs of the intersection have the same priority. The improvement is small at low volume traffic but it increases significantly as the traffic density increases. These results highlight the importance of an appropriate priority policy and how assigning higher priorities to vehicles on the high-volume traffic roads can decrease the overall delay and increase the throughput of the intersection significantly while dealing with a large number of vehicles at the intersection.

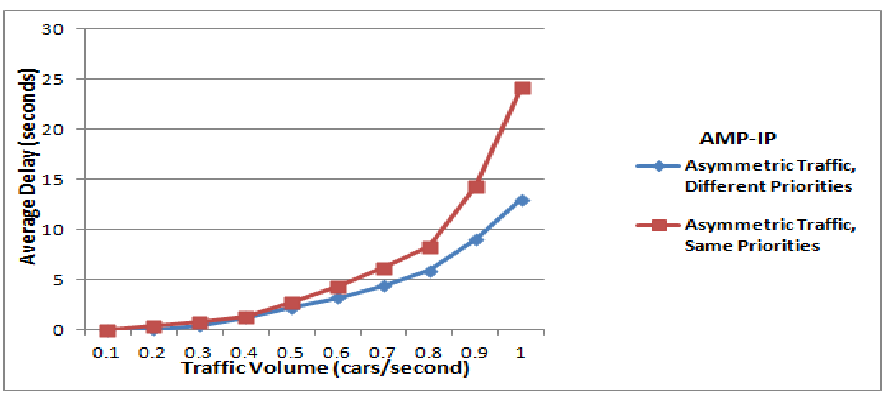


Figure 4-20: AMP-IP Average delays. Higher priority is assigned to higher volume roads.

4.3 High-Concurrency Protocols with Enhanced Vehicle Dynamics (HCP-EVD)

In both MCP and HCP categories, *potentially conflicting* vehicles with lower priority must come to a complete stop outside or inside the intersection area to allow the safe passage of higher-priority conflicting vehicle. When the vehicle comes to a complete stop inside or outside of the intersection box, it needs to start again and accelerate to reach its desired speed. The delay due to stopping and starting again depends on the vehicle's dynamics such as its acceleration parameter. This delay is not negligible, and multiple stops and moves increase the trip time of the vehicle.

We have designed the HCP-EVD scheme to decrease the delays due to complete stops, and also to increase the fuel efficiency of vehicles. Additionally, avoiding numerous stops will increase the comfort of passengers. To achieve these goals, HCP-EVD protocols will allow lower-priority conflicting vehicles to slow down while approaching an intersection and prior to reaching the conflicting cell, to provide the higher priority-vehicle with necessary time gap to cross. This minimizes a vehicle's need to get to a complete stop, and also the total number of stops and startups will be decreased significantly. HCP-EVD includes Advanced Cross Intersection Protocol (AC-IP) and Advanced Progression Intersection Protocol (AP-IP) [120].

4.3.1 Advanced Cross Intersection Protocol (AC-IP)

This protocol is designed to increase the throughput at intersections while avoiding collisions. This intersection management protocol is based on pure V2V communications. The key idea of this protocol is to allow non-conflicting vehicles to concurrently cross the intersection. Each vehicle uses ENTER, CROSS and EXIT safety messages to interact with other vehicles in its communication range.

In addition to the Intersection-states defined in chapter 3.3.3, we define the following intersection-state

- *Intersection-Wait*: when the vehicle is stopped at the entrance of the intersection and waiting for other vehicles.

The following notations will be used throughout the rest of this section:

- $IS_V = \Gamma_W$: Vehicles ***V***'s intersection state is Intersection-Wait, and it is waiting for vehicle ***W*** to cross the intersection.
- V_W : Current velocity of vehicle ***W***.

The following rules are applicable to all vehicles:

Algorithm 4.7: AC-IP, Sender Vehicle

Input: Vehicle's *intersection state*

Output: Broadcast intersection safety message

```
if STATE=Intersection-Approach or STATE=Intersection-Wait then
    Broadcast ENTER message
else if STATE=Intersection-Enter then
    Broadcast CROSS message
else if STATE=Intersection-Exit then
    Broadcast EXIT message
```

And here are the rules applied to a vehicle B when it receives intersection messages from a vehicle A (A ≠ B).

Algorithm 4.8: AC-IP, Receiver Vehicle

Input: Safety message received from vehicle A, ***RM***

Output: Vehicle B's movement at the intersection

```
if RM = ENTER then
    Run CDAI to detect trajectory conflicts with vehicle A and find TIC_{A,B}
    if (TIC_{A,B} = NULL) then
        Cross the intersection
    Else
        Run FCFS priority policy
        if (P_B > P_A) then
            Try to Cross the intersection
        Else
            Slow down and call Set Desired Speed
else if RM = CROSS then
    Run CDAI to detect trajectory conflicts with vehicle A and find TIC_{A,B}
    if (TIC_{A,B} ≠ NULL) then
        Slow down and call Set Desired Speed
    Else
        Compete with other vehicles in the same situation*
```

17. else if *RM = EXIT* **then**
18. **if** Intersection is cleared **then**
19. Cross the intersection

The desired velocity is calculated to allow the vehicle to slow down in time and arrive at the intersection when the higher-priority vehicle is exiting the intersection. The vehicle will then accelerate and increase its speed to the maximum speed limit and cross the intersection area as fast as possible.

Algorithm 4.9: *Set Desired Speed*

Inputs:
Exit-Time of higher-priority vehicle A, $\boldsymbol{ET_A}$
Acceleration parameter of vehicle B, $\boldsymbol{AC_B}$
Deceleration parameter of vehicle B, $\boldsymbol{DC_B}$
Vehicle B's trajectory length through the intersection, $\boldsymbol{D_B}$

Output: Vehicle B's *Desired Speed*, $\boldsymbol{DS_B}$

Use the Newtonian equation for motion and calculate the *Desired Speed*

$$DS_B = DC_B * (ET_A - CurrentTime) + V_B$$

Update the *Exit-Time* of vehicle B

$$ET_B = (ET_A - CurrentTime) + \frac{-DS_B + \sqrt{{DS_B}^2 + 2 * AC_B * D_B}}{2 * AC_B}$$

To avoid any collisions inside the intersection area, the lower-priority vehicle will still be waiting to receive the EXIT safety message while it is slowing down and approaching the intersection. In the case that the vehicle does not receive the appropriate EXIT message and its distance to the entrance of the intersection is less than a threshold, it will come to a complete stop and wait for that message before accelerating and crossing the intersection box.

We now illustrate AC-IP with an example. Figure 4.21 shows a simple scenario in which vehicles A and B are approaching an intersection. Since vehicle A has a lower Arrival-Time than vehicle B, it has a higher priority based on our FCFS priority policy. Vehicle A is going to cross the intersection without stopping or slowing down. In contrast, vehicle B has to slow down and adjust its speed to arrive at the intersection when vehicle A is exiting it. When vehicle B arrives at the intersection and receives the EXIT safety message from vehicle A, it knows that the intersection area is safe and clear for its passage.

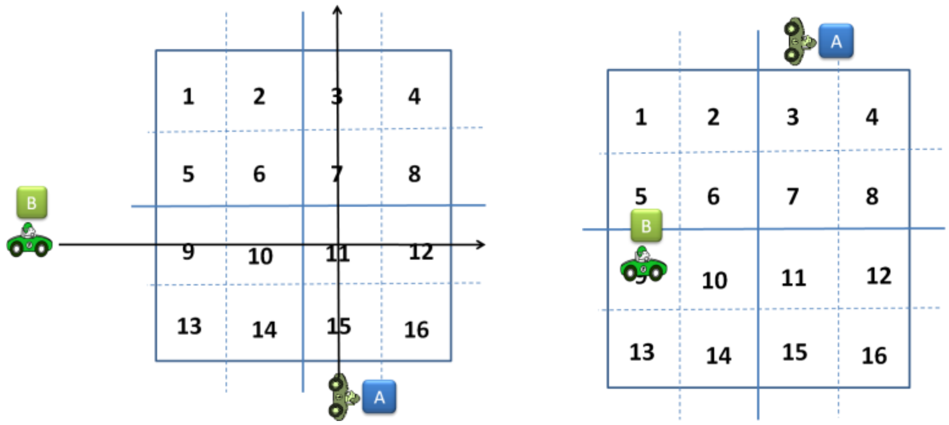


Figure 4-21: An example scenario of AC-IP

If no potential collision has been detected with the sender of the CROSS message, the receiver may still not be allowed to cross the intersection area. The reason is that there might be more than one vehicle which has no conflict with the crossing vehicle. In this situation, these vehicles may attempt to cross the intersection area concurrently without being aware that they may collide with each other.

The net result is that, the receiving vehicles make sure that they do not have trajectory conflicts with each other before entering the intersection area. As discussed before, they may use the received ENTER messages and detect any potential collisions with other receivers of the CROSS message, which are waiting to enter the intersection box. If no potential collision is detected with all other leader vehicles, it can cross. This means that it can cross the intersection safely while broadcasting the CROSS message.

Figure 4.22 shows two junction situations in which vehicle A is crossing the intersection box and is broadcasting the CROSS message. Vehicles B and C are receiving these safety messages and run the CDAI algorithm. Both vehicles get to the same decision that they do not have a potential collision with vehicle A. In Figure 4.22(a), vehicles B and C can cross at the same time as vehicle A, since none of them has a space conflict with the other two. As can be seen in Figure 4.22(b), vehicles B and C may collide as they have a conflicting trajectory along the intersection. Therefore, only one of them can safely cross through the intersection box while vehicle A is crossing. The other vehicle must slow down and enter the intersection box only after receiving the EXIT safety message from the higher-priority vehicle. In Assuming that vehicles B has a higher priority than and vehicle C according to the *priority policy*, it can cross, while vehicle C is slowing down to arrive at the intersection when vehicle B has exited it.

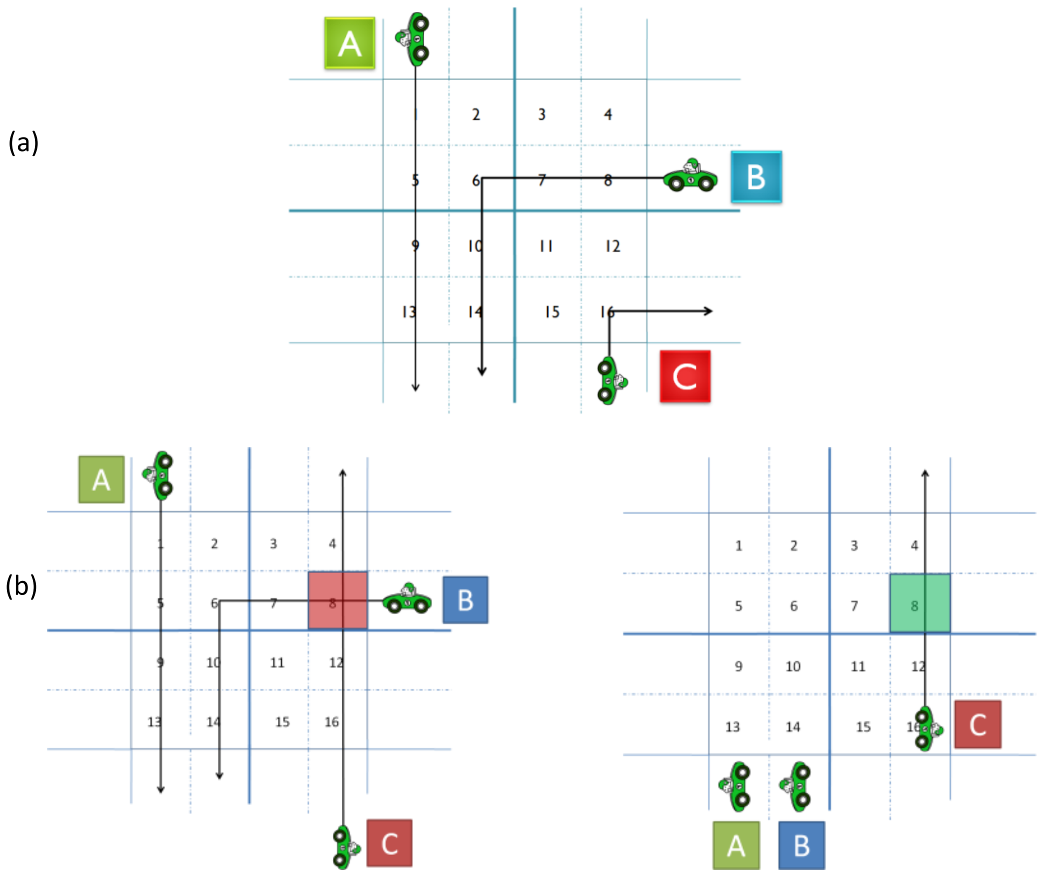


Figure 4-22: Example scenarios of AC-IP at intersections

A video clip of AP-IP from AutoSim is available at:

- https://youtu.be/VKoyaz2JmxU

4.3.2 Advanced Progression Intersection Protocol (AP-IP)

AP-IP is based on AMP-IP's key idea that conflicting vehicles can make concurrent progress inside the intersection grid when collisions can still be avoided. Additionally, AP-IP has the advantage of allowing the lower-priority vehicles to make smart speed decisions about crossing the conflicting cell.

The lower-priority vehicle's behavior will be determined based on various physical attributes and those of the higher-priority vehicle, such as their velocities, acceleration and deceleration parameters. The vehicle will make the appropriate decision for a safe passage through the intersection area. The lower-priority vehicle will pick one of the following actions, when it faces potentially conflicting scenarios:

1) Crosses the conflicting point and clears the trajectory intersection cell (TIC) before the arrival of the higher-priority vehicle to that cell.
2) Reduces its speed and arrives at the conflicting point when the higher-priority vehicle has cleared and exited that cell.

The same rules as in Algorithm 4.7 apply to all sender vehicles. Please note that each vehicle is broadcasting its updated TCL information within the ENTER and CROSS safety messages. This information includes the estimated arrival and exit times of each cell along vehicle's trajectory through the intersection grid.

The following rules are applied to a vehicle B when it receives intersection messages from a vehicle A, where (A ≠B).

Algorithm 4.10: AP-IP, Receiver Vehicle

Input: Safety message received from vehicle A: ***RM***
Output: Vehicle B's movement at the intersection
if *RM = ENTER* or *RM = CROSS* **then**
    Run CDAI to detect trajectory conflicts with vehicle A and find $TIC_{A,B}$
    if ($TIC_{A,B} = NULL$) **then**
        Cross the intersection
    Else
        Use FCFS priority policy
        if ($P_A < P_B$) **then**
            Cross the intersection
        Else
            $c = TIC_{A,B}$
            if ($[ET_{B,c} + \theta] < AT_{A,c}]$) **then**
                Cross the $TIC_{A,B}$
            Else
                Slow down and call *Set Desired Speed*
else if *RM = EXIT* **then**
    if $TIC_{A,B}$ is cleared **then**
        CROSS the intersection

, where θ is the *Safety Time Interval*. As mentioned earlier, to ensure the safe passage of both the potentially conflicting vehicles, we use a *Safety Time Interval* to increase the safety and make sure that the lower-priority vehicle has enough time to leave and clear the conflicting cell completely, before the arrival of the higher-priority vehicle to that cell.

Figure 4.23 shows an example scenario of vehicles following AP-IP rules. Vehicles A and B are approaching an intersection. Assume that vehicle A has a higher priority than vehicle B. Vehicle B will compare its arrival to the TCL cell number 11, to the exit time of the higher-priority vehicle A to the same cell. In the case that vehicle B arrives earlier and has enough time to clear the TCL before the arrival of vehicle A, it can progress and clear cell number 11. This behavior of the lower-priority vehicle will decrease the delay and increase the overall throughput of the intersection without sacrificing safety.

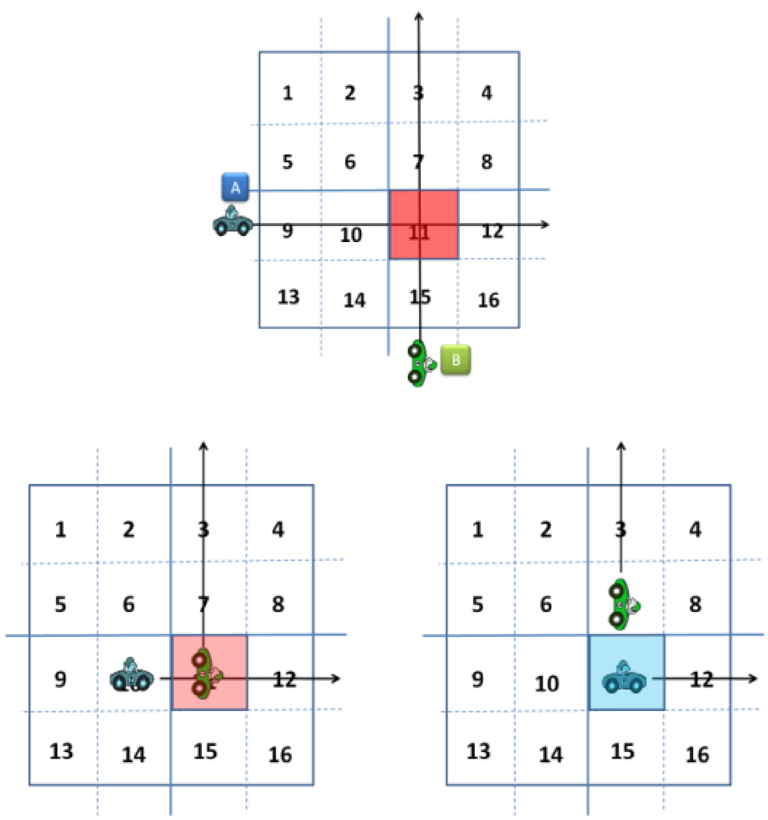


Figure 4-23: An example scenario of AP-IP

Figure 4.24 illustrates another scenario under AP-IP. In this case, the lower-priority vehicle B does not have enough time to progress and clear the TCL cell number 7, before the arrival of the higher-priority vehicle A. Therefore, vehicle B must adjust its velocity to prevent any potential collision at the TCL. It uses the information obtained by the received safety messages from vehicle A, its own digital map and GPS coordinates and physical model characteristics such as velocity, acceleration/deceleration parameters to determine the appropriate speed for approaching and progressing inside the intersection grid. The goal is to decrease the speed to arrive at the TCL right after the exit of the higher-priority vehicle from that cell. Please note that in the extreme case of slowing down would be getting to a complete stop before entering the TCL and waiting for the higher-priority vehicle to clear and exit the conflicting cell.

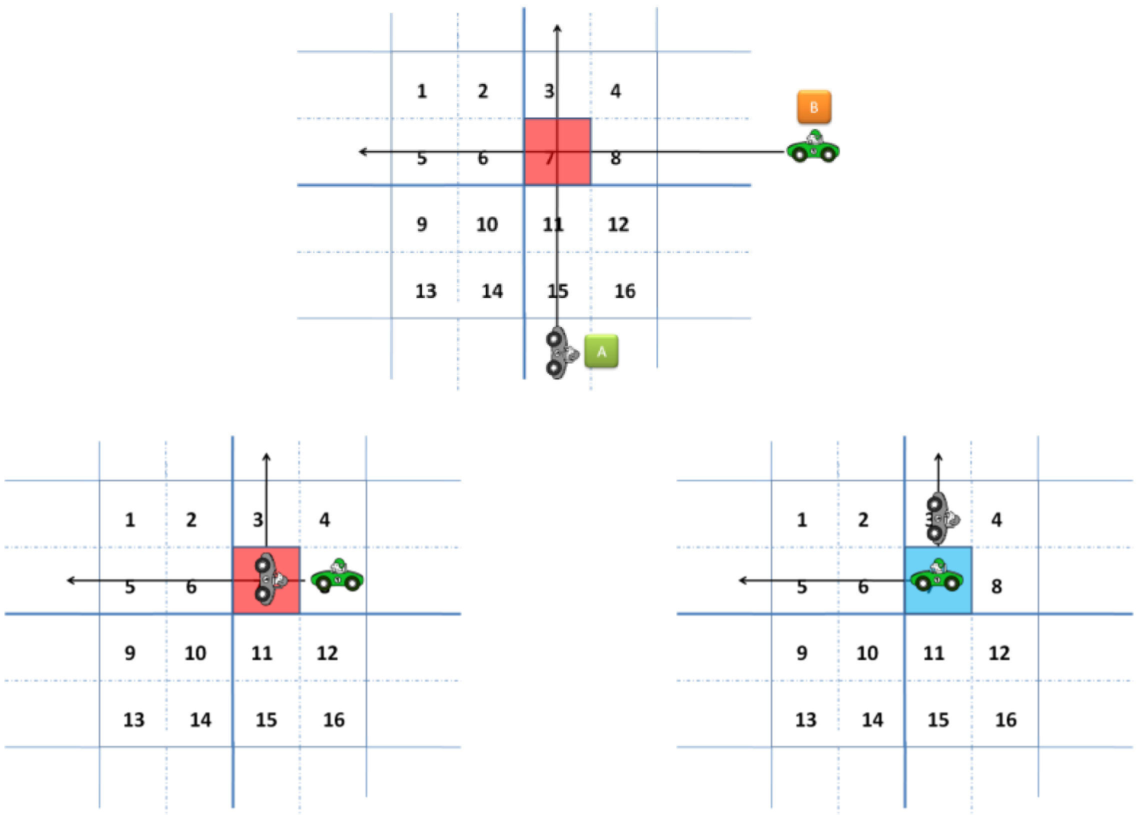


Figure 4-24: An intersection example scenario of AP-IP

A video clip of AP-IP from AutoSim:

- https://youtu.be/RbqEShPWlTE

4.3.3 Evaluation

Figure 4.25 shows the comparison among the traffic light with green light duration 30 seconds and 10 seconds and our new V2V protocols, Advanced Cross-Intersection Protocol (AC-IP) and Advanced Progression-Intersection Protocol (AP-IP). The X-axis marks the traffic volume in vehicles per hour and the Y-axis is the *Trip Delay* in seconds.

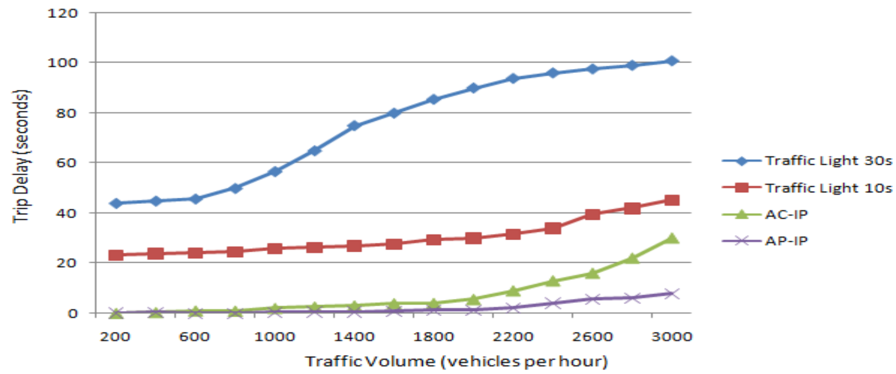


Figure 4-25: Trip delay comparison of different mobility models

We can see that our intersection management models significantly outperform the current technology. AC-IP improves throughput by up to 79.92% and 64.12% respectively, compared to the traffic light models of 30s and 10s green lights. AP-IP outperforms the traffic light model of 30s, 10s and AC-IP by respectively 92.51%, 87.82% and 72.26%. AC-IP and AP-IP have negligible delays for low and medium traffic volumes. AP-IP has very low delay even when dealing with high traffic volumes. By allowing multiple vehicles to cross simultaneously and avoiding multiple stops and moves by adjusting their speed before the arrival at the intersection, AP-IP achieves high performances.

4.4 Summary

In this chapter, we defined a family of distributed intersection protocols which rely mainly on vehicle-to-vehicle (V2V) communications. All V2V-IPs are designed to increase safety by avoiding vehicle collisions at intersections. Additionally, V2V-Intersection Protocols decrease the overall delay by increasing the parallelism and allowing the concurrent crossing of multiple vehicles through the intersection.

4.4.1 V2V-Intersection Protocol Categorization

V2V-Intersection Protocols are categorized based on the behavior of *potentially-conflicting* vehicles at intersections. The first generation of STIP protocols is called Low-Concurrency Protocols (LCP). In this category, the *potentially-conflicting* vehicle with higher priority can ignore the intersection safety messages from other lower-priority vehicles and cross the intersection without slowing down or stopping. However, any lower-priority vehicle is cautious and when it loses a competition, it comes to a complete stop before entering the intersection boundaries, and waits till it receives an EXIT message, from the higher-priority vehicle. This message informs the lower-priority vehicle that the higher-priority vehicle has crossed the intersection and now the intersection area is safe for its passage. LCP has the granularity of the intersection grid, meaning that vehicles consider the whole intersection grid as one big cell. Due to its granularity, LCP is the most suitable V2V-IP category when dealing with low positioning accuracy levels and low communication reliability.

Second generation of V2V-IPs is called High-Concurrency Protocols (HCP). The main goal of the proposed HCP family of intersection protocols was to further increase the parallelism inside the intersection area by allowing more vehicles to cross the intersection at the same time. To achieve this scheme's goal, it allows even *potentially conflicting* vehicles to make maximal progress inside the intersection area, without sacrificing the primary goal of safety. In contrast to LCP, in which lower-priority vehicles should stop before entering the intersection box and wait for the higher-priority vehicle to clear the intersection area, HCP allows all vehicles to progress inside the intersection grid, and only stop before the potential conflicting cell. Comparing to the LCP, the High-Concurrency Protocols (HCP) require intersection cell granularity. Therefore, high accuracy positioning system and digital map is needed for all vehicles. These requirements enable each vehicle to know the cell geometry of an approaching intersections, cell positions and vehicles position relative to the intersection cells. Vehicles are then able to update their Trajectory Cells List (TCL) while entering and leaving each cell along their trajectories.

In both MCP and HCP categories, *potentially conflicting* vehicles with lower priority must come to a complete stop outside or inside the intersection area to allow the safe passage of higher-priority conflicting vehicle. When the vehicle comes to a complete stop inside or outside of the intersection box, it needs to start again and accelerate to reach its desired speed. The delay due to stopping and starting again depends on the vehicle's dynamics such as its acceleration parameter. This delay is not negligible, and multiple stop-and-goes increase the trip time of the vehicle. We have designed the High-Concurrency Protocols with Enhanced Vehicle Dynamics (HCP-EVD) to decrease the delays due to complete stop-and-goes, and also to increase the fuel efficiency of vehicles. Additionally, avoiding numerous stops will increase the comfort of passengers. To achieve these goals, HCP-EVD protocols allow lower-priority conflicting vehicles to slow down while approaching an intersection and prior to reaching the conflicting cell, to provide the higher priority-vehicle with necessary time gap to cross. This minimizes a vehicle's need to get to a complete stop, and also the total number of stops and startups will be decreased significantly. In addition to constrains and requirements mentioned for the HCP, the High-Concurrency Protocols with Enhanced Vehicle Dynamics (HCP-EVD) requires tight time synchronization among vehicle agents and highly accurate timing calculations based on each vehicles specific physical parameters. Additionally, vehicles should be capable of accelerating and decelerating in a timely manner, and therefore, enhanced vehicle dynamics are needed. These requirements provide each vehicle with the capability to accurately calculate its arrival and exit time to each cell inside the intersection box, as well as setting the desired speed and appropriate acceleration/deceleration parameters to adjust its speed when necessary.

We conclude that all our V2V-intersection protocols achieve high throughput and outperform stop-sign and traffic-light models while guaranteeing the safe passage of vehicles through intersections. Within the V2V-IP category, we recommend using the Low-Concurrency Protocols (LCP) when fine-grained cell related information is *not* available. Considering the intersection box as a big cell, LCP only requires coarse-grained intersection geometry information and manages the safe and efficient crossing of autonomous vehicles through intersections despite dealing with higher levels of positioning inaccuracy or higher packet loss ratio. The High-Concurrency Protocols (HCP) are strongly recommended when fine-grained intersection cell information is available to all approaching vehicles. HCP achieves much higher throughput than LCP. However, HCP requires higher positioning accuracy levels and lower packet loss ratios in order to achieve its high performance. The High-Concurrency Protocol with Enhanced Vehicle Dynamics (HCP-EVD) represents the best-performing intersection protocol, since it provides the highest throughput among the V2V-IP protocols. To achieve this high performance, HCP-EVD also requires tight time synchronization among approaching vehicles and accurate knowledge of vehicle dynamics to be able to perform the necessary speed adjustments in a timely manner.

4.4.2 Delay Comparisons

Here is a summary of delay comparison among the stop-sign, traffic light models and our proposed V2V-based protocols: (1) *Low-Concurrency Protocols (LCP):* Throughput Enhancement Intersection Protocol (TE-IP) and Concurrent Currency Intersection Protocol (CC-IP). (2) *High-Concurrency Protocols (HCP):* Maximum Progression Intersection Protocol (MP-IP) and Advanced Maximum Progression Intersection Protocol (AMP-IP). (3) *High-Concurrency Protocols with Advanced Vehicle Dynamics (HCP-EVD):* Advanced Crossing Intersection Protocol (AC-IP) and Advanced Progression Intersection Protocol (AP-IP). Figure 4.26 shows this comparison for a perfect-cross intersection. The traffic is assumed to be symmetric, meaning equal amount of traffic volume in every direction and an equal amount of turn ratios. The X-axis is the traffic volume determined as cars per second and the Y-axis is the delay in seconds.

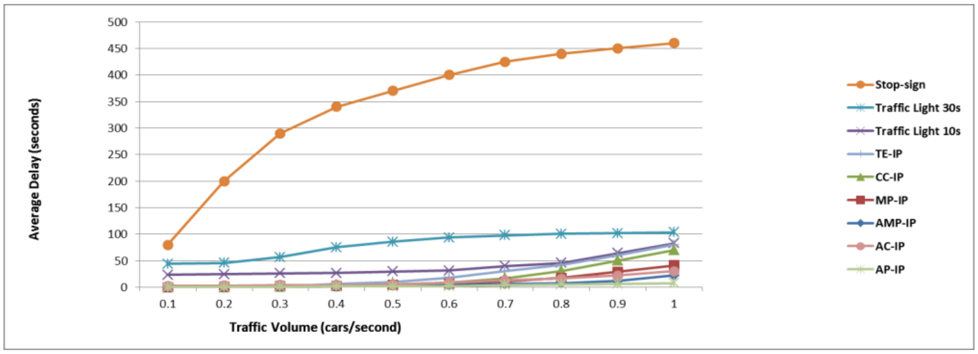


Figure 4-26: Delay comparison among different mobility models

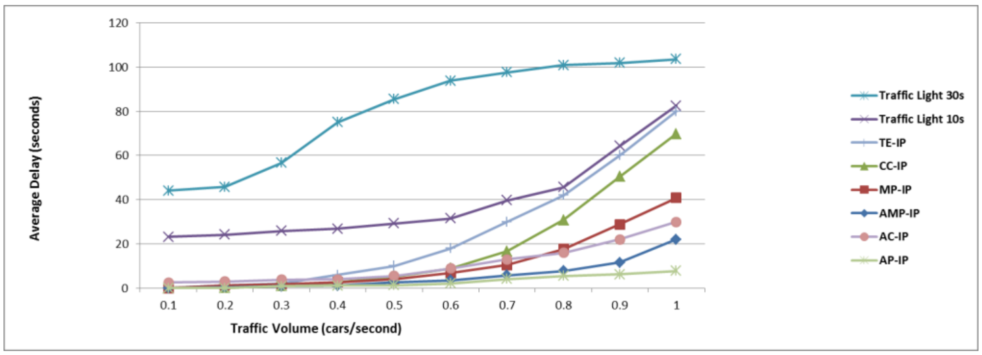


Figure 4-27: Delay comparison among different mobility models

As we can see in Figure 4.26, vehicles face very high delays under the control of stop-sign model since each vehicle has to stop at the intersection for a certain amount of time even if there is no other vehicle present at the intersection area. Figure 4.27 shows the zoomed-in version of the same results. All our V2V-based models outperform the traffic light models. TEP, CC-IP, MP-IP, AMP-IP, AC-IP and AP-IP have respectively 26%, 48.78%, 70.82%, 85.75%, 64.12% and 87.82% overall performance improvements over the traffic light model with a 10-second green light time. The average delay is very negligible for lower traffic volumes under all V2V-based models. Under MP-IP and AMP-IP, AC-IP and AP-IP the delays stay very low even with higher traffic volumes. Based on our results under AMP-IP and AP-IP, the average delay faced by vehicles at the intersection, even in very high traffic densities, is as low as 22 and 12 seconds respectively. Note that this traffic volume is significantly higher than the traffic density in Manhattan area during rush hour.

4.4.3 Noteworthy Aspects of Our V2V-Intersection Protocols

Each intersection can be governed by a different type of V2V-IP depending on the environmental characteristics as well as available positioning, communication levels and intersection map information. However, all approaching vehicles at a specific intersection should follow the same intersection protocols and run the same distributed set of V2V-IP rules to safely and efficiently cross the intersection.

In the examples provided throughout this chapter, we illustrated fixed-size vehicles which fit completely in one intersection cell. When dealing with larger vehicles, more than one cell will be occupied by the vehicle at any given time during its passage through the intersection grid. Occupying more than one intersection cell also happens when normal size vehicles are crossing the intersection area. For example, when a vehicle is performing a left turn, depending on the cell geometries and vehicle's maneuver characteristics, even more than two cells might be occupied by the vehicle at the same time. It is important to note that based on our V2V-intersection protocol rules, the vehicle's Trajectory Cells List (TCL) includes the current cell and the next cells along its trajectory through the intersection grid. Even if the vehicle is occupying more than one cell, all these cells are included in the TCL and therefore, no other vehicles can enter them. Therefore, all our intersection protocol rules hold and provide safe and efficient crossing even when dealing with larger vehicles and vehicles with different maneuver characteristics.

Chapter 5

V2V-Management at Roundabouts and Intersection Cascading

In Chapter 4, we described a family of vehicular network protocols, which use DSRC and WAVE technologies to coordinate a vehicle's movement through intersections. We have shown that vehicle-to-vehicle (V2V) communications can be used to avoid collisions at the intersection and also significantly decrease the trip delays introduced by traffic lights and stop signs. In this Section, we investigate the use of our proposed V2V-intersection protocols for autonomous driving at roundabouts. We have extended our hybrid emulator-simulator called AutoSim to implement realistic maps and mobility models to study traffic flow at roundabouts and have implemented our V2V-intersection protocols on roundabouts. We quantify the improvement in safety and throughput when our intersection protocols are used to traverse roundabouts [116], [117].

Additionally, we will discuss the extension of the V2V-Intersection Protocols (V2V-IP) to make them more suitable for managing the traffic not only at a single isolated intersection, but at multiple intersections along the vehicles trajectory from its source of travel all the way to the its destination. We will study the challenges faced by our intersection protocols for cascading intersections management. To deal with congested exit-lanes, we propose a method to avoid road blockage and congestion propagation.

5.1 Roundabouts

It is established that roundabouts are safer than junctions. According to a study of a sampling of roundabouts in the United States, when compared with the junctions they replaced, roundabouts have 40% fewer vehicle collisions, 80% fewer injuries and 90% fewer serious injuries and fatalities [3], [4].

While statistics collected by the Insurance Institute for Highway Safety (IIHS) show that when comparing roundabouts to signalized intersections, the number of accidents is decreased by 40% and delays are reduced up to 20% [5], we believe that by using V2V communications as a part of co-operative driving, we are able to further improve the safety and reduce delays more so than already.

A roundabout is a channelized intersection with one-way traffic flow circulating around a central island. Roundabouts are also considered as “traffic-calming” devices since all traffic is slowed to the design speed of the one-way circulating roadway. The average velocity allowed at roundabouts is between 15 and 25 mph. These slower speeds reduce the severity of crashes, and minimize the total number of all crashes inside the roundabout area. Roundabouts are small, generally from 70 to 160 feet in diameter compared to 300 to 400 feet and more for traffic circles and rotaries. Roundabouts have a distinct feature of raised entry splitter islands which constrain vehicle speeds just before entry [3], [4].

The Federal Highway Administration reports that, in just one recent year, approximately one death occurred every hour nationwide relating to intersections. Over nine thousand people lost their lives in traffic intersections in that recent year, equaling nearly one quarter of all traffic fatalities and amounting to a financial loss of over $96 billion due to traffic delays and fuel consumptions [96]. In addition to slower speeds, roundabouts have fewer conflict points than traditional intersections. Figure 5.1 shows a comparison of conflict points between a single-lane roundabout and a single-lane perfect cross intersection. Note that the cross intersection includes 32 conflict points while the number of conflict points at the roundabout is only a quarter of that number, meaning 8 points.

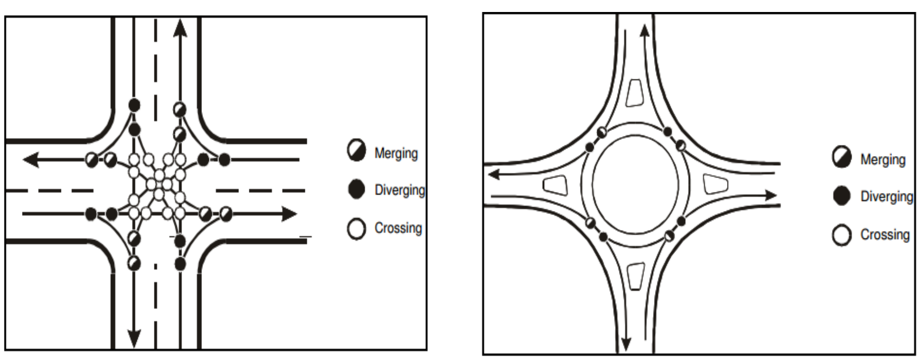


Figure 5-1: Traffic conflicting points at a simple cross intersection and a 1-lane roundabout [12]

Figure 5.2 shows that in multiple-lanes roundabouts, the number of conflict points increases, but it is still much less than the number of conflict points compared to a 2-lane cross intersection.

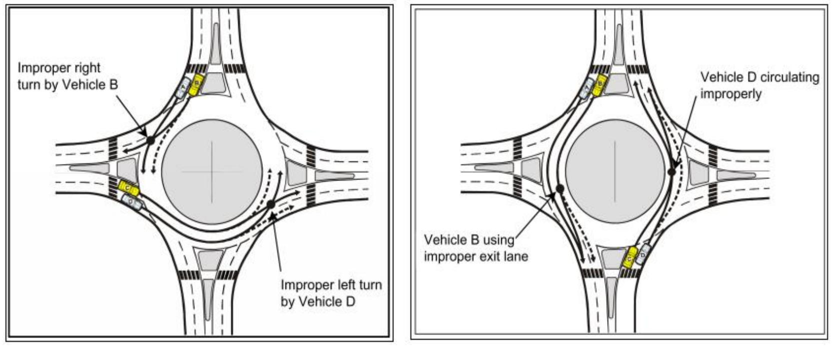


Figure 5-2: Additional conflicting points at multi-lane roundabouts

In addition to the safety benefits of roundabouts, the slower circulating speeds at roundabouts allow entering vehicles to accept smaller gaps in the circulating traffic flow, meaning more gaps are available, increasing the volume of traffic processed. Coming to a complete stop only happens when there is not enough gap due to the high density of traffic. However, when dealing with low traffic volumes, due to the continuously flowing nature of yielding only until a gap is available, roundabouts outperform traffic lights in regard to total throughput and capacity.

5.1.1 Collision Detection at Roundabouts

We define the roundabout as a channelized intersection, in which four roads converge towards a central island from different directions. Each road includes predefined entry and exit points for each lane connected to it. The roundabout area is considered to be a grid which is divided into small cells. Each cell in the roundabout grid is associated with a unique identifier. Figure 5.3 shows a 1-lane roundabout. Note that the roundabout grid is divided into eight small cells and each of them is big enough to fit an average sized vehicle ($4.5\text{m} * 2.5\text{m}$) in it. The cell geometry and number of cells is unique for each particular roundabout and depends on physical parameters of the roundabout area, such as the radius of the intersection and the size of its central island. Cell geometry is also determined based on the number of lanes entering the roundabout from each direction.

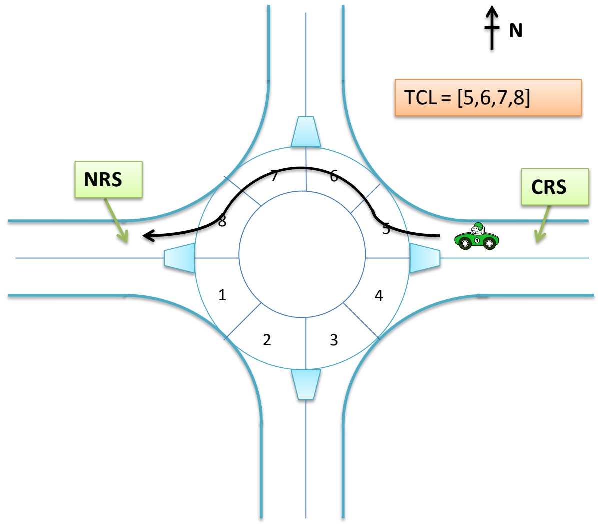


Figure 5-3: illustration of TCL, CRS and NRS at a roundabout grid

Each vehicle uses the information about the Current Road Segment (CRS), Next Road Segment (NRS) and the roundabout's cell geometry to create a list including the cells that will be occupied by the vehicle while crossing the roundabout. This list is called the Trajectory Cells List (TCL). The TCL is sorted based on the order of cells that are entered by the vehicle. Figure 5.3 shows the scenario in which the vehicle is entering the roundabout from the east and going to the west. Based on the CRS, NRS and the cell geometry, the vehicle builds its TCL as {5,6,7,8}. As mentioned, all the vehicles are supposed to be equipped with GPS devices and have access to the digital map database as well as the roundabout's coordinates. Therefore, each vehicle is able to use this information to map the current GPS coordinates to its current cell number. The current cell number will be then used to update the TCL and will be broadcast to surrounding vehicles as part of the basic safety message (BSM). Each vehicle uses the information about its current cell to update the TCL while crossing. Specifically when the vehicle leaves one cell and enters a new cell, the previous current cell gets deleted from the TCL. The updated TCL is useful for neighboring vehicles as it gives them explicit information about the cells which are not occupied anymore and might be used by other vehicles to cross the roundabout.

Our Collision Detection Algorithm for Intersections (CDAI), which was described in chapter 3.3, runs on all vehicles, using the information obtained from received safety messages, which are broadcast by surrounding vehicles. The algorithm uses the Trajectory Cells Lists of the sender and the receiver of the safety messages. By comparing the two lists, it determines if there is any common cell along their trajectories while crossing the roundabout. If a potential collision is detected by CDAI, the algorithm returns the first conflicting cell number which we refer to as the Trajectory-Intersecting Cell (TIC).

Figure 5.4 shows two example scenarios, in which two vehicles are crossing the roundabout at the same time. In Figure 5.4(a), one of the vehicles has the TCL of {1,2,3,4} and the other one's TCL is {5,6,7,8}. As there is no common cell along their trajectories, they are able to enter and cross the roundabout at the same time without the potential for any collision. On the other hand, Figure 5.5 illustrates another roundabout-crossing scenario, where there are common cells along crossing vehicles' TCLs and potential collisions may occur. In the example scenario of 5.5(a), the CDAI running on both vehicles will inform them that cell number 5 is the first Trajectory Intersecting Cell (TIC) along their trajectories. And in the case of Figure 5.5(b), cell number 7 is the first TIC of the crossing vehicles.

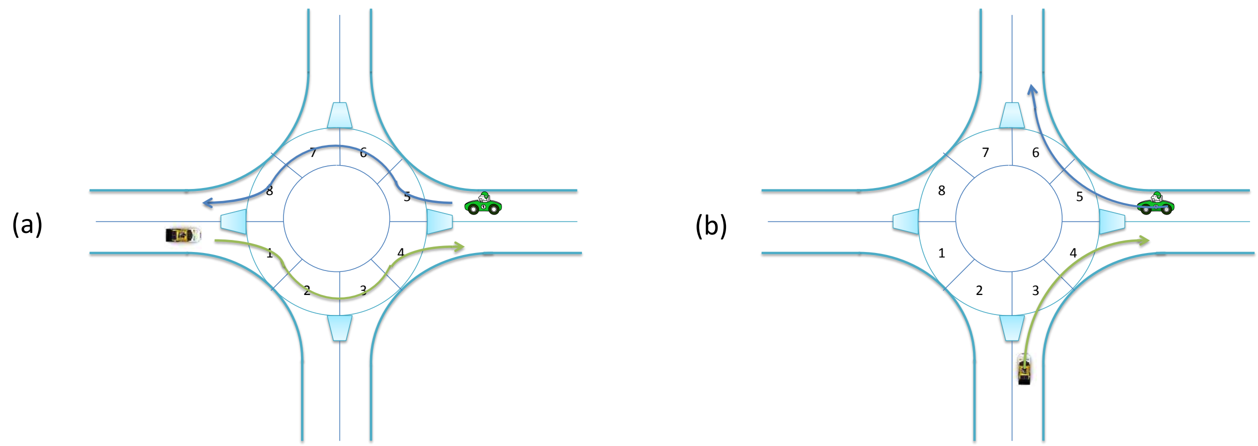


Figure 5-4: Example scenario in which no space conflict occurs at the roundabout

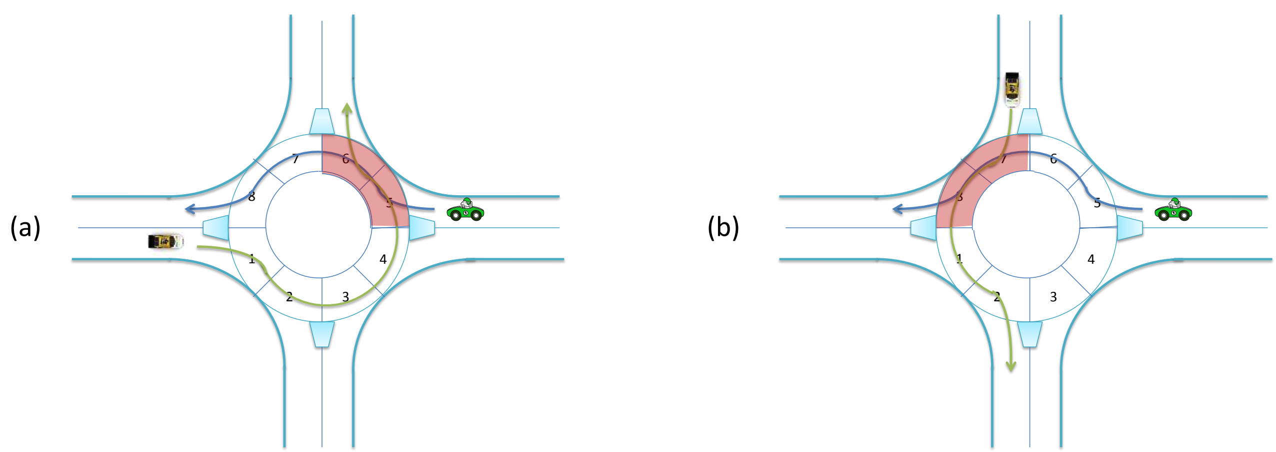


Figure 5-5: Example scenarios of space conflict at the roundabout

In the case that a potential collision is detected by CDAI, the "first come, first served" (FCFS) algorithm is used to assign priorities to vehicles. Based on FCFS, a vehicle, which gets to the entrance of the roundabout with a lower arrival time value, gets to cross the roundabout before other vehicles with higher arrival times. To avoid any deadlock situation, in which two or more vehicles have the same arrival time, tie-breaking rules apply. If vehicles arrive at a roundabout at the same time, our priority policy assigns higher priorities to vehicles entering the intersection using primary roads than vehicles arriving from secondary roads. If these still result in a tie among vehicles, the vehicle with a higher Vehicle ID Number (VIN) will have a higher priority and get to cross the roundabout grid first. The VIN is known unique for each vehicle.

We will now look at a few examples of the V2V-intersection protocols implemented on roundabouts. Please note that in all the V2V-intersection protocols for roundabouts, if no potential collision is detected among two or more approaching vehicles, then all of them enter the roundabout flow without slowing down or stopping, and cross simultaneously.

A video clip from AutoSim for V2V-IP on roundabouts is available at:

- http://youtu.be/DlQSwGAR4hw

5.1.2 Concurrent Crossing –Intersection Protocol at Roundabouts

In Figure 5.6(a), vehicle ***B*** and ***C*** may still collide as they have a conflicting trajectory along the roundabout. Therefore, only one of them can safely cross through the roundabout area while vehicle ***A*** is crossing. The other vehicle will come to a complete stop before entering the roundabout boundaries. Vehicles ***B*** and ***C*** will reach to a decision using the priorities assigned to them by the priority policy so that the vehicle with the higher priority can cross, while the other waits outside the roundabout till it receives the EXIT message from the higher priority vehicle.

In Figure 5.6(b), vehicles ***B*** and ***C*** can cross the roundabout at the same time as vehicle ***A***, since none of them has a conflict with the other two. So, the receiving vehicles make sure that they do not have trajectory conflicts with each other before entering the roundabout area. As discussed before, they may use the received ENTER messages and detect any potential collisions with other receivers of the CROSS message, which are waiting to enter the roundabout area. If no potential collision is detected with all other leader vehicles or if it has the highest priority among them, the receiver can cross the roundabout safely while broadcasting the CROSS message.

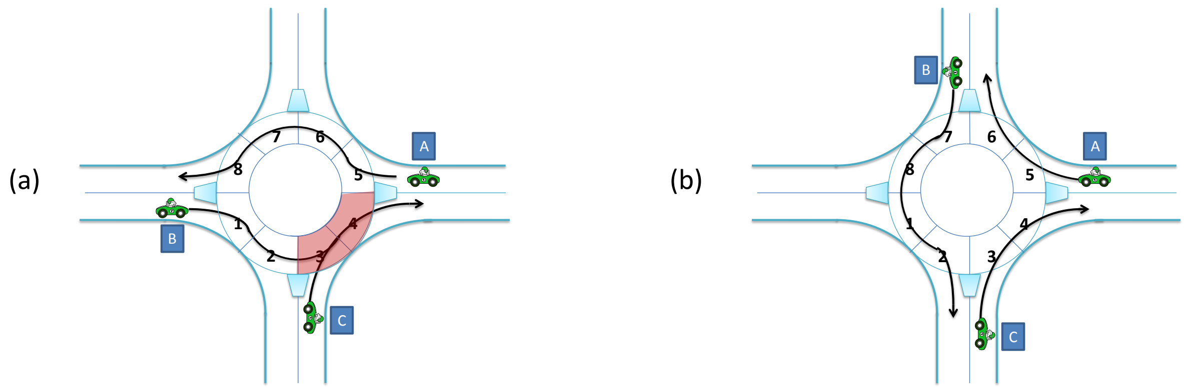
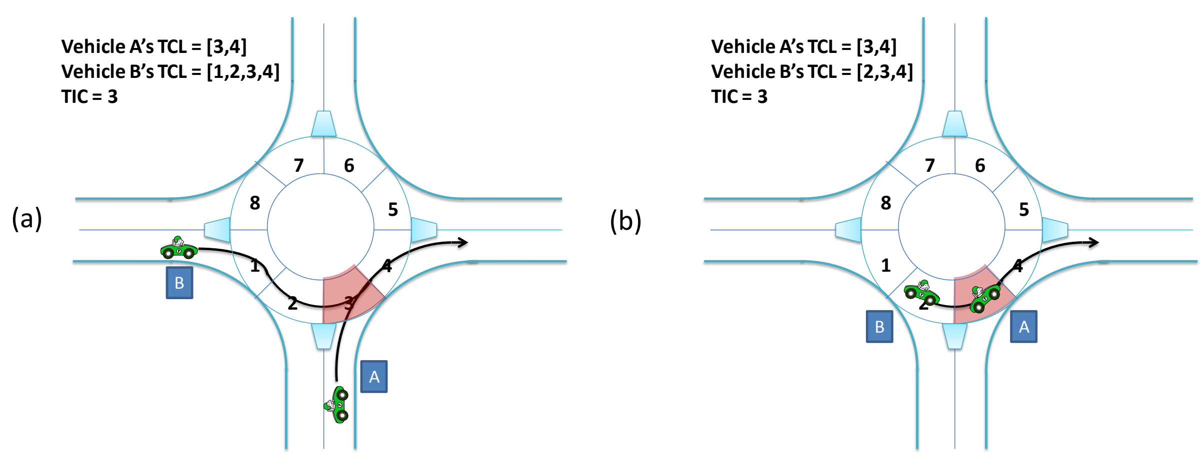


Figure 5-6: Two examples scenarios for CC-IP

5.1.3 Maximum Progression-Intersection Protocol at Roundabouts

Figure 5.7 shows two vehicles ***A*** and ***B*** approaching a roundabout. Assume that vehicle ***A*** has a higher priority than vehicle B. In this case, vehicle ***A*** gets to cross the roundabout without stopping or even slowing down. Vehicle B progresses inside the roundabout grid and stops before entering the first TIC with vehicle ***A***, which is cell number 3. As vehicle ***A*** leaves cell number 3, it updates its TCL to {4} and sends a CROSS message. This informs vehicle ***B*** that the TIC 3 is now clear and it can progress into that cell. Vehicle ***B***'s TCL gets updated to {3,4} and cell number 4 is now the new common cell between ***A*** and ***B***'s TCLs. Since cell number 4 is occupied by vehicle ***A***, vehicle B cannot progress into cell number 4 until it receives an updated message from A indicating that cell 4 is no longer occupied by vehicle ***A***.



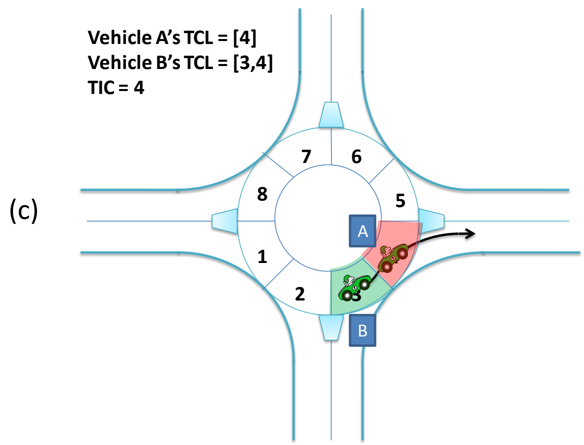


Figure 5-7: an example scenario for MP-IP

5.1.4 Advanced Crossing-Intersection Protocol at Roundabouts

Figure 5.8 shows a roundabout scenario, assuming that vehicle ***A*** has the highest priority, then vehicle ***B*** and then vehicle ***C***. As vehicle ***A*** has the highest priority among the three vehicles, it crosses the roundabout without slowing down or stopping in both cases. Even though vehicles ***B*** and ***C*** have no potential conflict with higher-priority vehicle ***A***, they might reach to a potential collision with each other. As vehicle ***B*** has a higher priority than vehicle ***C***, it crosses the roundabout at the same time as vehicle ***A***. In contrast, vehicle ***C*** must arrive at the roundabout only after the exit of higher-priority vehicle ***B***. Therefore, it slows down and sets its *Desired Speed* to make sure that its *Arrival Time* is after the *Exit Time* of vehicle B. By taking these actions, vehicle ***C*** does not come to a complete stop and since its arrival is after the exit of the higher-priority conflicting vehicle ***B***, it can now increase its speed up to the seed limit while crossing the roundabout.

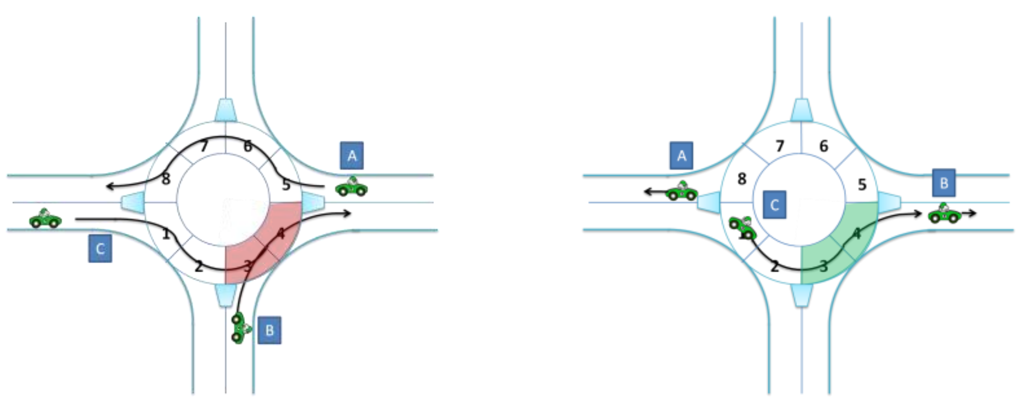


Figure 5-8: Example scenario of AC-IP at roundabouts

5.1.5 Advanced Progression-Intersection Protocol at Roundabouts

Figure 5.9 shows how vehicles behave at the roundabout while following AP-IP rules. The higher-priority vehicle ***A*** will cross the roundabout without slowing down or stopping. The lower-priority vehicle ***B*** estimates its own arrival time to and vehicle ***A***'s exit time from the TIC, cell number 3. If vehicle ***B*** has enough time to clear that conflicting cell before the arrival of higher-priority vehicle ***A***, it will go ahead and cross it. Otherwise it will estimate the appropriate velocity and reduce its speed to the *Desired Speed* in order to arrive at the Trajectory Conflicting Cell (TCL) exactly after the exit of vehicle ***A***.

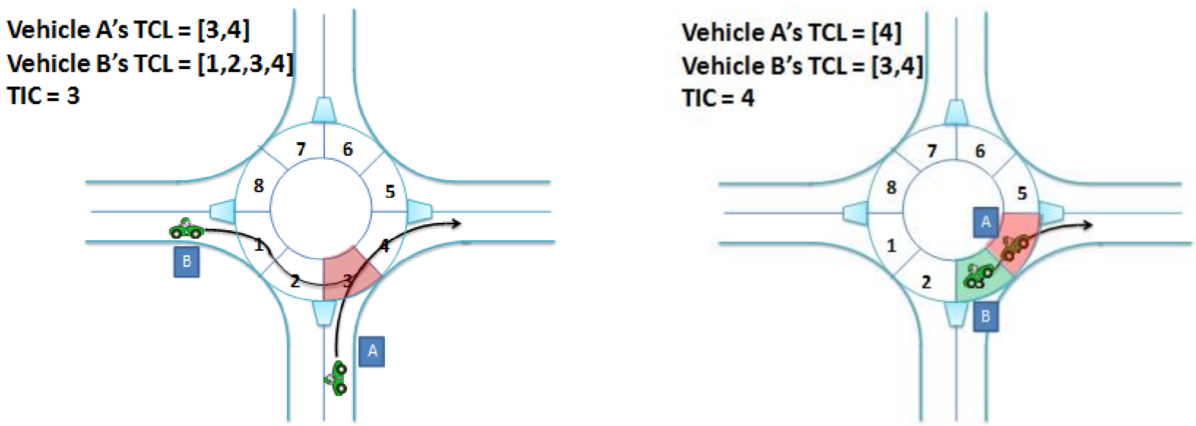


Figure 5-9: A roundabout example scenario of AP-IP.

5.1.6 Evaluation

In this section, we evaluate our proposed protocols, CC-IP, MP-IP and AC-IP and AP-IP for roundabouts. We have used real GPS coordinates from map databases to generate Route Network Definition File (RNDF) for roundabouts which already exist in the United States. Additionally, we have designed new mobility models to implement our V2V-intersection protocols within the roundabout area. All these models and roundabout RNDFs have been implemented in AutoSim.

We run our simulations on 1-lane and 2-lane roundabouts, as well as 1-lane and 2-lane signalized perfect cross intersections. The roundabout/intersection type, vehicle-birthing sequence, vehicle routes and turn-types are generated offline. Each vehicle is removed from simulation when it reaches its destination. This file is then fed into AutoSim to invoke the intersection protocols. Each simulation run uses 1000 vehicles, and each run is terminated when the last vehicle reaches its destination.

In this experiment, we compare our V2V mobility models for a 1-lane roundabout, in which one-lane roads are entering the roundabout area from all four main directions. The amount of traffic volume is equal in each direction of the roundabout. We can see this comparison in Figure 5.10. As we can expect, Maximum Progression Intersection Protocol (MP-IP) is more suitable for roundabouts and significantly outperforms Concurrent Crossing Intersection Protocol (CC-IP). The reason is that MP-IP allows vehicles to enter the roundabout as soon as there is an unoccupied cell and progress up to the conflicting cell. However, in the case of CC-IP vehicles will enter the roundabout only when they do not have any trajectory conflicts with the already crossing vehicle; otherwise they remain stopped outside of the roundabout and wait for the other vehicle to complete its passage inside the roundabout and exit it, which increases the delay.

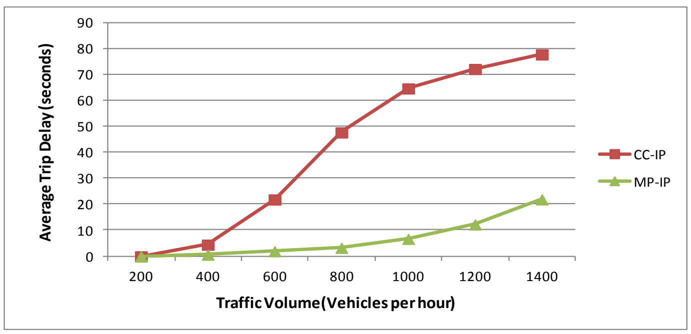


Figure 5-10: Delay comparison for 1-lane roundabouts managed by V2V models.

We then have replaced the same roundabouts with perfect cross intersections and have compared the trip delays in the case that the cross intersections are signalized. Two traffic light models have been used. One model has the green light duration of 10 seconds and the other one with the green light duration of 30 seconds per each direction. Figure 5.11 shows the results are based a wide range of traffic volumes; from 200 to 1400 vehicles per hour.

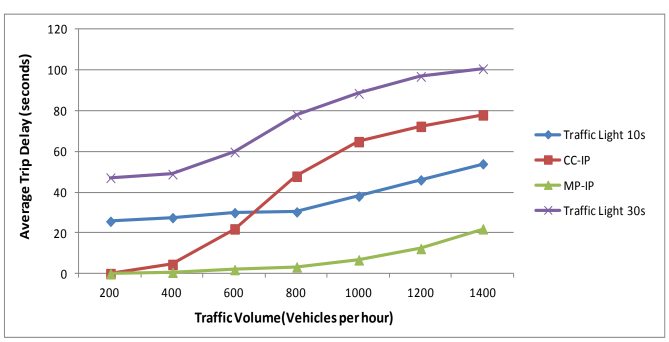


Figure 5-11: Delay Comparison between 1-lane intersections; V2V-roundabout models and signalized cross intersections.

According to the queueing theory, the average delay will asymptotically become very high when the arrival rate (i.e. traffic intensity) exceeds the service rate (throughput) at the intersection. This delay, however, occurs under steady-state conditions only after a considerable amount of time. Due to practical considerations, our simulations are run for finite durations, and hence capture only transient delay behaviors after overload conditions have been reached. Nevertheless, our results clearly indicate that before overload conditions are reached, the service rate (i.e. throughput) with the Maximum Progression Intersection Protocol (MP-IP) is noticeably better than the Traffic-Light models. MP-IP decreases the average trip delays by 80.91% and 71.32%, respectively comparing to the traffic light models with 30 seconds and 10 seconds of green light durations.

We then repeated the above experiment for a 2-lanes roundabout and the corresponding results are shown in Figures 5.12 and 5.13. Figure 5.12 shows that MP-IP is still outperforming the CC-IP, but the gap has been reduced to 47.1%. The reason is that when dealing with a 2-lanes roundabout, CC-IP allows more vehicles to cross the roundabout concurrently and it does not reach the saturation point even when dealing with higher traffic volumes.

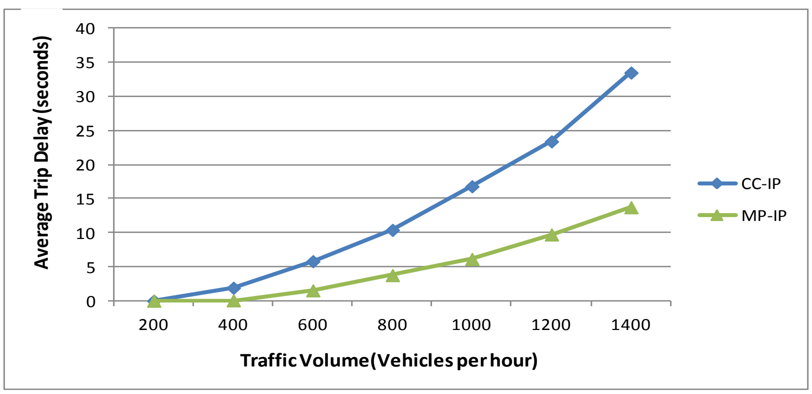


Figure 5-12: Delay comparison for 2-lanes roundabouts managed by V2V models.

Figure 5.13 shows the scenarios that 2-lanes are entering the intersection from each direction. Our results indicate that V2V models outperform the traffic light models, as the number of conflicting points are significantly high in a 2-lanes cross intersection and this leads to higher delays especially for the vehicles which are attempting to make left turns. The MP-IP model has negligible delay for low and medium traffic volumes and the average delay for very high traffic density is less than 15 seconds. MP-IP decreases the average trip delays by 90.29% and 75.88%, respectively comparing to the traffic light models with 30 seconds and 10 seconds of green light durations.

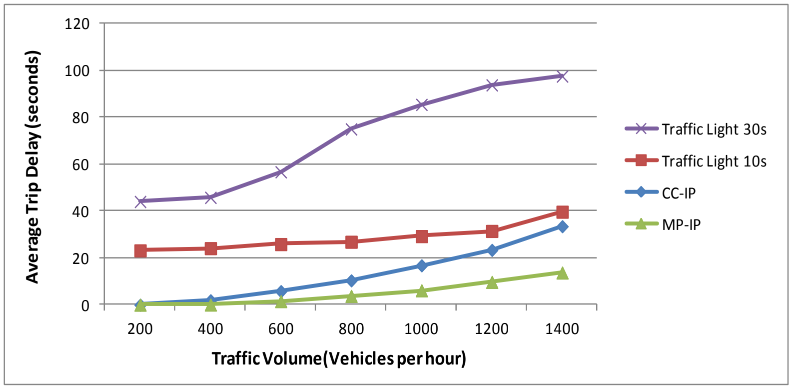


Figure 5-13: Delay Comparison between 2-lanes intersections; V2V-roundabout models and signalized cross intersections.

We finally have simulated the scenarios in which the traffic is asymmetric and the traffic volume on north and south legs are significantly higher than east and west legs of the intersection/roundabout. Figure 5.14 shows comparisons of average trip delays, for 2-lane signalized cross intersections and 2-lane roundabouts in cases of symmetric and asymmetric traffic flows. Note that the passage of vehicles through the roundabout is coordinated with MP-IP. When dealing with asymmetric traffic in a signalized intersection, vehicles which are approaching the intersection from high density roads face much longer delays and this increases the overall average delay of the intersection and decreases the throughput. We can see that for asymmetric traffic the average delays increase exponentially as the traffic volume increases and gets closer to the saturation phase However, it can be seen that in an MP-IP-managed roundabout, even though the delays are increased in asymmetric traffic, the increase is very negligible and almost zero for low and medium traffic volumes.

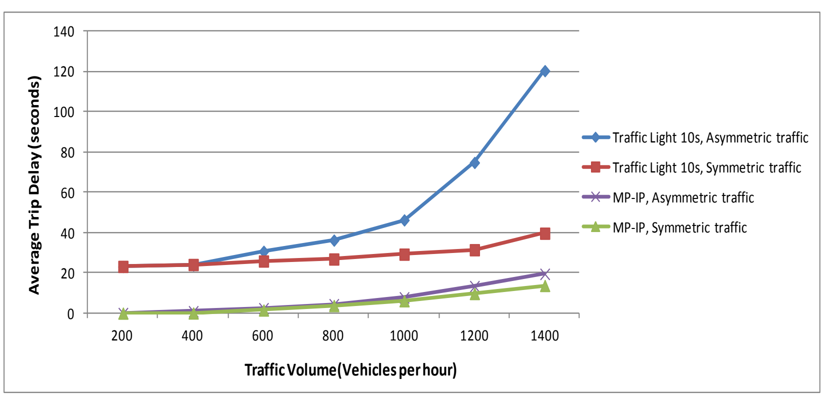


Figure 5-14: Delay Comparison for symmetric and asymmetric traffic between MP-IP at roundabout management and signalized cross intersections.

We have also studied the *trip delays* of a 1-lane roundabout where only 1-lane traffic is entering the roundabout from four directions. Vehicles follow the Advanced Cross Intersection Protocol (AC-IP) or Advance Progression Intersection Protocol (AP-IP) while crossing the roundabout area. We then replaced this roundabout by a 1-lane signalized intersection which is managed by the traffic light models. Figure 5.15 shows the comparison between the above models for traffic volumes with a range of 200 to 2000 vehicles per hour.

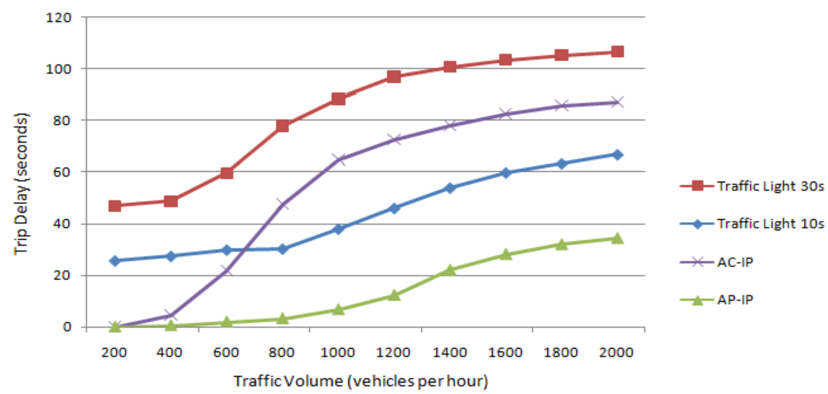


Figure 5-15: Delay comparison for 1-lane roundabout and 1-lane signalized intersection

Our results show that AP-IP performs significantly better than the traffic light models. AP-IP decreases the trip delays by 83.06% and 67.98% respectively compared to the traffic light models with 30 seconds and 10 seconds of green light duration. AC-IP does not perform well under higher traffic volumes. The reason is that lower-priority vehicles are not allowed to enter the roundabout area in the case of a potential conflict, and they must slow down and enter the roundabout grid only after receiving an EXIT safety message from the higher-priority vehicle. In the case of higher traffic volumes, this behavior results in longer stops before entering the roundabout. In contrast, AP-IP allows more vehicles to use the gaps among vehicles and progress inside the roundabout gird and cross concurrently.

We have performed the same test using a 2-lane roundabout, in which traffic is entering from 2-lanes in each direction. Figure 5.16 illustrates the trip delays when a 2-lane roundabout is ruled under AC-IP and AP-IP. It also show the results when the same roundabout is replaced by a signalized perfect cross-road which is managed by traffic light models.

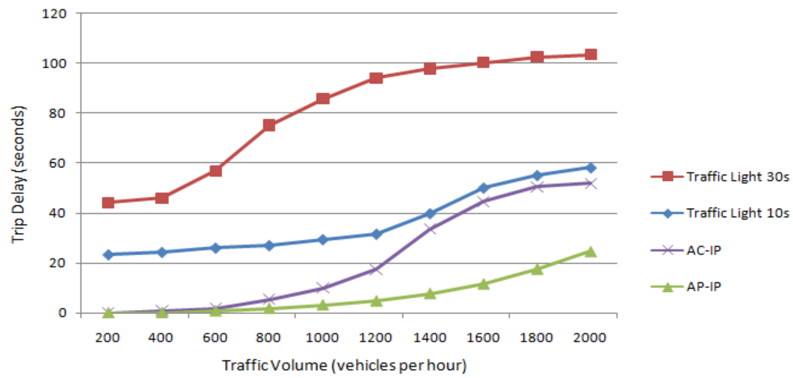


Figure 5-16: Delay comparison for 2-lane roundabout and 2-lane signalized intersection

5.2 Intersection Cascading

Our purpose is now to extend the V2V-Intersection Protocols (V2V-IP) to make them more suitable for managing the traffic not only at a single isolated intersection, but at multiple intersections along the vehicles trajectory from its source of travel all the way to the its destination. We also evaluate our intersection protocols and measure their performance when implemented on intersection cascading.

5.2.1 Congestion Awareness

Due to heavy traffic at the following intersection, vehicle break-downs, etc., traffic congestion can occur at the exit lanes of an intersection. This congestion might be propagated to previous intersections. Additionally, when an exit-lane is congested, the progress of more vehicles toward that lane leads to a blockage inside the intersection box. This intersection blockage prevents vehicles on perpendicular directions from crossing the intersection and may well lead to a starvation situation, especially when the intersection is managed by traffic lights.

To avoid the propagation of congestion and blockage of the intersection box, we have extended our V2V-IPs to deal with these situations. This Congestion Awareness method includes three phases:

1) Congestion Detection: The detection of the congested exit-lane by the autonomous vehicle.

2) Congestion Announcement: Informing other vehicles about the congestion situation.

3) Congestion Behavior: Behavior of the informed vehicles at the intersection.

We now demonstrate the details of this behavior through an example scenario shown in Figure 5.17.

1. Congestion Detection: Figure 5.17 illustrates a scenario in which vehicle ***A*** has exit the intersection-1 but cannot progress toward the intersectoion-2 due to the existing congestion in this lane. Vehicle ***A*** concludes that there is a congestion situation and no more vehicles are able to exit from intersection-1 to this lane, if two conditions are true at the same time. First, its current speed is less than a certain speed threshold and second, its distance from the exit line of intersection-1 is less than a certain distance threshold.

2. Congestion Announcement: When vehicle ***A*** detects a congestion situation on its current lane, which is an exit-lane of intersection-1, then it must inform the approaching vehicles to intersection-1. This Congestion Announcement is performed through broadcasting a new type of safety message called the CONGEST message. This message is in the format of Basic Safety Message (BSM) defined by the SAE-J2735 standard. CONGEST message includes the following information added to part II of the BSM:

    - *Last Intersection*: Each intersection is marked with a unique identification number. The *last intersection* parameter indicates the ID of the previous intersection on vehicle's trajectory.
    - *Congestion Road*: The road which is congested by traffic.
    - *Congested Lane*: The lane which is congested by traffic.
    - *Available Space*: The distance on the *congested lane* from the exit point of *last intersection* which is not occupied by any vehicles.

3. Congestion Behavior: The behavior of the receivers of the CONGEST messages depends directly on their intent at the intersection area. We first look at the vehicles such as vehicle ***B*** in Figure 5.17, which were planning to cross the intersection and exit toward the currently congested-lane. Due to the congestion, they must now change their intention. Vehicle B compares its length requirements to the advertised *available space* by vehicle ***A***. If the advertised *available space* is not sufficient for vehicle ***B*** to fit on the exit-lane, and it continues on progressing toward the congestion lane, it will not be able to completely exit the intersection box. Therefore, vehicle ***B*** will block the crossing passage for the vehicles on the perpendicular direction such as vehicle ***C***. To avoid this blockage, vehicle B has three action options, among which only one of them will be running on all the vehicles:

- *Stop & Wait*: In this case, vehicle ***B*** does not change its turning intention and still aims to exit to the *congested lane*. However, to avoid blocking the intersection grid, it delays its initial decision of cross the intersection right after vehicle ***A***. Therefore, It comes to a complete stop and waits while it receives the CONGEST messages from vehicle ***A***. As soon as a CLEAR message is received from vehicle ***A*** instead of the CONGEST message, vehicle ***B*** updates its arrival information and competes with other approaching vehicles for crossing the intersection based on the TE-IP rules.

  In contrast to the TE-IP for isolated intersections, even though the lower-priority vehicle ***C*** has trajectory conflicts with vehicle ***B***, it does not wait for vehicle ***B*** to cross first. The reason is that vehicle ***B*** has to wait until the congestion situation is resolved and will not attempt to cross the intersection. Therefore, in order to increase the throughput and avoid long delays for the lower-priority vehicle ***C***, this vehicle must cross the intersection. Vehicle ***C*** will then update its *arrival time* and broadcast its intentions to cross accordingly.

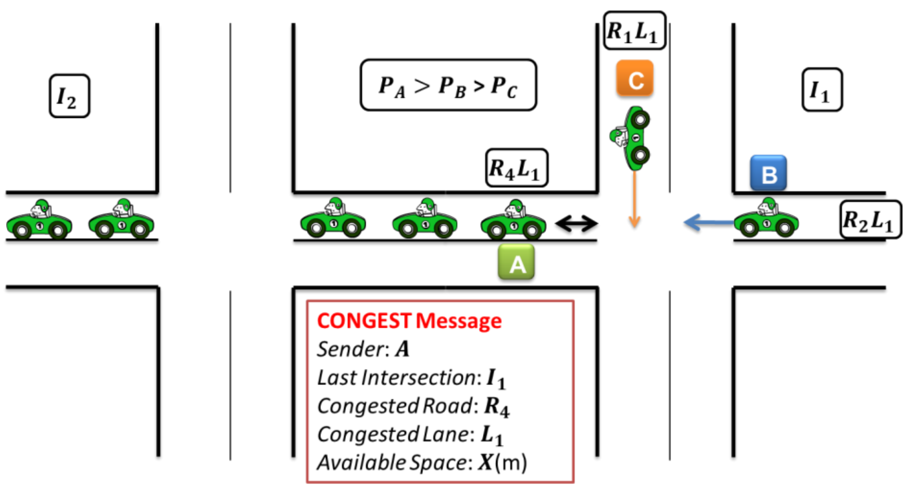


Figure 5-17: An example of the Congested lane scenario at single-lane intersection

- *Lane Change*: In the case of multi-lane intersections where multiple lanes can be used to go towards the same direction, performing a lane-change avoids long wait times. As can be seen in Figure 5.18, in this method, vehicle B performs a V2V lane-change as described in Chapter 3.3, and goes from R_2L_1 to the adjacent lane on R_2L_2 and crosses the intersection towards R_4L_2. This behavior decreases the delays faced by the vehicles intending to exit towards the *congested lane*.

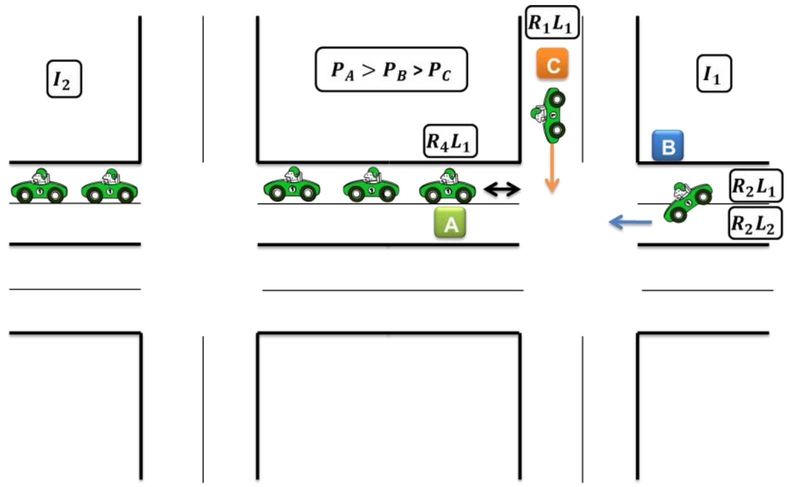


Figure 5-18: An example of the Congested lane scenario at multi-lane intersection

We use our Throughput Enhancement Intersection Protocol (TE-IP) and enhance it by adding the Congestion Awareness behavior. The following rules are applied to all vehicles:

The following *send* rules are applicable to all sender vehicles:

Algorithm 5.1: Sender Vehicle

Input: Vehicle's *Intersection-State* based on its distance to the intersection

Output: Broadcasting the appropriate intersection safety message

1. **If** ($STATE = INTERSECTION\_APPROACH \ or \ STATE = INTERSECTION\_ENTER$) **then**

2. Broadcast *ENTER* message

3. **Else if** ($STATE = INTERSECTION_{EXIT}$) then

4. **If** (Congestion is Detected)

5. Broadcast *CONGEST* message

6. **Else**

7. Broadcast *EXIT* message

And here are the rules applied to a vehicle ***B*** when it receives intersection messages from a vehicle ***A*** ($\boldsymbol{A} \neq \boldsymbol{B}$).

Algorithm 5.2: Receiver Vehicle

Input: Safety message received from vehicle A, *Received Message (RM)*

Output: Vehicle B's movement at the intersection

If ($RM = ENTER$) **then**

Run CDAI to detect trajectory conflicts with vehicle A and find $TIC_{A,B}$

If ($TIC_{A,B} = NULL$) **then**

Cross the intersection

Else

Run FCFS priority policy

If ($P_B > P_A$) **then**

Cross the intersection

Else if ($Next\_Lane_A = Congested\_Exit\_lane$) **then**

Compete with other vehicles in the same situation*

Else

Stop at the intersection

Else if ($RM = CONGEST$) **then**

If ($Next\_Lane_B \neq Congested\_Exit\_lane$) **then**

Cross the intersection

Else if ($Available\ Space > Th_{Space}$) **then**

Cross the intersection

Else

Stop at the intersection

Else if ($RM = EXIT$) **then**

If ($TIC_{A,B}$ is cleared) **then**

Cross the intersection

---

*: When a vehicle receives an ENTER safety message, it uses the CDAI to detect any potential trajectory conflict with the sender of the ENTER message. If no potential collision has been detected by CDAI, it crosses the intersection without stopping or slowing down. In the case that a potential collision is detected, if it has higher priority than the sender of the ENTER message then it crosses the intersection. Otherwise, if it has lower priority than the sender of the ENTER message, it checks for the congestion situation. If there is any congestion on one of the exit lanes of the intersection and the higher-priority

vehicle is intending to go to the congested lane but cannot do so due to the congestion, then the receiving vehicle can cross the intersection. Please note that the lower-priority vehicle should still account for other vehicles in the same situation and compete with them to gain permission for a safe crossing.

5.2.2 Evaluation

In this section, we show our simulation results for cascading intersections. We have considered a scenario with three back-to-back intersections. The distance between intersections is configurable in our hybrid emulator-simulator AutoSim. However, we have picked 100meteres distance between the centers of each two intersections in a row. Each intersection is a perfect cross with two lanes entering the intersection from all four directions. Vehicles approaching from the right lane can turn right or go straight and vehicles in the left lane can go straight or turn left. The traffic generation is based on Poisson random process and 1000 vehicles are generated at each step of the simulation related to a certain traffic volume. We have looked at traffic volumes from 0.1 to 1 cars per second in each directions, with 0.1 increments. The simulation ends and *Trip Delays* are calculated when the last vehicle reaches its destination. Figure 5.19 shows a snapshot of the tested cascading intersections from AutoSim.

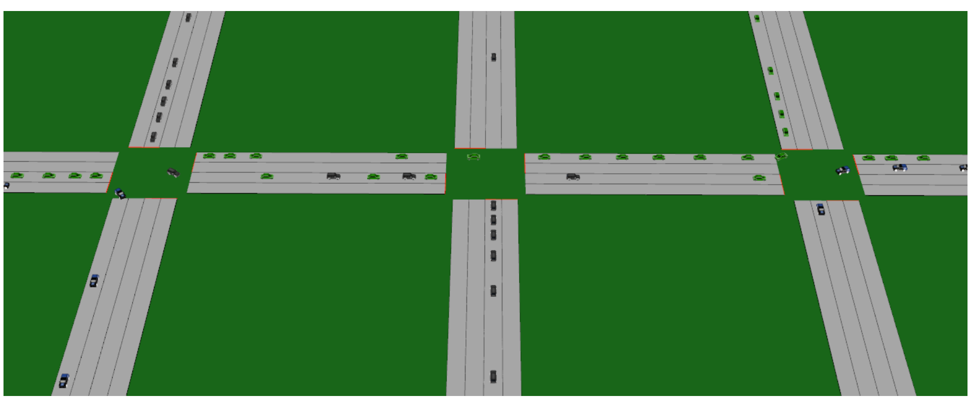


Figure 5-19: Cascading intersections with V2V-IP. This is a snapshot from AutoSim.

Figure 5.20 shows the average trip delay comparison between traffic light models with green light duration of 10 and 30 seconds, with all our V2V-Intersection Protocols modified for cascading intersections. The three generations of V2V-IPs for cascading intersections are: (1) Low-Concurrency Protocols (LCP): Throughput Enhancement Intersection Protocol (TE-IP) and Concurrent Currency Intersection Protocol (CC-IP). (2) High-Concurrency Protocols (HCP): Maximum Progression Intersection

Protocol (MP-IP) and Advanced Maximum Progression Intersection Protocol (AMP-IP). (3) High-Concurrency Protocols with Advanced Vehicle Dynamics (HCP-EVD): Advanced Crossing Intersection Protocol (AC-IP) and Advanced Progression Intersection Protocol (AP-IP).

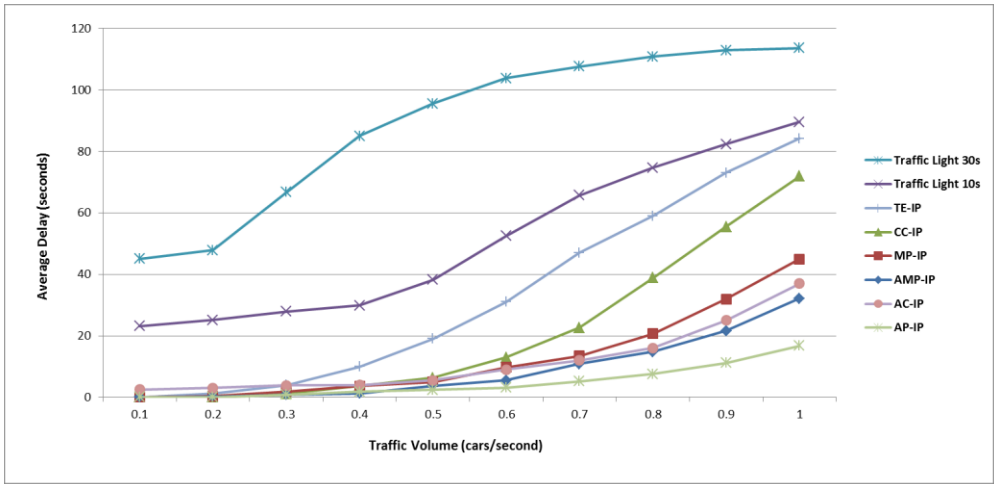


Figure 5-20: Trip delay comparison of different mobility models

As can be seen in Figure 5.20, our intersection protocols outperform the traffic light models. The average delay is negligible for lower traffic volumes under all V2V-based models. Average Trip Delay increases as the traffic volume increases. This increase is more significant in cascading intersections than an isolated intersection since delays at one intersection affects the upcoming traffic from previous intersections. This is more sever in the case of traffic congestions at any exit lanes of an intersection and the congestion might be propagated to other lanes and directions of previous intersections. The overall performance improvements over the traffic light model with a 10-second green light time achieved by our V2V-IPs are as follows: TE-IP by 35.48%, CC-IP by 58.09%, MP-IP by 74.13%, AMP-IP by 82.09%, AC-IP by 76.81%, and AP-IP by 90.38%. Our V2V-IPs perform well even for high volume traffic. The reason is that by increasing the parallelism and allowing the simultaneous passage of multiple vehicles, they avoid congested lanes and saturation at the entering queues of each intersection and therefore, provide low latency travel for vehicles from all directions.

Next we have looked at the effects of congested lanes at cascading intersections. To test the efficiency of our Congestion Awareness method, as can be seen in Figure 5.21 (a) we simulate a vehicle breakdown in AutoSim. Vehicle ***A*** will stop for a fixed amount of time which leads to traffic backup behind it and congestion in that exit-lane. As expected, average *Trip Delay* increases when there is a congested lane. Without using the congestion awareness method, vehicles progress inside the intersection box and in case of congestion on their intended exit-lane, they are forced to stop in the middle of the intersection box, and therefore, vehicles from perpendicular directions face blocked trajectories. This significantly increases the overall delay and can cause congestion propagation to previous intersections. Figure 5.21 (b) illustrates the same scenario as before, but in this case, congestion awareness is in use and vehicle ***B*** detects the congestion situation and informs the neighboring vehicles which are in its communication range. Therefore, vehicles that were intending to go towards the congested exit-lane must stop and wait while allowing the continuous traffic flow in other directions. In this case the congestion propagation is avoided and the overall delay is significantly lower.

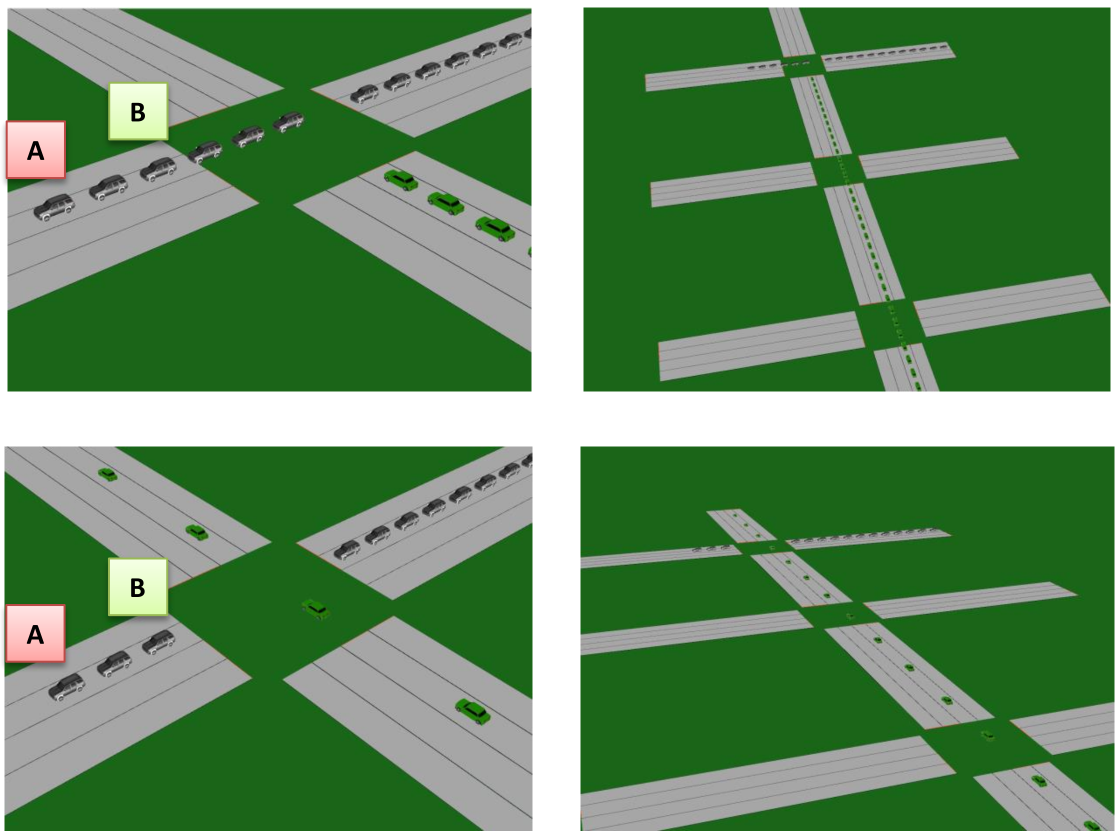


Figure 5-21: Snapshots of vehicle break-down at cascading intersections from AutoSim. (a) Congestion propagation. (b) Congestion awareness.

Video clips from AutoSim demonstrating congested exit-lane scenarios, road blockage and congestion propagation in cascading intersections:

- http://youtu.be/DtFw4evjRVo
- http://youtu.be/yohQOHqMKGY
- http://youtu.be/7N3Meh0AN-s
- https://youtu.be/N8Nu1By0hKM

5.3 Summary

Roundabouts have already a few benefits compared to traditional cross intersection. These traffic calming devices enforce lower speeds for entering vehicles, and have less conflicting points than intersections. Additionally, roundabouts provide one-direction traffic flow and allow vehicles to insert themselves in available gaps to enter and cross. In this chapter, we proposed the use of our V2V-Intersection Protocols for managing the traffic through roundabouts. Our simulation results show that these protocols are suitable for collision avoidance at roundabouts and increase the safety. Our results indicate promising overall performance improvements using our V2V-IP for roundabouts compared to signalized intersections.

We also discussed the cascading intersections where there are multiple intersections in a row on a long road. We modified our V2V-IPs to be compatible with the characteristics of cascading intersections. Our simulation results showed that our intersection protocols are suitable for cascading intersections and can avoid congestion propagation to other intersections by increasing the parallelism and allowing multiple vehicles to cross at the same time. V2V-Intersection Protocols provide low delays and high throughputs even when dealing with high volume traffic. Additionally, we proposed a method to detect road congestions due to vehicle break-downs, road construction, etc., and avoid road blockage and congestion propagation by informing the approaching vehicles about the congestion situation. The informed vehicles must then modify their intents and behavior at the intersection for both safety and efficiency purposes.

Chapter 6

V2V-Intersection Management Challenges

In this chapter, we will discuss the main challenges faced by our V2V-Intersection Protocols (V2V-IP). We first study how position inaccuracy of on-board GPS devices may lead to errors in distance measurements and describe our solution to avoid collisions inside and outside of the intersection box despite these errors. We will then look at the effects of channel impairments such as fading and packet collisions, and measure the communication reliability of our safety application. We will finally investigate possible deadlock scenarios, in which all vehicles progress inside the intersection area as much as possible without getting into a collision. In addition, we will present mathematical proofs for the deadlock-freedom property of our proposed system.

6.1 Positioning Inaccuracy

Localization is crucial for safety applications such as intersection collision avoidance. It is important for us to take into consideration the position information accuracy provided by on-board Global Positioning System (GPS) devices. GPS position inaccuracy affects various distance measurements and may lead to vehicle collisions inside and outside of the intersection/roundabout area. Each vehicle's decision at the intersection area strongly depends on the knowledge of its position and the known position of the other vehicles to make safety-critical decisions. These inaccuracies affect current position estimations as well as various distance measurements such as vehicle's distance to the intersection which determines its intersection state. These errors in distance measurements will lead to wrong decisions by the vehicle and endangers the safety goal of our intersection management system [118], [120].

There are various sources of error in positioning calculation of GPS devices such as multipath interference, satellite and clock errors, orbit errors, satellite geometry and atmospheric interference. The presence of large obstacles such as tall buildings at the corners of urban intersections increases the effects of multipath as one of the main GPS error sources [106].

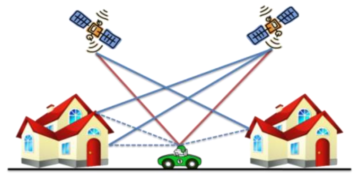


Figure 6-1: GPS error due to multi-path

There are various GPS technologies available today [105], [106]. Selective Availability is the intentional degradation (limits accuracy of satellite signals) of the GPS system by the U.S. Department of Defense for security reasons. At this time there is no Selective Availability in force; however, it can be reactivated without notice to GPS users. Real-time Differential GPS (DGPS) employs a second, stationary GPS receiver at a precisely measured spot, usually established through traditional survey methods. This receiver corrects or reduces errors found in the GPS signals, including atmospheric distortion, orbital anomalies, Selective Availability (when it existed), and other errors. A DGPS station is able to do this because its computer already knows its precise location, and can easily determine the amount of error provided by the GPS signals. DGPS cannot correct for GPS receiver noise in the user's receiver, multipath interference, and user mistakes. In order for DGPS to work properly, both the user's receiver and the DGPS station receiver must be accessing the same satellite signals at the same time.

The Wide Area Augmentation System (WAAS) is an experimental system designed to enhance and improve aircraft flight approaches using GPS and WAAS satellites. The WAAS can be considered an advanced real-time differential GPS. It uses its own geo-stationary satellites positioned over the equator to transmit corrected GPS signals to receivers capable of receiving these signals. Problems with WAAS include poor signal reception under dense tree canopy and in canyons, as well as decreased capability in northerly latitudes. Many GPS receivers are now capable of receiving the WAAS signal. However, WAAS should not be considered a consistently reliable source for improving the accuracy of GPS until the technology improves.

Different methods can be deployed to improve the position accuracy such as using high-accuracy Differential GPS (DGPS), Wide Area Augmentation System (WAAS), gyroscopes and local sensing. However, DGPS and WAAS are significantly costlier than common GPS devices. Additionally, all GPS receivers have finite accuracy, with commonly-used inexpensive GPS receivers having errors of up to a few meters. Figure 6.2 shows the position accuracy comparison among three different types of GPS devices. We study the impact of such errors on our intersection protocols and propose a simple technique to overcome such inaccuracies.

GPS Device Type	Position Accuracy in meters
SA-deactivated	± 10 m
DGPS	± 3-5 m
WAAS	± 1-3 m

Figure 6-2: GPS position accuracy comparisons

We have studied the impact of such errors on our intersection protocols and proposed some techniques to overcome such inaccuracies. We have modified our intersection protocols with a realistic GPS model. They have been implemented in our hybrid emulator-simulator AutoSim.

We have modified our V2V car-following model which was based on the V2V-Distance Keeping explained in Chapter 3. Each vehicle uses its GPS coordinates, map database and the information received in regular BSM messages to measure its current distance to the vehicle in front of it. The vehicle then adjusts its speed according to the leader vehicle's velocity to maintain a *Safe Distance*. This *Safe Distance* is measured based on the vehicle's physical characteristics such as acceleration/deceleration parameters and ensures that no accidents occur when the leader vehicle suddenly reduces its speed. Figure 6.3 shows two screen-shots from AutoSim, in which vehicle B is following vehicle A on its way to the intersection. In this scenario, due to a high position error, vehicle B may not maintain a *Safe Distance* to its current leader vehicle A, leading to a potential collision before entering the intersection.

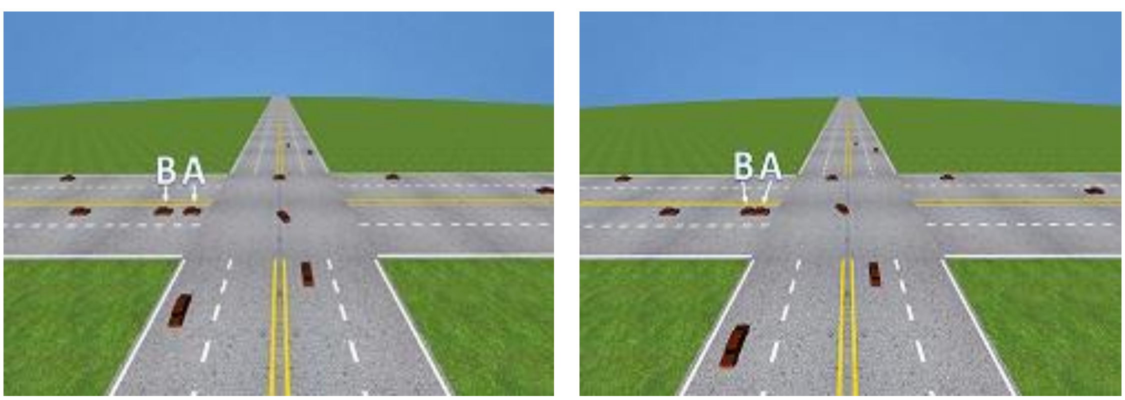


Figure 6-3: Snapshots from AutoSim. Collision outside of the intersection area

To avoid these collisions outside of the intersection grid, when dealing with high levels of positioning inaccuracy, each vehicle uses an updated dynamic *Safe Distance* parameter depending on its GPS positioning error parameter. This increased buffer distance which is added to *Safe Distance,* prevents following vehicles from getting very close to each other and gives them the capability to slow down without causing an accident when the leader vehicle brakes suddenly.

The impact of position inaccuracy is more severe in High-Concurrency Protocols (HCP) and High-Concurrency Protocols with Enhanced Vehicle Dynamics (HCP-EVD) of STIP protocols, since this group of intersection protocols explicitly utilize information relating to a vehicle's progression inside the intersection area. Therefore, a failure in locating a vehicle's current cell information correctly may lead to vehicle collisions inside the intersection grid. Each vehicle computes its own Trajectory Cells List (TCL) using the digital map database, and it uses its GPS coordinates to determine its current cell and updating its TCL based on its current cell. In other words, the vehicle deletes the cleared cells from the TCL and only broadcasts the information about the current cell and next cells along its trajectory through the intersection area. However, due to the positioning error, the vehicle might update its TCL without having completely crossed its previous cell. Figure 6.4 shows a scenario in which a collision occurs between vehicles A and B. The higher-priority vehicle A is broadcasting an incorrect TCL within its CROSS safety message. As the lower-priority vehicle B receives the updated TCL from vehicle A and calculates that the conflicting cell is now clear, it will progress into that cell. As vehicle A is still occupying the conflicting cell, a potential collision occurs between vehicles A and B.

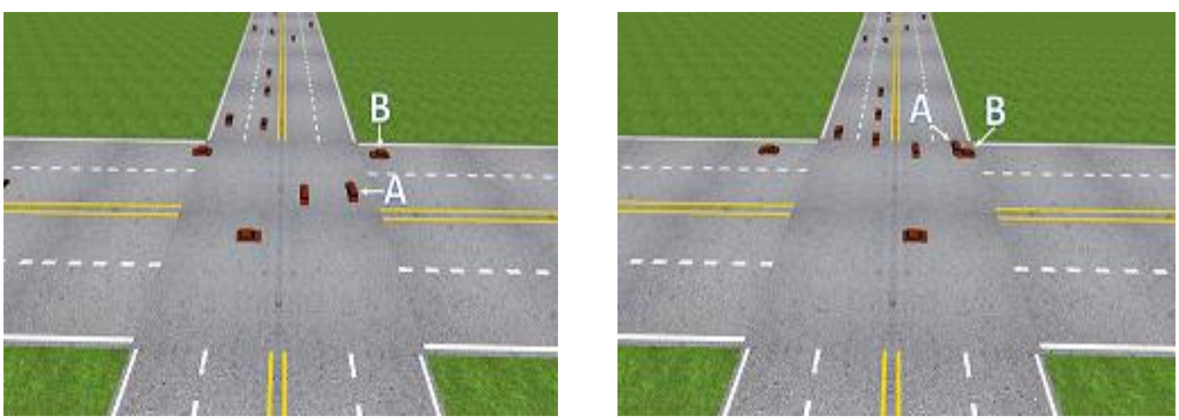


Figure 6-4: Snapshots from AutoSim. Collision inside the intersection area

To avoid these safety violations, each sender vehicle adds a safety buffer called *Safety Cell Buffer* to its updated TCL. As described previously in Chapter 4, the TCL includes the current and the next cells of vehicle's trajectory inside the intersection grid. Thus, we add a safety buffer of one intersection cell ahead of and prior to the current cell to assure the safe passage of vehicle. Our simulation results indicate that in case of GPS positioning inaccuracies in the order of 0 to 5 meters, adding one cell to the vehicle's TCL as the *Safety Cell Buffer* prevents collisions among potentially conflicting vehicles inside the intersection area. However, the size of this *Safety Cell Buffer* is a function of the GPS error characteristics and, if the GPS inaccuracy is too high, then collisions can be avoided by increasing the buffer size to more than one cell. In addition to inserting the *Safety Cell Buffer*, The receiver vehicle assures its safety by increasing the value of *Safety Time Interval* (θ) according to the vehicle's GPS position accuracy [Chapter 4.2.2]. The default value of a *Safety Time Interval*, which is calculated based on the vehicle's passage through one intersection cell, is now dynamic and gets adapted to the position accuracy level of the vehicle's GPS receiver device.

This guaranteed safety comes with the price of reduced throughput at the intersection. The receiver vehicle can also assure its safety by increasing the value of Safety Time Interval according to vehicle's GPS position accuracy. The default value of Safety Time Interval, which is calculated based on the vehicle's passage through one intersection cell, can be changed and adopted to the position accuracy level.

The reader may observe correctly that position inaccuracy might also affect the vehicle's ability to correctly determine its lane information. This can be avoided by using local sensing technologies (available on autonomous vehicles) such as cameras to perform lane detection and lane localization.

In order to analyze our intersection protocols and the effects of position inaccuracy on them, the GPS model and the traffic flow at intersections need to be studied. We now evaluate effects of position inaccuracy on some of our V2V-Intersection protocols.

Figures 6.5 and 6.6 present the results for a perfect-cross intersection where vehicles are following AC-IP and AP-IP rules respectively. Our results show that as due to the modifications for higher GPS inaccuracies and increased safety parameters, our new V2V-Intersection models have expected lower throughput compared to their counterparts with lower-inaccuracy and perfect GPS assumption.

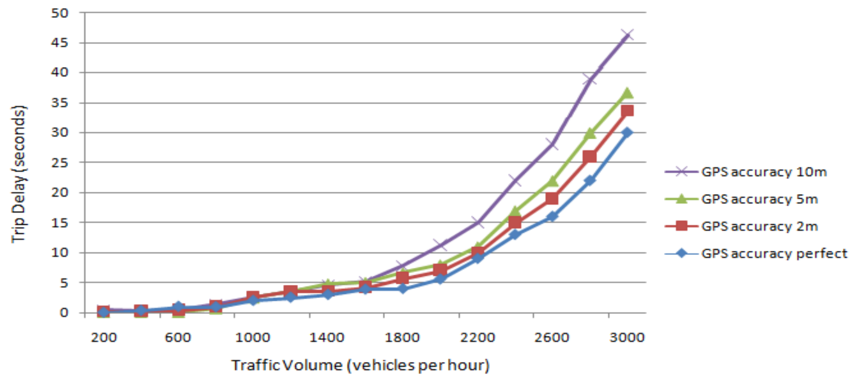


Figure 6-5: Trip delay comparison of AC-IP under different GPS position accuracies

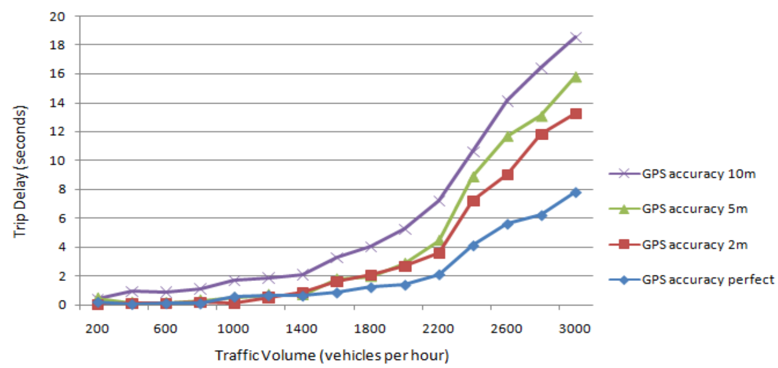


Figure 6-6: Trip delay comparison of AP-IP under different GPS position accuracies

Figure 6.7 shows that, despite the reduced throughput of modified V2V-Intersection models, AC-IP and AP-IP have 47.82% and 74.16 % overall performance improvements respectively over the traffic light model with a 10-second green light time. AP-IP outperforms AC-IP by 50.48%. These are still significant benefits.

We have logged the statistics for all simulated vehicles such as their position information at any moment while crossing the intersection. This information has been used to log any accidents among the vehicles trying to concurrently pass through the intersection area. Our simulation results show, that due to modification in our protocols as of the safety parameters, no accidents happen in any tested traffic volumes at the intersection when dealing with high levels of GPS position inaccuracies. We therefore conclude that our proposed intersection protocols support safe traversal through intersections at substantially higher throughput even with imperfect and commonly-used GPS devices.

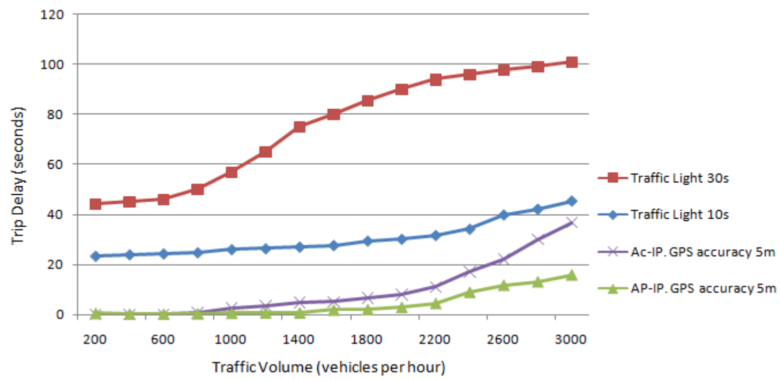


Figure 6-7: Delay comparison among different mobility models

GPS positioning inaccuracy can be substantial depending on the technology used and the environment characteristics. For instance, loss of the GPS signal is common in dense urban environments especially with the presence of tall buildings and obstacles. In these cases, the autonomous vehicle can benefit from its vehicle-resident sensor system to avoid collisions due to positioning errors. Vision and perception technologies can assist autonomous vehicles for self-localization and also to infer the necessary information regarding the position of their neighboring vehicles and maintain safe distances between vehicles.

6.2 Communication Failure

As described in Chapters 4 and 5, our intersection protocols mainly rely on vehicle-to-vehicle communications. All vehicles use V2V messages to interact with one another and use the information within these messages to control their movements such as adjusting their speed during their trajectory through the intersection area. We know that wireless communication is not perfect and channel impairments decrease the reliability of vehicular communications. As vehicles approach an intersection with relatively high speeds, it is vital to receive the intersection safety messages within a very short time interval to be able to react, and get to a full stop before entering the intersection area when necessary. Channel impairments such as fading and packet collisions will decrease the communication reliability by increasing the packet loss ratio. Therefore, a high rate of packet loss will affect the communication as vehicles do not receive the information soon enough to avoid collisions at the intersection. This problem is more sever in urban scenarios, where Line-of-Sight (LOS) conditions are not always available due to the presence of big buildings and other obstacles at intersection corners [81], [82].

We have studied the impact of imperfect V2V communications on our intersection protocols. We have therefore implemented realistic channel propagation models. They have been implemented in our hybrid emulator-simulator AutoSim [119].

Figure 6.8 illustrates an intersection crossing scenario from our hybrid emulator-simulator, AutoSim. In this scenario, vehicle A is attempting to enter the intersection from the North and turn left heading east. Vehicle B arrives at the intersection slightly after vehicle A, and attempts to go straight. As they have a trajectory conflict, they may get to a potential collision if they attempt to cross the intersection at the same time. When the communication medium is perfect and there is no packet loss, vehicle B will receive the intersection safety messages from vehicle A. As vehicle B is assigned a lower priority based on its arrival time, it allows vehicle A to safely cross the intersection first. In contrast, when the packet loss rate is too high, intersection safety messages among these vehicles can be lost, and vehicle B has no information about the higher-priority vehicle, A. So, it attempts to cross the intersection without stopping or slowing down and this leads to a collision between vehicles A and B.

Figure 6-8: Snapshots from AutoSim simulator (a) No packet loss and safe passage of vehicles, (b) High packet loss rate results in an accident

An often used realistic and probabilistic model for wireless signal propagation using DSRC channels is the *Nakagami-m* model [17]. It has been proven to significantly match with empirical results for signal propagation using DSRC/WAVE. This model estimates the received signal strength in multipath environments, in which the channel is influenced by various degrees of fading.

Nakagami-m fading with the shape parameter *m* and distribution spread parameter *Ω* is expressed as:

$$f(x) = \frac{2m^m x^{(2m-1)}}{\Gamma(m)\Omega^m} \exp\frac{(mx^2)}{\Omega}, x > 0, \Omega > 0, m > \frac{1}{2} \quad (6.1)$$

When the signal amplitude follows the *Nakagami-m* distribution, the power follows the Gamma distribution,

$$p(x) = (\frac{m}{\Omega})^m \frac{x^{(m-1)}}{\Gamma(m)} \exp(-\frac{mx}{\Omega}) \tag{6.2}$$

, where Γ_m is a complete gamma function of parameter m.

Taliwal et al. [18] have shown that this model agrees with empirical data. Figure 6.9 shows the probability of reception based on the distance between the transmitter and the receiver for various values of *m* and the communication range of 500 meters.

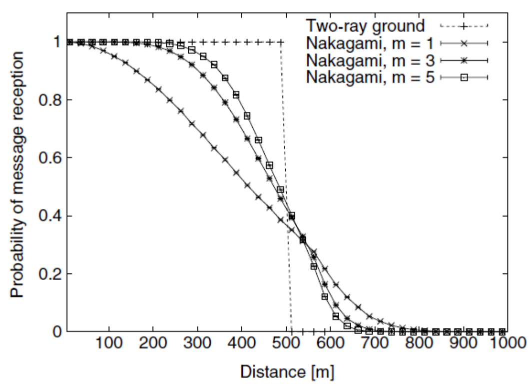


Figure 6-9: Probability of successful packet reception.

Yin et al. [15], [16] have performed statistical fading analysis based on DSRC empirical data. Their analysis shows that, for distances less than 100m, the fading appears to follow a Rician fading distribution, in which $m > 1$. When the distance is greater than 100m, it generally follows a Rayleigh fading distribution, in which $m = 1$ and it models a harsh Non-Line-Of-Sight (NLOS) scenario. They claim that the fading level $m = 3$ matches with their results for urban environments.

In the case that there is only 1 sender vehicle, channel propagation becomes the most influencing factor since there will be no interference. We have gathered results around different urban areas in Pittsburgh, PA, while using a single pair of DSRC transmitter and receiver. Our results matches with Nakagami model that the fading level $\mathrm{m} = 3$. Killat et al. [56], [57] have shown that the probability of successfully receiving packets when $\mathrm{m} = 3$ is analytically derived by

$$P_R(x,\psi) = e^{-3\left(\frac{x}{\psi}\right)^2}(1 + 3\left(\frac{x}{\psi}\right)^2 + \frac{9}{2}\left(\frac{x}{\psi}\right)^4) \quad (6.3)$$

, where x denotes the distance between sender and receiver, and ψ states the chosen transmission power in meters as introduced before.

Our metric is Packet Delivery Ratio (PDR). PDR has been widely used as the major metric to evaluate radio channel characteristics. PDR is defined as the probability of successful packet reception and is measured as the ratio of the successfully received packets to the total number of packets transmitted within a pre-defined time interval.

We now measure the PDR value based on the distance between the transmitter and the receiver of intersection safety messages in various traffic scenarios. We look at the intersections with different amounts of obstacles which lead to different multipath degrees. To simulate a harsh NLOS environment, we use m = 1 in our Nakagami-m propagation model and bigger values of m are used to model the intersections with less number of obstacles such as tall buildings. We use three values for the fading parameter m = 1, 2, 3 and transmission power of 20dBm. A deterministic Two-ray Ground propagation model has been assumed for the transmission power for the Nakagami model. Using this model, we have set the effective Communication Range (CR) of 200m and transmission rate of $f = 10Hz$ in our simulations.

We have implemented the Nakagami-m model and the following empirical models in our hybrid simulator-emulator AutoSim. Figure 6.10 shows the PDR comparison among intersection environments with different fading degrees. Based on the results of the *Nakagami-m* propagation model and as we expected, for the lower values of fading parameter m, the PDR values drop faster as the distance increases between the transmitter and the receiver of the intersection safety messages.

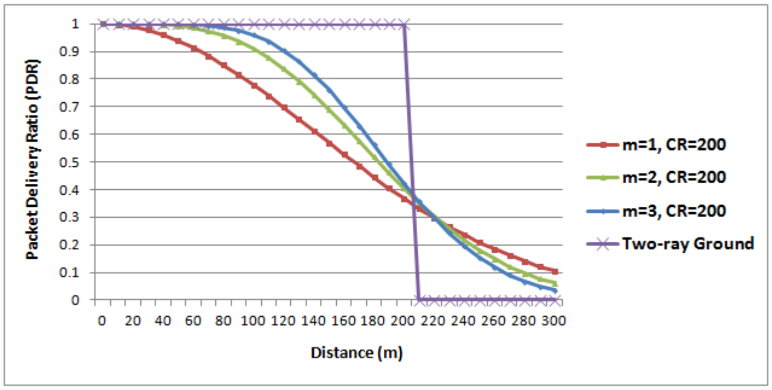


Figure 6-10: Packet Delivery Ratio with communication range of 200 meters

The results in Figure 6.10 confirm that higher degrees of fading caused by harsh NLOS environments, lead to lower PDRs. As can been seen in this Figure, packet loss is much higher for the fading level of $m = 1$ and the PDR drops to less than 80% when the distance between the transmitter and receiver is 100 meters.

As mentioned before, the above results are based on the assumption that there is only one transmitter of safety messages. Therefore, it only captures the impact of packet loss due to channel fading. However, based on our V2V-Intersection protocols, all approaching vehicles must broadcast the intersection safety messages and therefore, there are multiple senders which are competing to access the channel. The main parameters affecting the probability of successful packet reception are vehicular traffic density of broadcasting vehicles δ $[vehicle/km]$, safety message transmission rate f $[Hz]$, and transmission power of ψ $[\mathrm{m}]$.

The *communication density*, which was introduced by Jiang et al. [110], [111] has been conceived as a metric for assessing the load on the communication channel and simply states the number of sensible events per unit of time. It is calculated as the product of communication range, vehicle density and transmission rate, yielding a value expressed in packet transmissions per unit time: $\xi = \psi.f.\delta$

The empirical model that considers the *communication density* and also matches our collected data has been introduced by Killat et al. [56], [57] as follows:

$$P_R(x,\delta,\psi,f) = e^{-3\left(\frac{x}{\psi}\right)^2}\left(1+\sum_{i=1}^{4} h_i(\xi,\psi)\left(\frac{x}{\psi}\right)^i\right) \tag{6.4}$$

, where

$$h_i(\xi,\psi) = \sum_{j,k>0} h_i^{(j,k)} \xi^j \psi^k,\ i = 1 \ldots 4 \qquad \text{, with } \xi = \psi.f.\delta \text{ and } j + k \leq 4$$

Increasing the transmission power will eventually increase the communication range. In sparse traffic conditions, the channel load is light and increasing the transmission power or transmission rate does not carry negative consequences and results in higher Packet Delivery Ratio (PDR) and communication reliability. However, when dealing with busy urban intersections in which the traffic is dense, a high number of safety messages is broadcast, and results in higher channel load and may lead to channel congestion.

Figure 6.11 shows our simulation results for three different traffic volume scenarios. In all scenarios the Communication Range (CR) is set to 200 meters so it can completely cover the intersection area. The transmission frequency is 10Hz to match the recommendation of SAE J2735 standard for V2X safety applications, and the Nakagami-m fading level of $m = 3$ which matches the urban intersection environment characteristics. As illustrated in Figure 6.11, PDR is high for lower vehicle densities. In contrast to low traffic volume scenarios, in case of high volume traffic scenarios as more of vehicles compete to access the same channel, packet collision becomes more frequent. Therefore, the PDR decreases drastically when the distance is increased between the transmitter and the receiver.

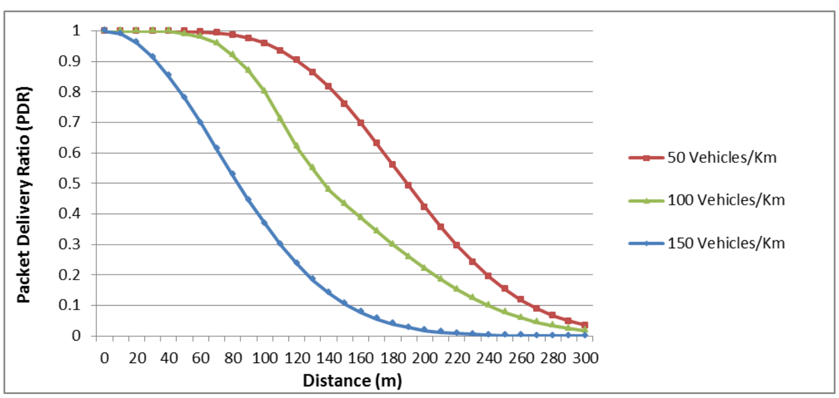


Figure 6-11: Packet Delivery Ratio for fixed communication range of 200m and packet generation rate of 10Hz.

We will now look at the effects of communication failure on our V2V-Intersection Protocols. Fan Bai et al. [14] define the Safety application reliability as the probability of successfully receiving at least one single packet from neighbor vehicles during the tolerance time window *T*. This is calculated as follows:

$$P_{Application} = 1 - (1 - P_{Comm})^N \quad (6.5)$$

Where, N is the number of messages sent during the time window T and P_{Comm} is the communication reliability which is calculated as the probability of successfully receiving each packet. In our proposed protocols, vehicles start broadcasting the safety messages when their distance to the entrance of the intersection is less than D_{ENTER}, which is set to 20 meters in our simulations. For the transmission frequency of frequency of 10Hz for the intersection safety messages, the tolerance time window T is at least 500ms. This has been calculated based on vehicle's speed and deceleration parameters, and the safe distance to get to a complete stop before entering the intersection box.

Figure 6.12 shows the measured safety application reliability for our intersection protocols in various multipath environments with medium traffic of 100 vehicles per km and tolerance time windows of 500ms and 300ms. We notice that our proposed V2V-Intersection management protocols have the average application reliability very close to 100%, for distances of up to 100m between the transmitter and the receiver vehicles.

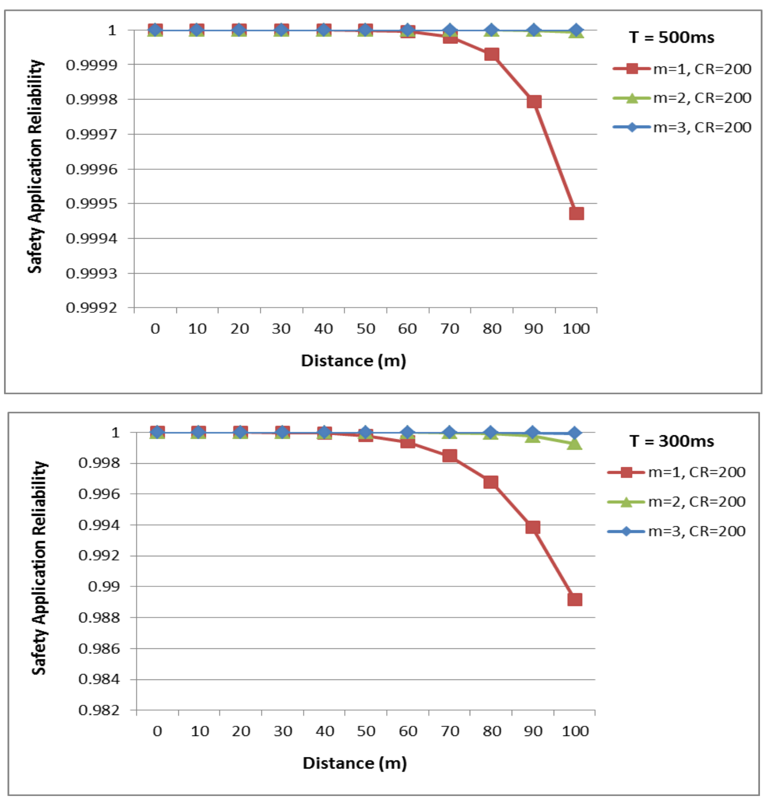


Figure 6-12: Application reliability of V2V-Intersection protocols, for 3 different fading levels with communication range of 200 meters and tolerance time window of (a) 500ms, (b) 300ms

We have also logged the statistics for all simulated vehicles such as their position information at any moment while crossing the intersection. This information has been used to log any accidents among the vehicles trying to concurrently pass through the intersection area.

After implementing the communication model and testing our intersection protocols for various environments, our results show that absolutely no accidents happen in any tested low, medium and high traffic volumes at the intersection. In these simulations, the communication range is 200 meters and all vehicles are broadcasting the intersection safety messages with frequency of 10Hz. All the vehicles make their decision about how to cross the intersection, while they are approaching it and, based on the intersection safety messages sent by other vehicles every 100ms. This surprisingly positive result is because of receiving at least one safety message from any other approaching vehicle is sufficient to detect any potential collisions using the CDAI, and to come to a complete stop before entering the intersection boundaries. Since it takes seconds to cross an intersection, at least one such message is received on time.

We therefore conclude that our proposed intersection protocols support safe traversal through intersections at substantially higher throughput even with imperfect and practical wireless environments. However, we believe that in extreme environment scenarios where the channel is congested and the packet loss rate is very high, local sensing technologies such as cameras, radars, lidars and thermal images can be combined with V2V and V2I communications to avoid any potential collisions. These methods will be discussed in Chapter 8.

6.3 Deficiencies of the *Nakagami-m* Model

We have implemented the *Nakagami-m* model in our simulator-emulator AutoSim to study the impact of imperfect V2V communications due to fading. We assume a deterministic model for transmission power in the *Nakagami-m* model, that is, the power necessary to reach a communication range of certain distances. We have picked the *Nakagami-m* model due to its match with empirical results for DSRC channels. However, communication researchers have introduced numerous fading models which have their own advantages and drawbacks depending on the environment characteristics. As a future research direction, we suggest implementing various proposed DSRC channel models, validating them by comparing their respective empirical results in different environments, and their impact on V2V-intersection protocols. Specifically the *Nakagami-m* model does not consider the correlation between packet losses. The probability of consecutive packet losses is more important than the probability of a single packet loss when dealing with safety applications such as our V2V-intersection protocols, in which, vehicles are broadcasting intersection safety messages periodically. Future extensions can benefit from models that capture the packet loss correlation when consecutive and bursty packet loss occurs.

6.4 Deadlock

A deadlock is a situation in which two or more competing actions are each waiting for another to finish, and thus none ever does. A deadlock situation can occur inside the intersection area, among the vehicles which are trying to cross the intersection at the same time. We investigate possible deadlock scenarios, in which all vehicles progress inside the intersection area as much as possible without getting into a collision. Therefore, in this chapter, we will define a set of rules as a part of our V2V-Intersection Protocols to avoid deadlock. Additionally, we will present a mathematical proof for the deadlock-freedom of our proposed system [119], [120].

6.4.1 MP-IP Deadlock Freedom

We now investigate a possible deadlock scenario for an intersection under the rules of Maximum Progression Intersection Protocol (MP-IP). In this scenario, all vehicles progress inside the intersection area as much as possible without getting into a collision.

As we can see in Figure 6.13, vehicle A's next cell is occupied by vehicle D, vehicle D's next cell is occupied by vehicle C, vehicle C's next cell is occupied by vehicle D, and finally vehicles B's next cell is occupied by vehicle A. This means that none of these vehicles can progress inside the intersection grid as each of their next cells are occupied by other vehicles.

To better explain deadlock scenarios, we use *wait-for* graphs. A *wait-for* graph is a directed graph used for deadlock-detection in operating systems and relational database systems. A deadlock exists if the graph contains any cycles.

For the purpose of this thesis, we define the elements of our intersection *wait-for* graph as follows. Vehicles are represented as the nodes of our *wait-for* graph, and an edge from vehicle B to vehicle A implies the vehicle A is holding a cell that vehicle B needs, to complete its trajectory through the intersection grid. Thus, vehicle B is waiting for vehicle A to release (leave) that specific cell. It can be seen clearly in Figure 6.14 that the corresponding *wait-for* graph contains a cycle and therefore it is a deadlock situation.

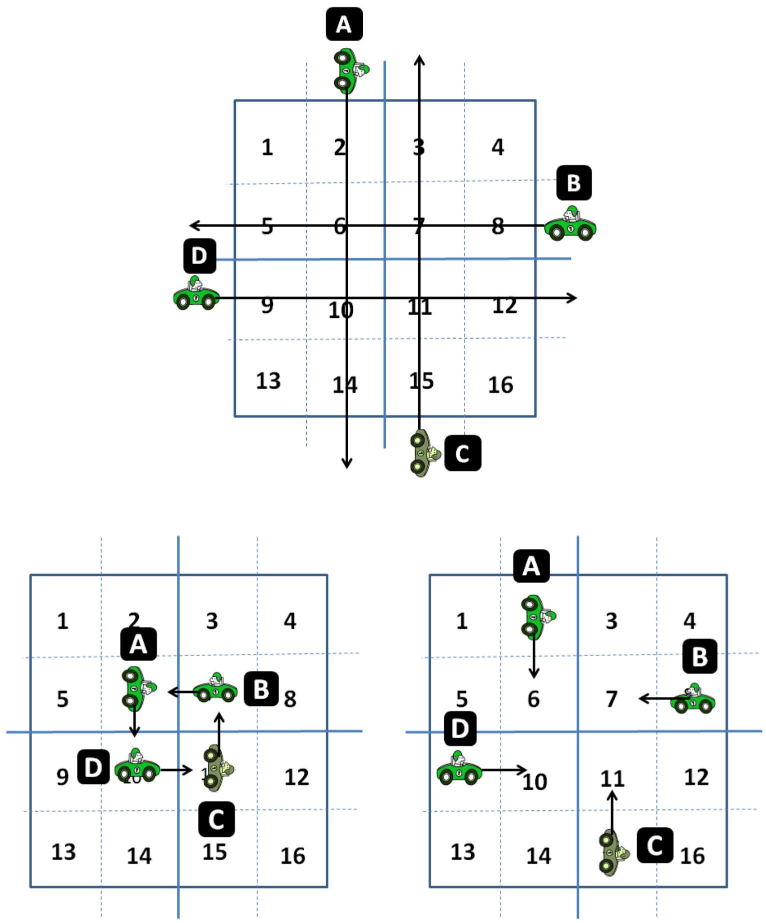


Figure 6-13: A Deadlock scenario

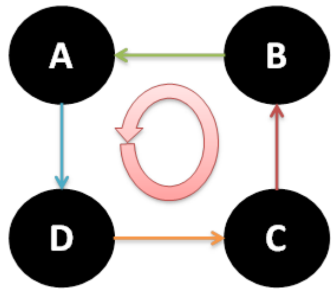


Figure 6-14: Wait-for graph for an example deadlock scenario

<u>Definition 6.1</u>: *Trajectory Dependency*

Vehicle A's trajectory depends on vehicle B's trajectory iff two conditions are true at the same time:

1 The priority of vehicle A is lower than the priority of vehicle B.

2 There is a common cell along their trajectory cells.

The above statement can be written as:

$$[(P_A < P_B)\ and\ (S_A \cap S_B \neq \phi)] \Leftrightarrow\ A \longrightarrow B$$

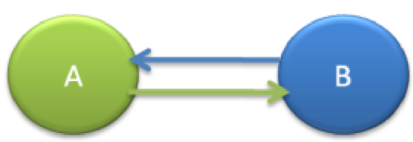
<u>Rule 6.1</u>: *MP-IP Rule*

If vehicle A's trajectory depends on vehicle B's trajectory, then vehicle A cannot enter any of the cells reserved by vehicle B.

$$(A \longrightarrow B) \Rightarrow C_A \notin S_B$$

<u>Theorem 6.1</u>: *Without loss of generality, the MP-IP is deadlock-free.*

Proof: We prove the theorem by contradiction. Suppose we have two vehicles. Deadlock condition is as follows: $C_A = N_B\ \ and\ \ C_B = N_A$



Suppose that $P_A > P_B$, and we have:

$$C_B = N_A \Rightarrow S_A \cap S_B \neq \phi \tag{6.5}$$

Based on the *Trajectory Dependency* and the *MP-IP Rule*, from Equation (6.5), we have:

$$B \longrightarrow A \;\Rightarrow C_B \notin S_A \tag{6.6}$$

But from the deadlock condition, we have $C_B = N_A$ so:

$$C_B = N_A \Rightarrow C_B \in S_A \tag{6.7}$$

Equations (6.6) and (6.7) cannot be true at the same time. This is a contradiction. So $C_A = N_B$ cannot be true while $C_B = N_A$.

We now consider the deadlock situation with n vehicles, $n > 2$. We must therefore have

$C_A = N_B \; and \; C_B = N_C \; and \; \ldots \; C_Y = N_Z \; and \; C_Z = N_A$

Suppose that $P_A > P_B > P_C > \cdots > P_Z$

So we have: $P_A > P_B > P_C > \cdots > P_Z \;\Rightarrow\; P_A > P_Z$

$$C_Z = N_A \Rightarrow S_A \cap S_Z \neq \phi \tag{6.8}$$

Based on the Trajectory Dependency and the MP-IP Rule, from (6.8):

$$Z \longrightarrow A \Rightarrow C_Z \notin S_A \tag{6.9}$$

But the deadlock condition states that $C_Z = N_A$, so:

$$C_Z = N_A \Rightarrow C_Z \in S_A \tag{6.10}$$

(6.9) and (6.10) are contradictory. So $C_Z = N_A$ cannot be true while $C_A = N_B$ and $C_B = N_C$ and $C_Y = N_Z$. So we can conclude that the deadlock situation is avoided by applying the *MP-IP Rule*. ■

We now apply MP-IP to the deadlock scenario of Figure 6.13. Figure 6.15 shows that vehicle A can progress without worrying about other vehicles, as it has the highest priority among them. Vehicle B progresses to cell number 7, and stops before entering cell number 6, since it is a part of vehicle A's TCL.

The same MP-IP rule applies to vehicles C and D. Since D has potential conflicts with vehicles A and C, and both of them have higher priorities than D, then D has to stop before entering any of those conflicting cells, numbers 10 and 11. As cell number 10 is the first conflicting cell along vehicle D's trajectory, it stops before entering this cell and waits in cell 9 until A crosses and leaves cell 10. So, no cycle is formed and the highest-priority vehicle A has all the cells cleared for its trajectory through the intersection area. After the last step showed in Figure 6.15, all the vehicles can progress to the next cell along their trajectory and cross the intersection area safely, without causing any deadlock situation.

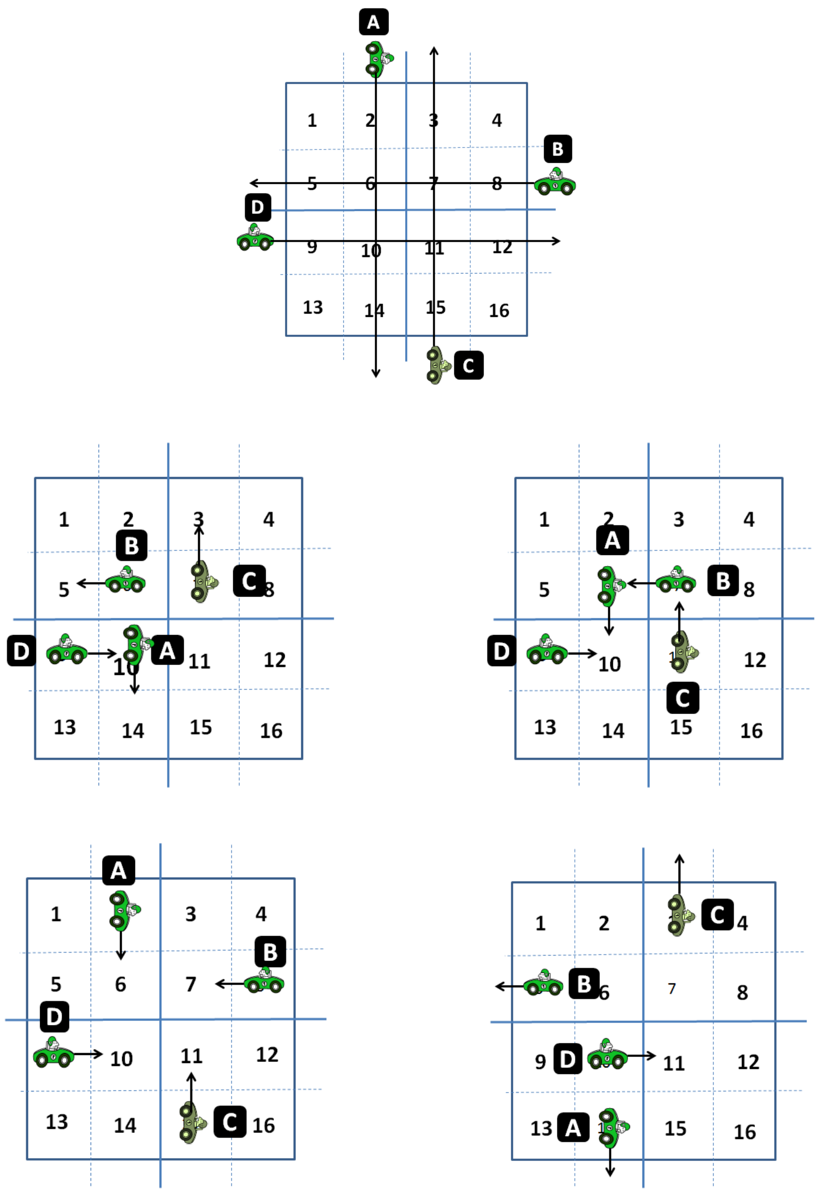


Figure 6-15: Deadlock is avoided by the MP-IP Rule

Video clips from a deadlock situation and deadlock-freedom using the MP-IP Rule:

- https://youtu.be/7do-QOU3KnI
- https://youtu.be/_yhJ44Xg4YA

6.4.2 AMP-IP Deadlock Freedom

In this section, we prove that using AMP-IP cannot lead to a deadlock situation.

Rule 6.2: **A*MP-IP Rule***

If vehicle A's trajectory depends on vehicle B's trajectory, then A cannot enter the $TIC_{B,A}$, unless it is able to leave $TIC_{B,A}$ before B arrives to that cell.

Suppose that $n = TIC_{B,A}$. The AMP-IP rule can also be stated as:

$$\{(A \longrightarrow B) and \left(ET_{A,n} > AT_{B,n}\right)\} \Rightarrow C_A \notin S_B$$

Theorem 6.2: *There is no deadlock under AMP-IP.*

Proof: We prove these properties using contradiction. Suppose we have two vehicles. Deadlock condition is as follows:

$$C_A = N_B \; and \; C_B = N_A$$

Suppose that $P_A > P_B$

Based on the trajectory dependency:

$$[P_A > P_B \; and \; S_A \cap S_B \neq \phi] \Rightarrow B \longrightarrow A \quad (6.11)$$

From the deadlock condition, we have $C_A = N_B = TIC_{A,B}$. So vehicle A is already in cell $TIC_{A,B}$:

$$C_A = N_B \Rightarrow \; ET_{B,TIC_{A,B}} > AT_{A,TIC_{A,B}} \quad (6.12)$$

By AMP-IP rule and from Equations (6.11), (6.12):

$$C_B \notin S_A \tag{6.13}$$

From Deadlock, we have:

$$C_B = N_A \Rightarrow C_B \in S_A \tag{6.14}$$

Equations (6.13) and (6.14) cannot be true at the same time. This is a contradiction. So $C_B = N_A$ $cannot be true while $C_A = N_B$.

Now consider the deadlock situation with *n* vehicles, $n > 2$.

$C_A = N_B \; and \; C_B = N_C \; and \; \ldots \; C_Y = N_Z \; and \; C_Z = N_A$

Suppose that $P_A > P_B > P_C > \cdots > P_Z$

So we have: $P_A > P_B > P_C > \cdots > P_Z \; \Rightarrow \; P_A > P_Z$

Based on the Trajectory Dependency,

$$[P_A > P_Z \; and \; S_A \cap S_Z \neq \phi] \Rightarrow Z \longrightarrow \tag{6.15}$$

From the deadlock condition, we have $C_A = N_Z = TIC_{A,Z}$. So vehicle A is already in cell $TIC_{A,Z}$, therefore:

$$C_A = N_Z \Rightarrow \; ET_{Z,TIC_{A,Z}} > AT_{A,TIC_{A,Z}} \tag{6.16}$$

By AMP-IP rule and from equations (6.15), (6.16):

$$C_Z \notin \; S_A \tag{6.17}$$

From the deadlock condition, we have:

$$C_Z = N_A \Rightarrow C_Z \in S_A \tag{6.18}$$

Equations (6.17) and (6.18) are contradictory. So $C_Z = N_A$ cannot be true while $C_A = N_B$ and $C_B = N_C$ and $C_Y = N_Z$. ■

Let us apply the AMP-IP rule to the deadlock scenario of Figure 6.13. Since vehicle D does not have enough time to clear $TIC_{C,D}$ before vehicle C arrives at that cell, it will not even enter the first TIC, which is $TIC_{A,D}$. So the trajectory is not blocked for the higher-priority vehicle A and deadlock does not happen. Hence the same scenario as in Figure 6.15 occurs. However, if vehicle D has enough time to clear both $TIC_{A,D}$ before vehicle A gets there and clear $TIC_{C,D}$ before vehicle C gets there, it will cross both conflicting cells. As we can see in Figure 6.16, this behavior of vehicle D, will allow the road to be clear for higher-priority vehicles A and C, and again no deadlock occurs.

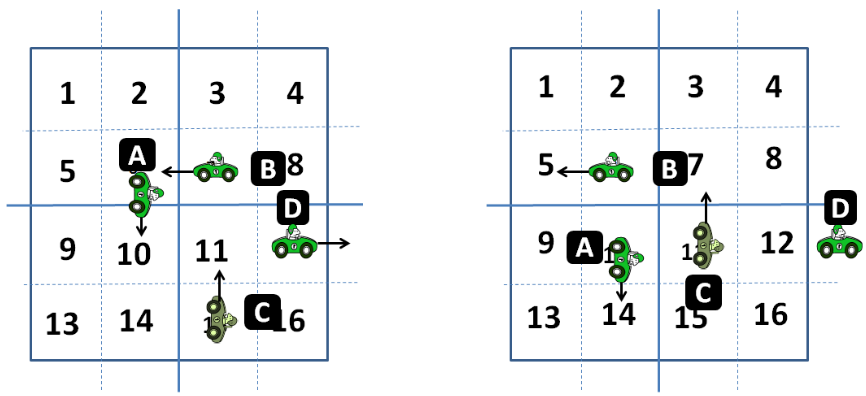


Figure 6-16: An example scenario for AMP-IP

6.4.3 AC-IP Deadlock Freedom

We now investigate a possible deadlock scenario, in which all vehicles arrive at the intersection in very close time intervals. In Figure 6.17, vehicles A, B, C and D have all reduced their speeds and came to a complete stop at the intersection entrance. No vehicle is crossing the intersection to avoid potential collisions with other vehicles present on other legs of the cross-road.

We define the elements of our intersection wait-for graph as follows. Vehicles are represented as the nodes of our wait-for graph, and an edge from vehicle B to vehicle A implies the vehicle B is waiting for vehicle A, to complete its trajectory through the intersection grid. Since vehicle B is waiting at the intersection entrance for vehicle B, its updated *STATE* is *Intersection-Wait*. It can be seen clearly in Figure 6.17 that the corresponding wait-for graph contains a cycle and therefore it is a deadlock situation. We now show that under AC-IP, such deadlock cannot occur.

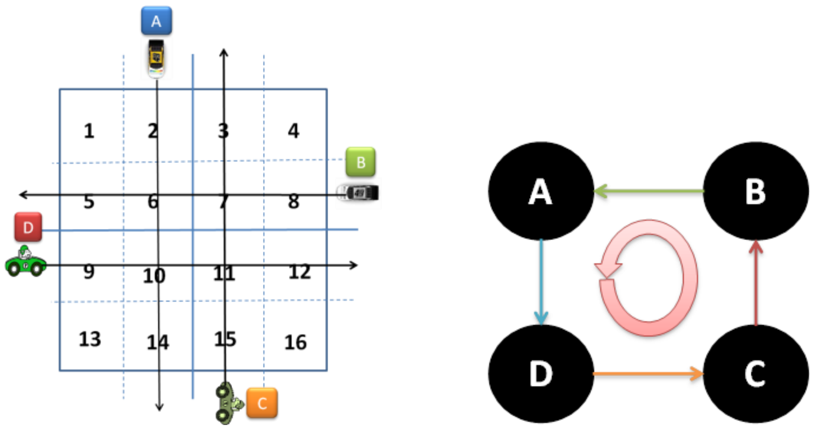


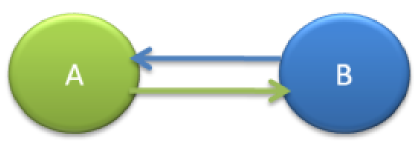
Figure 6-17: A Deadlock Scenario and the Wait-for graph

<u>Rule 6.3</u>: ***AC-IP Rule***

If vehicle B's trajectory depends on vehicle A's trajectory, then vehicle B waits for vehicle A to cross the intersection and vehicle A does not wait for vehicle B to cross the intersection.

$$B \rightarrow A \;\Rightarrow IS_A \neq \Gamma_B$$

<u>Theorem 6.2</u>: *AC-IP is deadlock-free.*



Proof: We prove the theorem by contradiction. Suppose we have two potentially conflicting vehicles.

Please note that the deadlock situation happens only when these 2 vehicles have a common cell along their trajectories and they might get to a potential collision if they cross the intersection at the same time. Otherwise, both vehicles will safely cross the intersection simultaneously and no deadlock occurs. The deadlock condition is as follows:

$$IS_A = \Gamma_B \text{ and } IS_B = \Gamma_A$$

Suppose that, for potentially conflicting vehicles A and B, we have: $P_B > P_A$.

$$S_A \cap S_B \neq \emptyset \tag{6.19}$$

Based on the Trajectory Dependency and AC-IP Rule, from Equation (3):

$$A \rightarrow B \;\Rightarrow\; IS_B \neq \Gamma_A \tag{6.20}$$

But from the deadlock conditions, we have

$$IS_B = \Gamma_A \tag{6.21}$$

Equations (6.20) and (6.21) cannot be true at the same time. This is a contradiction. So $IS_B = \Gamma_A$ cannot be true while $IS_A = \Gamma_B$.

We now consider the deadlock situation with *n* vehicles, where $n > 2$. We must therefore have:

$$IS_B = \Gamma_A \text{ and } IS_C = \Gamma_B \text{ and } \ldots IS_Z = \Gamma_Y \text{ and } IS_A = \Gamma_Z$$

Suppose that: $P_A > P_B > \cdots > P_Y > P_Z$.

Therefore for conflicting vehicles *A* and *Z* we have:

$$P_A > P_B > \cdots > P_Y > P_Z \Rightarrow P_A > P_Z$$

$$S_A \cap S_Z \neq \emptyset \tag{6.22}$$

Based on the Trajectory Dependency and the AC-IP Rule, from Equation (6):

$$Z \rightarrow A \Rightarrow IS_A \neq \Gamma_Z \tag{6.23}$$

But the deadlock condition states that:

$$IS_A = \Gamma_Z \tag{6.24}$$

Equations (6.23) and (6.24) are contradictory. So $IS_A = \Gamma_Z$ cannot be true while $IS_B = \Gamma_A$ *and* $IS_C = \Gamma_B$ *and* … $IS_Z = \Gamma_Y$. So, we conclude that deadlock is avoided by applying the AC-IP Rule. ■

We now apply AC-IP to the deadlock scenario of Figure 6.17. Figure 6.18 illustrates the behavior of vehicles under the AC-IP Rule. Vehicle A has the highest priority, and its trajectory does not depend on any other vehicle at the intersection, so it does not wait for the passage of other vehicles. Therefore, it crosses without stopping or slowing down. Since vehicle B and D's trajectories depend on vehicle A's trajectory, then, by the AC-IP Rule, these vehicles will not enter the intersection box and will wait for vehicle A. Vehicle C has no potential collision with the currently crossing vehicle, and it crosses the intersection. Then, vehicle B starts crossing and vehicle D starts its passage through the intersection concurrently with vehicle D. So, the deadlock situation is avoided due to the priority policy and the AC-IP rule.

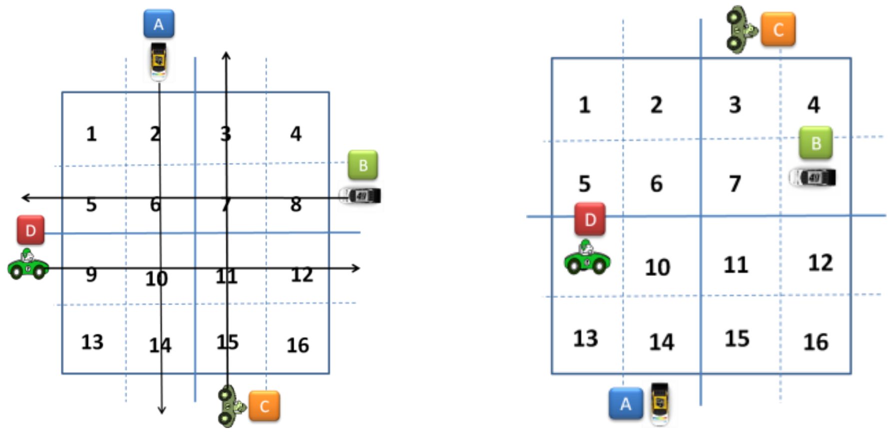


Figure 6-18: Deadlock is avoided by AC-IP

6.5 Summary

V2V-based safety applications face different challenges and our V2V-Intersection Protocols are not any exception to this rule. In this chapter, we have identified three problematic areas that can hamper the safety and efficiency promised by our intersection protocols: positioning inaccuracy, communication failure and deadlock.

Positioning inaccuracy impacts the measurements such as distance to intersection and arrival and exit times of vehicles approaching an intersection. This is a serious matter for our intersection protocols since these errors can lead to vehicle collisions around the intersection area. The impact of positioning inaccuracy on Low-Concurrency Protocols (LCP) is less than other generations of V2V-IPs, as in LCP protocols the whole intersection box is considered as a big cell and does not require highly fine-grained measurements. However, the impact of positioning errors is more sever in the case of HCP and HCP-EVD families of intersection protocols as they require fine-grained measurements with the granularity of an intersection cell. To study the effects of positioning inaccuracy on our intersection protocols, we have implemented realistic GPS models with different profiles based on the characteristics of current GPS technologies in the market. In this chapter, we have proposed using additional safety distance buffers outside of the intersection box and safety cell buffers inside the intersection area depending on the protocol in use and the level of positioning inaccuracy. Even though the throughput is slightly less than the case with no GPS inaccuracy, our simulation results show that the proposed intersection protocols support safe traversal through intersections at substantially higher throughput even with imperfect and commonly-used GPS devices.

We have benefited from various realistic DSRC channel models which are proved to match the empirical results. We have implemented DSRC signal propagation models and studied the effects of channel impairments such as packet loss due to fading on our V2V protocols. Additionally, we have studied the effects of packet collision due to the medium access control in different traffic volumes. Finally, the application reliability has been used to measure the reliability of our V2V safety application. Our simulation results indicate that these protocols benefit from high application reliability even in harsh NLOS environments such as intersections with tall buildings at all corners. In scenarios where V2V communications has a high packet loss ratio due to obstacles or channel congestion, local-sensing technologies can be used to avoid collisions at the intersection. We believe that, by combining V2V communications with local-sensing information obtained by sensors, cameras, radars, lidars and thermal images, highly reliable collision avoidance is achievable even in extreme environment scenarios.

We have investigated possible deadlock scenarios, in which all vehicles progress inside the intersection area as much as possible without getting into a collision. In this chapter, we have defined a set of rules as a part of our V2V-Intersection Protocols to avoid deadlock in the system and have presented mathematical proofs for the deadlock-freedom property of our proposed systems.

Chapter 7

Synchronous Movement Intersection Management

In this section, we introduce a spatio-temporal technique called the Ballroom Intersection Protocol (BRIP) to manage the safe and efficient passage of autonomous vehicles through intersections. To achieve high throughput at intersections, BRIP aims to maximize the utilization of the capacity of the intersection area by increasing parallelism. By enforcing a synchronized arrival of autonomous vehicles at intersections, BRIP allows vehicles approaching from all directions to simultaneously and continuously cross without stopping behind or inside the intersection area. Our simulation results show that we are able to avoid collisions and increase the throughput of the intersections by up to 96.24% compared to common signalized intersections. Under BRIP, the optimal intersection capacity utilization of 100% is achievable in certain cases [121][122].

In contrast to previously mentioned techniques, BRIP is not dependent on V2X communications. It allows vehicles to efficiently and continuously enter and cross the intersection in a synchronized manner. This method provides safety through the intersection while significantly increasing the throughput and decreasing the overall delay comparing to previous techniques. In this approach, vehicles do not stop before or inside the intersection boundaries, by using synchronized and staggered arrivals and departures. This synchronous arrival and movement of vehicles at the intersection permits a continuous traffic flow, in which, vehicles from all approaching directions can simultaneously cross with a constant speed. An arrival synchronization pattern is known or broadcast to all approaching vehicles. This includes the information regarding the turn restrictions for all traffic lanes and the desired entrance speed which will be maintained throughout the intersection. It also includes the permitted synchronized and staggered time slots during which a vehicle can enter the intersection area. This allows any vehicle to choose the correct lane based on its turning intentions, adjust its speed and enter the intersection box during a permitted time slot.

The rest of this paper is organized as follows. We first describe the assumptions and requirements of this cyber-physical system. We will then introduce our Ballroom Intersection Protocol (BRIP) and some examples to illustrate its efficiency and usage. In this section, we will also prove the deadlock-freedom property of BRIP. This chapter also includes the evaluation of our protocol and demonstrates comparisons between BRIP and common intersection management systems. At the end a conclusion and provisioned future work related to synchronized-movement intersection management is provided.

7.1 Assumptions and Requirements

Figure 7.1 illustrates an example of an enhanced vehicle system. The system includes a digital map database, a navigation system and an autonomous vehicle controller. The controller controls the operation of the vehicle, including steering, brake, throttle, etc., if the vehicle is autonomous or semi-autonomous. The map database stores map information at any level of detail that is available, including specific information about intersections called the Geometric Intersection Description (GID) [97]. The GID defines a digital map of an intersection down to the lane level. It is designed to provide vehicles with (1) a local, geo-referenced coordinate system; (2) the location of drivable lanes; and (3) an extensible scheme capable of incorporating future content. The map database operates in association with the navigation system to display various map views and other information that is available, and allow a user to input, plan and display a route. The vehicle also includes a wireless interface that allows the vehicle to wirelessly transmit and receive information from many sources, such as the Internet, satellite or a wireless infrastructure. The wireless interface also allows the vehicle to benefit from V2X (V2I, V2V and beyond) communications.

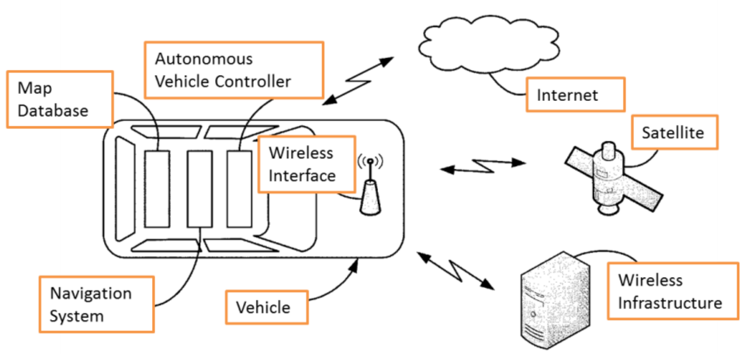


Figure 7-1: Illustration of an enhanced vehicle system

As mentioned earlier, vehicles are equipped with high-accuracy Global Positioning System (GPS) devices and have access to a digital road-map database. Based on a vehicle's intention at the intersection and the information obtained from the GPS device and GID of an approaching intersection, it can determine the *Current Road Segment (CRS)* and *Next Road Segment (NRS).*

Each intersection has its own restrictions for entering lanes. For example, in some intersections left lanes can only be used to go straight or only to turn left or a combination of both. We define the *Intersection Type* based on the intersection's turn restrictions. Our method can be implemented on various *Intersection Type*, and due to space restrictions, only the following three *Intersection Types* will be used as examples throughout this paper, just to demonstrate the core of the Ballroom Intersection Protocol (BRIP).

- Type I: Vehicles on all lanes are restricted to only go straight and no turns are allowed.
- Type II: Vehicles on the left lane must go straight and vehicles on the right lane must turn right.
- Type III: Vehicles on the left lane must turn left, vehicles on the middle lane must go straight, and vehicles on the right lane must turn right.

Throughout this Chapter, we assign unique identifiers to each road segment and lane attached to the intersection area. For entering lanes from all directions, the lane number is equal to zero for the leftmost lane and its value increases with an increment of 1 toward the rightmost lane. Figure 7.2 shows an intersection scenario in which vehicle A is approaching an intersection from the West and intents to go to the North. Therefore, its *CRS* is R_{west} and the *NRS* is R_{north}. Using the GID information in its map database, the vehicle knows that the approaching intersection is of *Type III.* Based on its *CRS, NRS* and the *Intersection Type*, it should be entering the intersection on the left lane L_0, in order to perform the appropriate left turn and go to the intended destination. Therefore, the vehicle enters the intersection area from (R_{west}, L_0) and exit to (R_{north}, L_0) as illustrated in Figure 7.2.

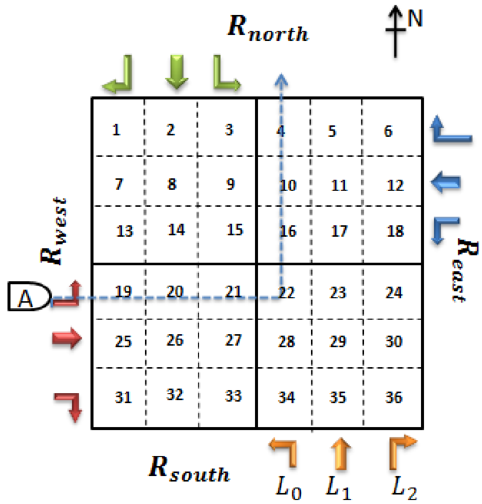


Figure 7-2: Turn restrictions of a Type III intersection.

7.2 The Ballroom Intersection Protocol (BRIP)

In this section, we define a spatio-temporal method to manage traffic at intersections by synchronizing the arrival of autonomous vehicles. The Ballroom Intersection Protocol (BRIP) is designed to enhance the capacity utilization and increase parallelism. In other words, our goal is to maximize the intersection area occupied by vehicles at the same time, without causing any accidents or deadlocks. Using this method the throughput of the intersection is significantly increased as multiple vehicles are able to cross the intersection simultaneously. Additionally, the BRIP protocol allows a continuous flow, in which, vehicles cross the intersection area with a constant speed, without stopping before or inside the intersection box. This behavior also increases the passenger comfort and fuel consumption, by reducing the delays of each commuter due to multiple stop and go movements.

Why is the name Ballroom used? The Ballroom Intersection Protocol (BRIP) is inspired by the main idea of the synchronized movements of participants in ballroom dancing. A group of ballroom dancers are all moving across a dance floor simultaneously without colliding into one another, while occupying the dance floor with a fairly high density. In our current context, vehicles replace people and perform synchronized movements in order to cross the intersection area safely and efficiently.

7.2.1 Synchronized Intersection Arrival Pattern (SIAP)

In the BRIP, each intersection is assigned a predefined traffic arrival pattern. This pattern depends on the intersection geometry and parameters such as the number of entering/exiting lanes and turning restrictions. The approaching vehicle has to be in the appropriate lane before entering the intersection box and enter the intersection area during a permitted arrival time slot and maintain a certain speed while crossing. We refer to this information as the Synchronized Intersection Arrival Pattern (SIAP). As stated previously, SIAP contains the following information for each intersection:

- *Intersection Type*: As mentioned earlier, the *Intersection Type* is a part of the intersection's GID. It includes the turn restriction information of each entering lane of an intersection.
- *Arrival Time Slots*: Vehicles are allowed to enter the intersection only at specific time slots. These permitted *Arrival Time Slots* may be different for each entering lane of the intersection.
- *Desired Speed*: Approaching vehicles are only allowed to enter the intersection with a certain speed depending on their entering lane. This speed should be maintained while crossing the intersection area.

It is required that each vehicle has access to the accurate SIAP of the approaching intersection. There are various ways to achieve this requirement. As described earlier in this paper, the enhanced vehicle system is equipped with a digital map database. Therefore, SIAP can be residing on-board the vehicle for a given intersection as a part of its road-map database. The information can be initially provided to vehicles in any suitable manner, such as through the Internet, satellite, radio service or cellular signals from a remote server. It can also be sent using vehicle-to-infrastructure (V2I) communications from a Road Side Unit (RSU) located at the intersection to the On-Board Unit (OBU) in the vehicle. Localization and tight time-synchronization is provided by high accuracy GPS devices. For autonomously controlled vehicles, this information is automatically provided to the vehicle controller and it follows the planned route through the intersection.

Based on the BRIP, the following rules are applied to vehicle *X*, when it approaches an intersection:

Algorithm 1: BRIP, Receiver Vehicle

Input: Received SIAP for the approaching intersection

Output: Vehicle *X*'s behavior at the intersection

1. Use the *Intersection Type* information in the received SIAP and vehicle's turning intent at the intersection to find the appropriate entering/exiting lanes.

2. Performing lane(s) change to be in the desired entering lane.
3. Use the *Arrival Time Slots* and *Desired Speed* information in the received SIAP, and the vehicle's controller model to set the appropriate acceleration/deceleration parameter. The goal is to arrive at the intersection with the SIAP's *Desired Speed*} and at an eligible *Arrival Time Slot*.
4. Cross the intersection with the SIAP-specified *Desired Speed*, without stopping or slowing down.

Now, we define the terms that will be used throughput this section.

- (r, r): Intersection cell size.
- (l, w): Vehicle's size, respectively length and width.
- $D\_\{p, q\}$: Distance between points ***p*** and ***q***.
- $D\_\{X, Y\}$: Distance between the centers of vehicle ***X*** and vehicle ***Y***.
- Γ_X: Arrival time of vehicle ***X*** at the intersection.
- V_X: Speed of vehicle ***X***.
- L_X: Lane number of vehicle ***X***.
- T: SIAP time slot duration.

T also represents the time required for the vehicle to cross an entire intersection cell. Since vehicles should maintain the constant desired speed through the intersection, T is defined as follows:

$$T = {}^{r}/_{V} \tag{7.1}$$

We posit that the synchronized arrivals of vehicles from different directions allow them to cross the intersection with maximal concurrency. Figure 4 demonstrates an example scenario of a simple *Type I* intersection, with 1-lane per direction. In this example scenario, based on the SIAP, all entering lanes have the same arrival requirements. Therefore, all four vehicles must arrive at the intersection at the same time $\Gamma_A = \Gamma_B = \Gamma_C = \Gamma_D$, and maintain the same constant speed while crossing $V_A = V_B = V_C = V_D$

We *start* at time step t_0 when all the vehicles have arrived at the intersection at the same time, and have not entered the intersection boundaries yet. In the next few time steps, vehicles enter and progress inside the intersection box at a constant speed. As we can see in Figure 7.3, the transition between states at time slots t_1 and t_2 is similar to the synchronized ballroom dance movements. This synchronized and continuous movement of vehicles allows them to enter the next cells along their trajectories without colliding with each other, and continue at a constant speed to the point that all vehicles have safely traversed and exited the intersection area.

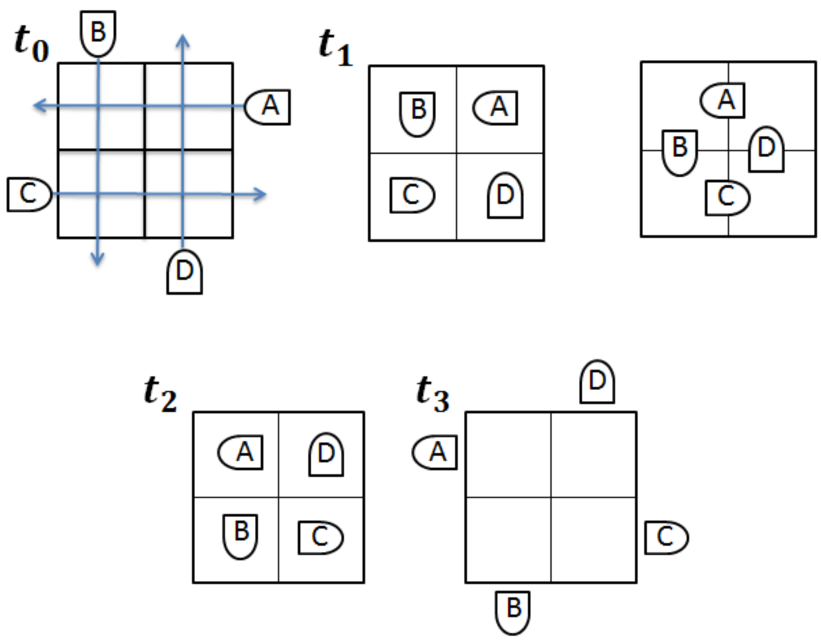


Figure 7-3: An example scenario of BRIP for Type I intersection

7.2.2 Collision Freedom

To achieve the goal of BRIP to allow safe and efficient passage of vehicles through intersections, we identify the physical requirements such as the intersection size and vehicle's physical parameters, and distance constraints among following vehicles. As we mentioned earlier, the intersection grid is divided into smaller cells, each of which can fit an average-size vehicle in it. Therefore, it is logical to assume that no more than one entire vehicle fits in one cell. This can be stated as $l < r < 2l$.

An accident occurs if two or more vehicles occupy the same space at the same time. Figure 7.4 shows an example scenario of a *Type I* intersection. The potential space conflict zones are the squares with size (w, w), same as the width of vehicles, at the center of each intersection cell, which are marked as $\varsigma_1, \varsigma_2, \varsigma_3, \varsigma_4$. We call these potential space conflict zones the *critical sections*. We can now state that there is a potential conflict among two or more vehicles if there is a common *critical section* along their trajectories through the intersection.

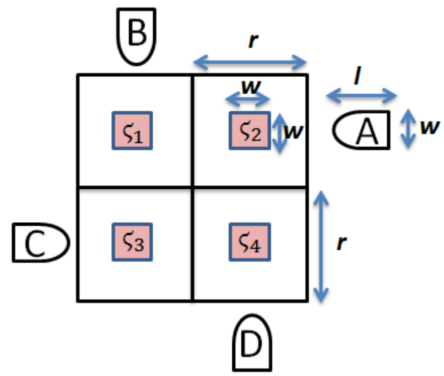


Figure 7-4: Critical Sections for Type I intersection

Figure 7.5 shows the scenario in which, vehicles ***A*** and ***B*** have entered an intersection *Type I* at the same time, and are now in the middle of the first cell along their trajectories. Point $\boldsymbol{p_1}$ denotes the left-down corner of the *critical section*, which is indeed the last possible point of collision where point ***a*** of vehicle ***A*** might collide with point ***b*** of vehicle ***B***.

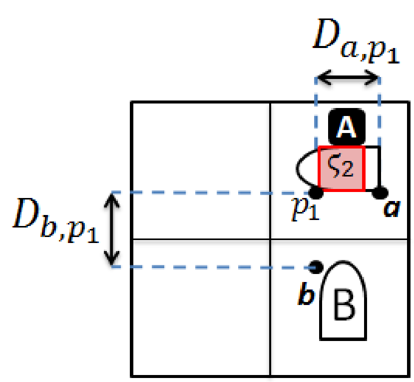


Figure 7-5: Distance constraints for Type I intersection

Based on the SIAP, vehicles A and B must enter the intersection box at the same time i.e. $\Gamma_A = \Gamma_B$. Additionally, they should arrive with the same speed $V_A = V_B$, and maintain that speed through their trajectories inside the intersection region. Therefore, to avoid an accident at the time that vehicles are at point $\boldsymbol{p_1}$ or any time before that, we must have:

$$D_{b,p_1} > D_{a,p_1} \Rightarrow \frac{r-l}{2} + \frac{r-w}{2} > w + \frac{l-w}{2}$$

$$\Rightarrow r - \frac{l+w}{2} > \frac{l+w}{2}$$

So,

$$r > l + w \tag{7.2}$$

We now calculate the distance and timing requirements for the vehicles which enter the intersection area following vehicles ***A*** and ***B***. Figure 7.6 shows the same scenario as Figure 6, in which vehicle ***C*** is arriving at the intersection from the same direction/lane as vehicle ***A***. Point $\boldsymbol{p_2}$ denotes the last possible point of collision where point ***b*** of vehicle ***B*** will collide with point ***c*** of vehicle ***C***.

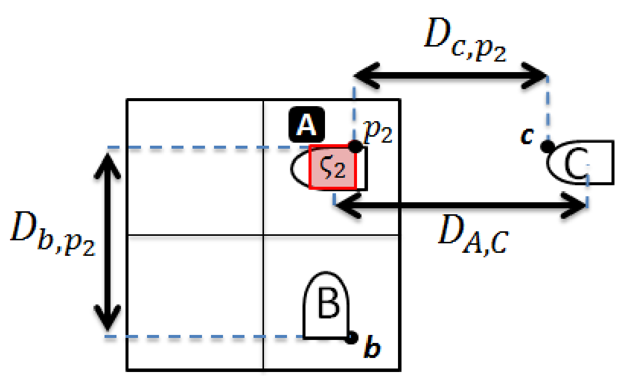


Figure 7-6: Car-following distance constraints for Type I intersection

To prevent a collision at the time that both vehicles are at point $\boldsymbol{p_2}$ or any time before that, the following condition should be true:

$$D_{c,p_2} > D_{b,p_2}$$

, where

$$D_{b,p_2} = l + w + \frac{r-w}{2} + \frac{r-l}{2} = r + \frac{l+w}{2}$$

So,

$$D_{c,p_2} > r + \frac{l + w}{2} \tag{7.3}$$

We can now calculate the distance constraint between vehicle A and its following vehicle C:

$$D_{A,C} = D_{c,p_2} + l - \frac{l - w}{2}$$

Therefore,

$$D_{A,C} = D_{c,p_2} + \frac{l + w}{2} \tag{7.4}$$

From Equations (3) and (4):

$$D_{A,C} > r + \frac{l + w}{2} + \frac{l + w}{2} = r + l + w \tag{7.5}$$

From Equation (2), we have $r > l + w$, therefore Equation (5) becomes:

$$D_{A,C} > 2(l + w) \tag{7.6}$$

This means that the distance between two consecutive vehicles in the same lane should be bigger than $2(l + w)$ to avoid any accidents with crossing vehicles in perpendicular directions. As r is greater than $l + w$, we can set the distance between two consecutive vehicles in this arrival pattern to be:

$$D_{A,C} = 2r \tag{7.7}$$

Therefore, the inter-arrival time between those vehicles is as follows:

$$\lambda = \frac{D_{A,C}}{V} = \frac{2r}{V} = 2T \tag{7.8}$$

Since the intersection is assumed to be symmetric, these constraints are applied to vehicles arriving from all four directions.

Using the above distance and timing constraints for a 2*2 lanes *Type I* intersection, the SIAP is as follows:

$$\Gamma_X = n\lambda = 2nT, \qquad n = 1,2,\ldots \tag{7.9}$$

Figure 7.7 illustrates an example scenario where the traffic flow entering the intersection uses every permitted slot. Therefore, there is always a vehicle in the dedicated arrival pattern and no spot is left empty in the SIAP. We refer to this situation as the *maximum entrance flow*. When dealing with a *maximum entrance flow*, we enter a steady state in which all intersection cells are occupied by crossing vehicles at any given time slot T .

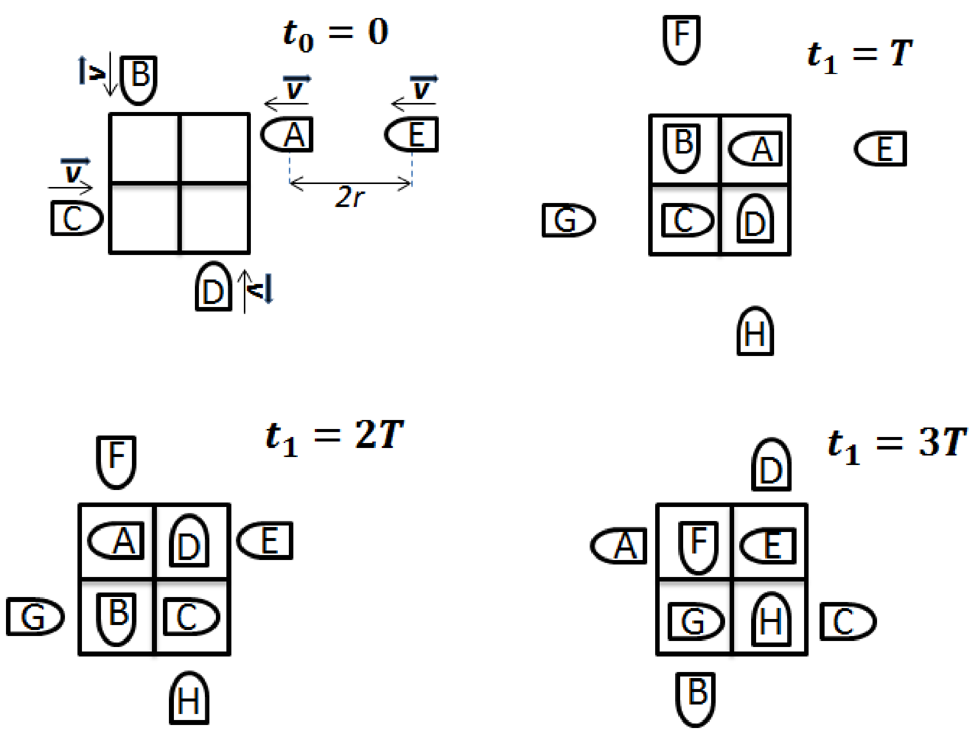


Figure 7-7: Maximum entrance flow for Type I intersection

From time step t_1 all intersection cells are occupied by vehicles and this steady state will last while there are vehicles arriving at all available time slots in the arrival pattern. We can also observe that the entrance pattern is repeated after every two time slots. For example, the patterns at t_1 and t_3 are isomorphic with respect to each other. Therefore, the arrival pattern of the *Type I* intersection is periodic with a period value of $2T$.

Please note that not every allowed slot in the arrival pattern needs to be occupied by a vehicle, and can be left empty without causing any disruption in the system. For example, when dealing with low-volume traffic, some of the slots in the SIAP will be unoccupied and therefore, fewer vehicles will be present at the intersection area at any given time and not all the intersection cells will be occupied. This will not in any way affect the entrance flow of the vehicles and their safe passage through the intersection grid.

An example scenario from AutoSim of asymmetric traffic management using BRIP:
https://www.youtube.com/watch?v=CH76UH5Z014

7.2.3 Deadlock Freedom

As described in earlier chapters, a deadlock is a situation in which two or more competing actions are each waiting for another to finish, and thus none ever does. A deadlock situation can occur inside the intersection area among the vehicles which are trying to cross the intersection at the same time. To represent these scenarios, we use *wait-for* graphs. A *wait-for* graph is a directed graph used for deadlock detection in operating systems and relational database systems. A deadlock exists if the graph contains any cycles.

We now investigate a possible deadlock scenario, in which all vehicles progress inside the intersection area as much as possible without colliding with other vehicles.

As we can see in Figure 7.8, vehicle ***A***'s next *critical section* ς_1 is occupied by vehicle ***B***, vehicle ***B***'s next *critical section* ς_3 is occupied by vehicle ***C***, vehicle ***C***'s next *critical section* ς_4 is occupied by vehicle ***D***, and finally vehicles ***D***'s next *critical section* ς_2 is occupied by vehicle ***A***. This means that none of these vehicles can progress inside the intersection grid as each of their next *critical sections* is occupied by other vehicles.

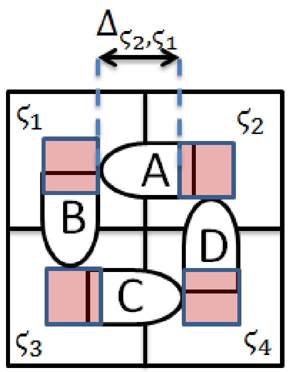


Figure 7-8: A deadlock scenario at intersection.

For the purpose of this paper, we define the elements of our intersection *wait-for* graph as follows. Vehicles are represented as the nodes of our *wait-for* graph, and an edge from vehicle ***A*** to vehicle ***B*** implies that vehicle ***B*** is holding a critical section that vehicle ***A*** needs to complete its trajectory through the intersection grid. Thus, vehicle ***A*** is waiting for vehicle ***B*** to release (leave) that specific *critical section*. It can be seen clearly in Figure 7.9 that the corresponding *wait-for* graph contains a cycle and therefore, it represents a deadlock situation.

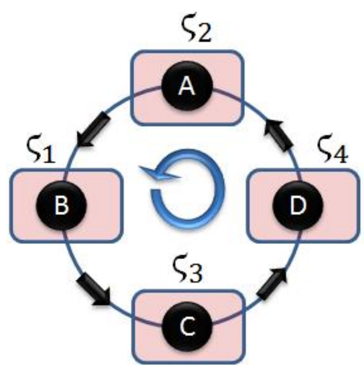


Figure 7-9: Wait-for graph

We will use the following terms in our proofs:

- $\Phi_X = \varsigma_n$: Vehicle ***X*** is at the border of *critical section* ς_n, and waiting to enter ς_n.
- $\Delta_{\varsigma_n,\varsigma_m}$: Distance between two following *critical sections* ς_n and ς_m.

Theorem 1: BRIP is *Deadlock-free.*

Proof. Without loss of generality, we will use a 4-way intersection to prove this theorem. The deadlock condition is as follows:

$$C_A = \varsigma_2 \ and \ C_B = \varsigma_1 \ and \ C_C = \varsigma_3 \ and \ C_D = \varsigma_4$$

And, at the same time:

$$\Phi_A = \varsigma_1 \ and \ \Phi_B = \varsigma_3 \ and \ \Phi_C = \varsigma_4 \ and \ \Phi_D = \varsigma_2$$

The distance between *critical sections* occupied by vehicles ***A***, ***B***, ***C*** and ***D*** is:

$$\Delta_{\varsigma_2,\varsigma_1} = \Delta_{\varsigma_1,\varsigma_3} = \Delta_{\varsigma_3,\varsigma_4} = \Delta_{\varsigma_4,\varsigma_2} = r - w \quad (7.10)$$

From the deadlock condition, we have:

$$C_A = \varsigma_1 \ and \ \Phi_A = \varsigma_2$$

This means that vehicle ***A*** is partially in *critical section* ς_2 and also at the border of *critical section* ς_1. Therefore:

$$l > \Delta_{\varsigma_1,\varsigma_2} \quad (7.11)$$

From Equation (2), we had $r > l + w$.

Therefore, using Equations (1) and (11):

$$l > \Delta_{\varsigma_1,\varsigma_2} \Rightarrow l_A > (r - w) > (l + w - w) \Rightarrow l > l \quad (7.12)$$

Equation (12) is a contradiction. Therefore, the deadlock conditions of $C_A = \varsigma_2$ and $\Phi_A = \varsigma_1$ cannot be true at the same time. Similar arguments apply to vehicles B, C and D. □

We can prove the deadlock-freedom for other *Intersection Types* and multi-lane intersections, by using the same core assumptions and method as described above.

7.2.4 Multi-Lane Intersections

In this subsection, we look at multi-lane intersections. We first consider a *Type I* intersection, with 2-lanes per direction. Figure 7.11 shows a scenario in which vehicles are approaching an intersection from all four directions. If all approaching vehicles enter at the same time and the following vehicles arrive with the periodicity of $2T$, the set of vehicles arriving from perpendicular roads with same lane numbers such as vehicles (***A***, ***B***, ***C***, ***D***) as well as vehicles (***E***, ***F***, ***G***, ***H***) can all safely cross. But collisions will eventually occur during the next arrival periods among vehicles arriving from perpendicular roads with different lane numbers such as vehicles ***A*** and ***N*** which are approaching from (R_{east}, L_0) and (R_{north}, L_1) respectively.

To avoid these potential collisions, in addition to the synchronized arrival of them, it is necessary to insert a staggering offset between the arrival of vehicles on the adjacent lanes L_0 and L_1 from any direction. This offset will result in the staggered arrival of vehicles depending on their current lane. As a result of the distance and speed constrains, the minimum staggering offset required is equal to the SIAP time slot duration T, which is the time required for a vehicle to cross an entire cell. This offset prevents vehicles ***A*** and ***N*** to occupy their common *critical section* ς_5 at the same time. Vehicle ***A*** completely leaves ς_5 before the arrival of vehicle ***N***. Therefore, the SIAP can be expressed as follows:

$$\Gamma_X = \begin{cases} 2nT, & L_X = 0 \\ 2nT + T, & L_X = 1 \end{cases} \tag{7.13}$$

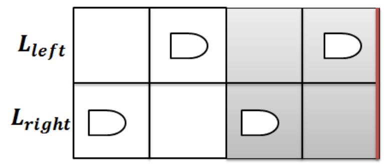


Figure 7-10: Arrival pattern for Type I intersections

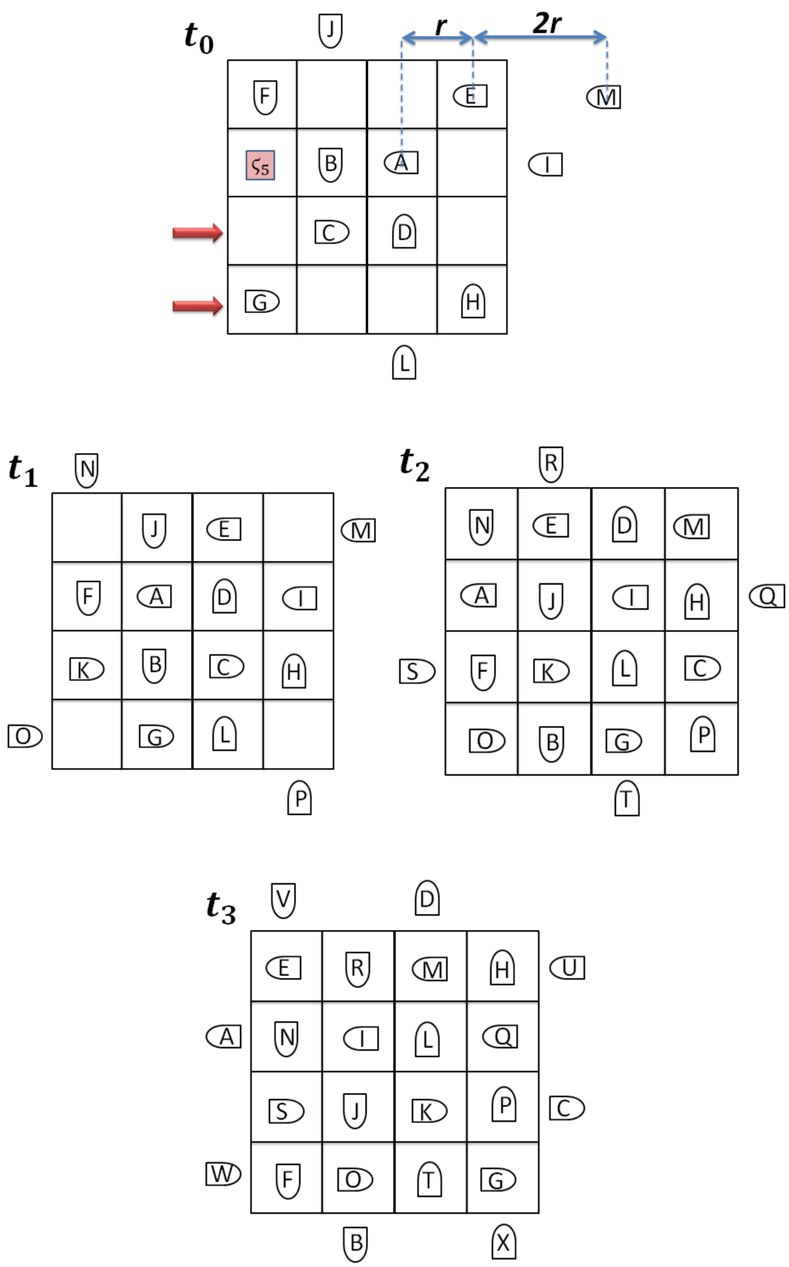


Figure 7-11: Example scenario for Type I intersections

Therefore, the staggered arrival pattern of this *Type I* intersection is periodic and repeats every $2T$.

A simulation video of a *Type I* intersection can be seen at:

- https://www.youtube.com/watch?v=shJZZGSXW8o

We now generalize the arrival pattern for *Type I* intersections with λ-lanes per direction, where $\lambda \geq 1$. To avoid collisions between crossing vehicles, a staggering offset is inserted for each additional entering lane. In particular, vehicle X's arrival pattern is specified as follows:

$$\Gamma_X = n\alpha T + \beta T \tag{7.14}$$

, where α and β are called the *periodic pattern coefficient* and the *staggering offset coefficient* respectively. The value of α depends on the intersection's arrival pattern periodicity. As the arrival pattern of *Type I* intersection is periodic with the periods $2T$, we have $\alpha = 2$. The value of β depends on the current lane of the vehicle and is equal to the lane number as the defined convention in Section II. Hence $\beta = L_X$.

We now consider a *Type II* intersection with 2-lanes per direction. Figure 7.13 shows an example of such an intersection. In this case, vehicles on the left lane must go straight, and vehicles on the right lane must turn right. Vehicles on the left lane have the same constraints as in *Type I* intersections, therefore, they have a similar arrival pattern. On the other hand, as vehicles on the right lane do not have any trajectory conflicts with other vehicles at the intersection, they can cross the intersection at back-to-back time slots. The SIAP of this *Type II* intersection is as follows:

$$\Gamma_X = \begin{cases} 2nT, & L_X = 0 \\ nT, & L_X = 1 \end{cases} \tag{7.15}$$

A simulation video of a *Type II* intersection under BRIP can be seen at:

- https://www.youtube.com/watch?v=LKj2YscDk8s

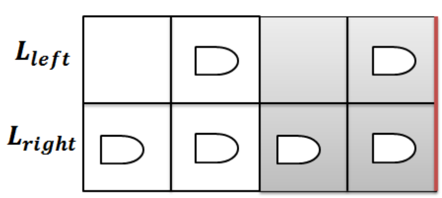


Figure 7-12: Arrival pattern for Type II intersections

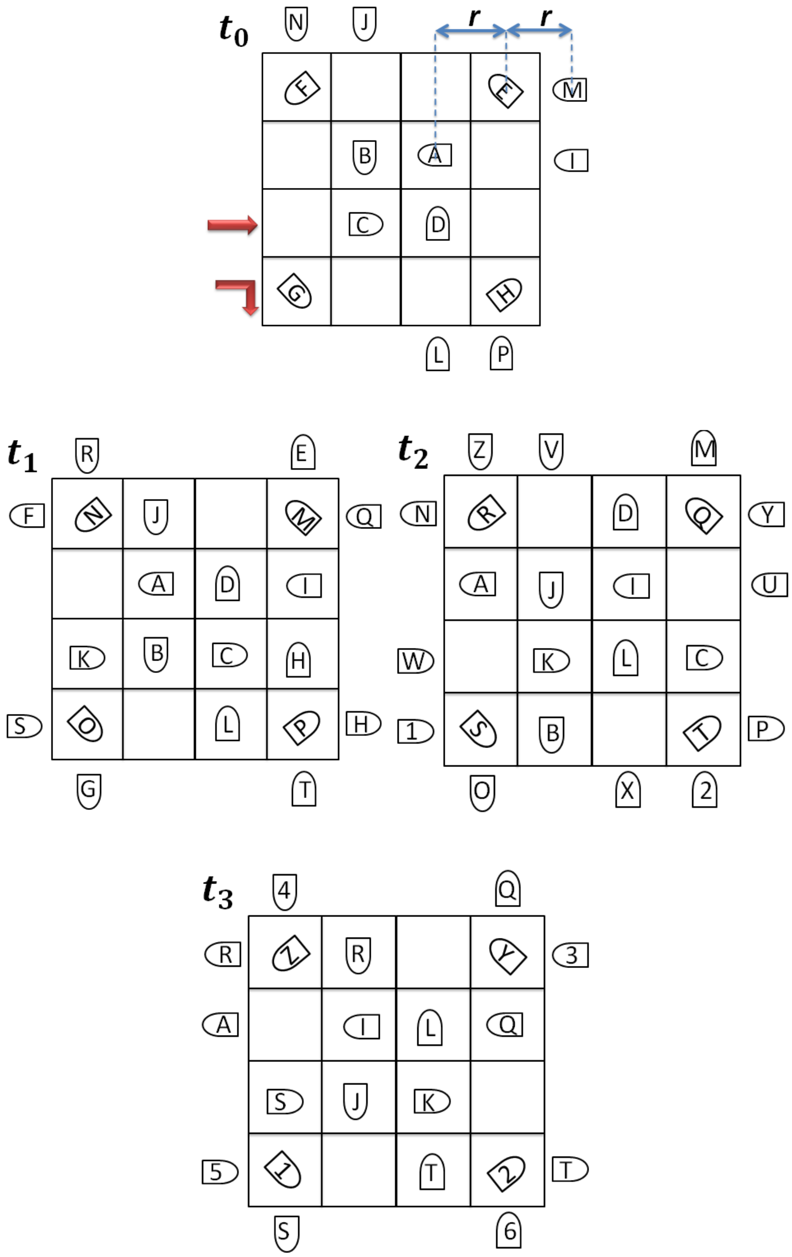


Figure 7-13: Example scenario for Type II intersections

We now consider general *Type II* intersections consisting of λ-lanes per direction, where λ_1 lanes are restricted on going straight, and λ_2 lanes are restricted to turn right. The general form for the arrival pattern is as follows:

$$\Gamma_X = \begin{cases} n\alpha T + \beta T, & 0 < L_X < \lambda_1 \\ nT, & \lambda_1 < L_X < \lambda \end{cases} \tag{7.16}$$

The arrival pattern is periodic with period value of $2T$. Therefore, $\alpha = 2$. Based on the Section 2 convention on numbering the entering lanes, $\beta = L_X$.

Next, we study common *Type III* intersections with 3-lanes per direction. Figure 7.15 shows an example of such an intersection. Comparing to going straight, the left turn is longer in distance, and each vehicle occupies more *critical sections* to complete its trajectory along the intersection grid. Vehicles on the right lane have no potential trajectory conflict with other vehicles and therefore, they can turn right in back-to-back arrival slots. This is not the same case for vehicles on the middle and left lanes. In addition to potential conflicts among vehicles on the left lane, they might also collide with vehicles going straight using the middle lane. This directly affects the SIAP and more arrival slots must be left empty to provide the safe passage of vehicles in all directions. These conflicts also need to be resolved by inserting staggering offsets of T and $2T$ for vehicles on the middle lane, so that no common *critical section* is occupied by more than one vehicle at any given time slot. The SIAP of intersection *Type III* is as follows:

$$f(x) = \begin{cases} 5nT, & L_X = 0 \\ 5nT + T \text{ and } 5nT + 2T, & L_X = 1 \\ nT, & L_X = 2 \end{cases} \tag{7.17}$$

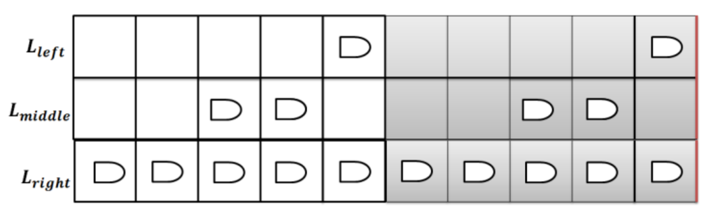
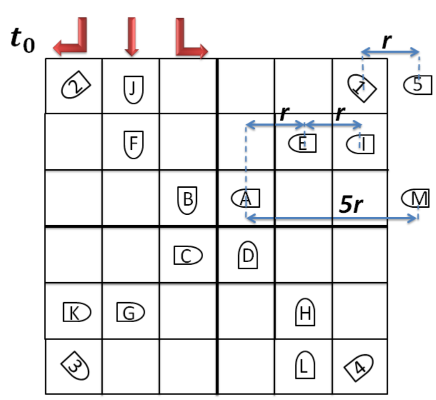


Figure 7-14: Arrival pattern for Type III intersections



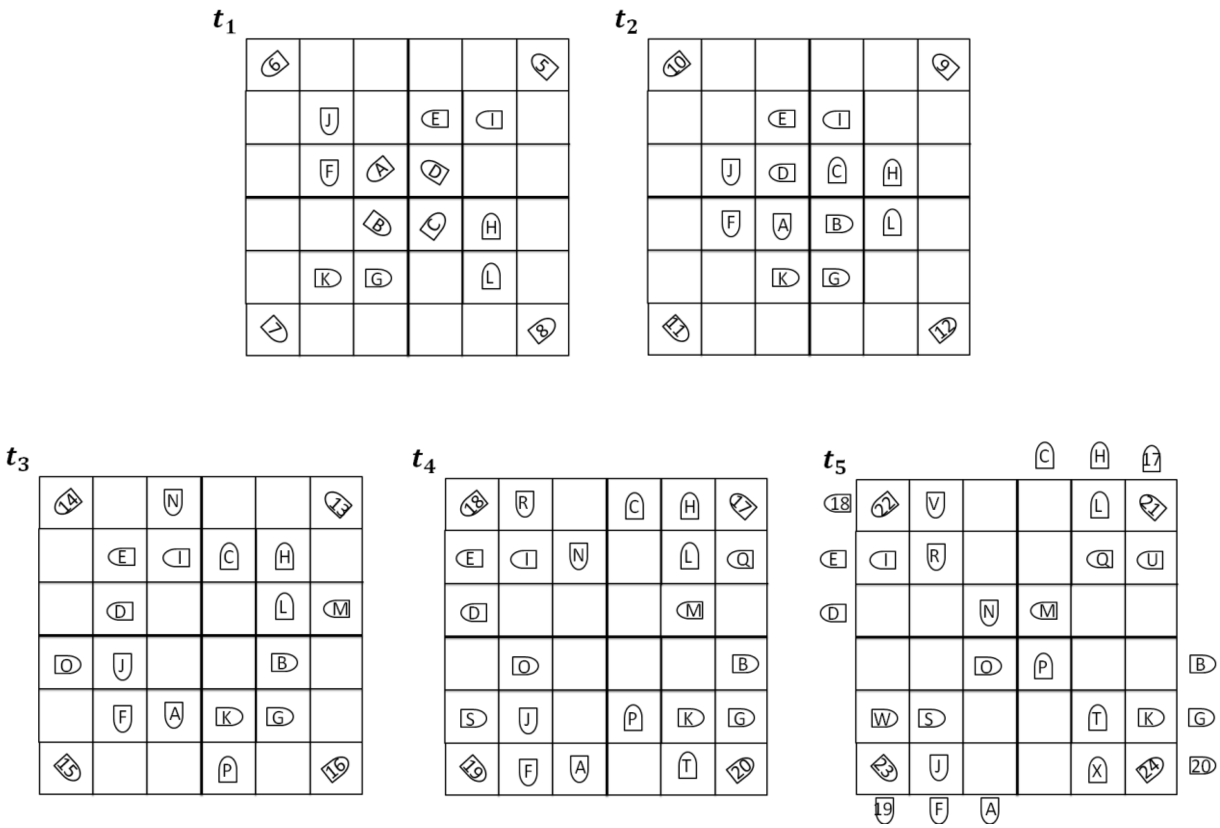


Figure 7-15: Example scenario for Type III intersections

The arrival pattern of the *Type III* intersection is periodic with a period value of $5T$. More simulation videos of BRIP can be seen at:

- https://www.youtube.com/watch?v=dQM0e5ilE_c
- https://www.youtube.com/watch?v=pPojYhVkGXI

We conclude that to achieve the maximum capacity utilization of an intersection, each vehicle uses the unique SIAP information of an approaching intersection. This information is used by each vehicle to be on the correct entry lane and adjusts its velocity, to arrive at the intersection during an allowed arrival slot and also enter with the SIAP-specified speed which will be maintained throughout its intersection traversal.

7.2.5 Anomalies and Mishaps at the Intersection

V2I and/or V2V wireless communications can be employed to deal with anomalies such as vehicle breakdowns, flat tires or other mishaps. V2I and/or V2V wireless communications can also be used for recovery and collision avoidance in case of such anomalies. In this case, approaching vehicles will be informed using safety messages and stop before entering the intersection boundaries to avoid collisions. Once the transient has passed, normal operation resumes. For autonomously controlled vehicles, this information will be automatically provided to the vehicle controller where the vehicle follows the planned route through the intersection.

Time synchronization is provided by GPS devices and is in the order of nanoseconds. Centimeter positioning accuracy is required to achieve the optimal solution and maximize the capacity utilization under BRIP. This level of accuracy is provided by Differential-GPS techniques such as Real-Time Kinematics (RTK). Since the common GPS receivers have the accuracy level of a few meters, it is important to deal with error margins due to positioning inaccuracy. In our ongoing work, we propose a method which involves increasing the required distance between following vehicles by having more empty slots in the arrival pattern. This safety distance buffer will be determined based on the intersection grid's cell size and the level of the positioning inaccuracy. The safety will guaranteed even with high degrees of positioning inaccuracy but with the price of lower throughputs than the optimal case.

7.3 Evaluation

In this section, we also analyze our work by comparing the performance of BRIP rules at intersections to current intersection management technologies such as stop signs and traffic lights. As described in previous chapter, we use the *trip time* and average trip delays across all cars in a simulation sequence as our metric of comparison.

Additionally, in order to measure the effectiveness of BRIP in increasing the parallelism and capacity utilization of the intersection, we have defined a metric called the Intersection Capacity Utilization (ICU). ICU is the fraction of occupied intersection cells to the total number of available cells during the steady state period.

This can be also stated as follows:

$$ICU = \frac{\sum_{i=j}^{j+\psi-1} O_i}{\psi . N} \tag{7.18}$$

, where

- O_i: Number of occupied cells at time slot i.
- N: Total number of intersection cells.
- ψ: Steady state's period. $O_i = O_{i+\psi}$

We have compared the common traffic light models to our proposed Ballroom Intersection Protocols for three different *Intersection Types*. Figures 7.16 and 7.17 show this comparison for perfect-cross intersections of *Types I and III* respectively. The traffic is assumed to be symmetric, meaning an equal amount of traffic volume in every direction and an equal amount of turn ratios. The X-axis is the traffic volume in vehicles per second and the Y-axis is the delay in seconds. Traffic light models face significantly higher delays than our BRIP models. In the case of the traffic light models, vehicles arriving at the intersection when there is a red light have to stop for the other directions with a green light. These vehicles must wait for the green light even if there are no other vehicles on perpendicular roads. In contrast, BRIP models increase the parallelism and allow the continuous passage of vehicles from all entering directions.

Under the BRIP rules, there is no delay at the entrance of the intersection and vehicles can cross with the constant desired speed based on the intersection's Staggered and Synchronized Arrival Pattern. The only source of delay is from vehicle decelerations in order to adjust their speed to the desired speed, and to obey the car-following distance constraints, so that the vehicle enters the intersection grid at allowed time slots.

Figure 7.16 shows the overall delay comparison for a *Type I* intersection managed by the following mobility models. (1) Traffic light models with green-light durations of 10 and 30 seconds; (2) V2V-Intersection protocols: Advanced Crossing and Advanced Progression Intersection Protocols (AC-IP and AP-IP); and (3) Ballroom Intersection Protocol (BRIP). As can be seen in this figure, BRIP model outperforms the traffic light models significantly. BRIP has no delay for low-volume traffic and a negligible delay for medium and high-volume traffic. BRIP improves the performance by 98.03%, 96.24%, respectively comparing to the traffic light models with green-light durations of 30 seconds and 10 seconds.

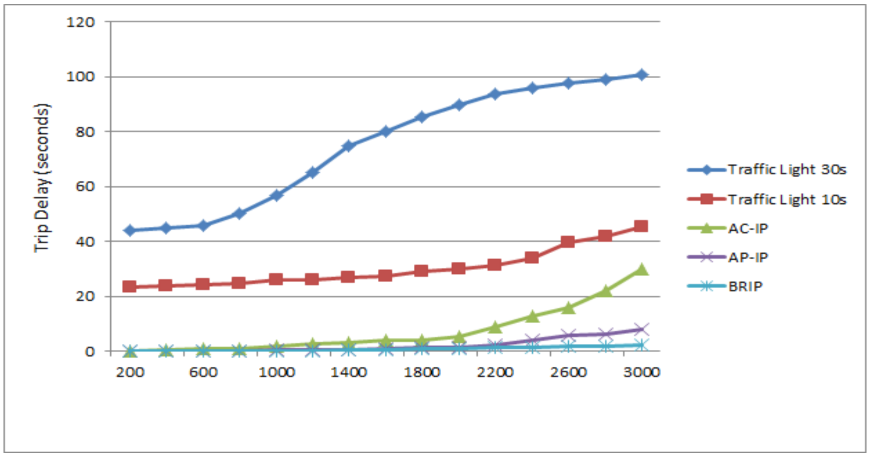


Figure 7-16: Delay comparison for Type I intersection

Figure 7.17 shows the delay comparisons between the BRIP model and traffic light models for *Type III* intersection. For this type of intersection, BRIP has longer delays than it has for *Type I* intersections due to a higher number of empty slots in its arrival pattern which guarantees the safety of left-turning vehicles. Despite the larger number of empty slots, BRIP outperforms the traffic light and stop sign models as it increases the parallelism and allows the simultaneous and continuous crossing of vehicles from all four directions.

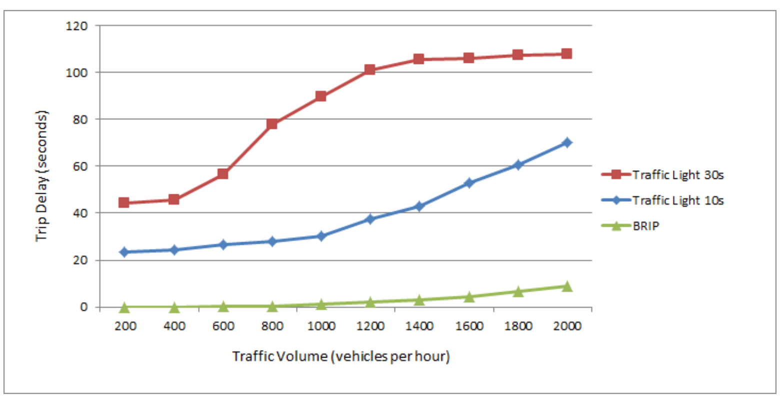


Figure 7-17: Delay comparison for Type III intersection

Next, we look at asymmetric traffic where major and minor roads intersect. In this case, the traffic volume is significantly different on the intersection roads. Therefore, under BRIP rules, most of the allowed slots in the major road will be occupied. On the other hand, for minor roads of the same intersection, many slots are left empty without causing any disruptions. Figure 7.18 shows the delay comparison between the BRIP and traffic light models with the green-light duration of 10 seconds, for asymmetric traffic at the same *Type I* intersection. As can be seen in this Figure, our BRIP model significantly outperforms the traffic light models. BRIP decreases the delays by approximately 95.4% over the traffic light model. As can be seen in the zoomed-in figure, in contrast to the traffic light models, delay values under BRIP management are very similar to the cases of symmetric and asymmetric traffic intersections. Therefore, BRIP is also suitable for asymmetric intersections and manages the traffic with high efficiency in different traffic scenarios.

A simulation video of an asymmetric traffic intersection can be seen at:

- https://www.youtube.com/watch?v=CH76UH5Z014

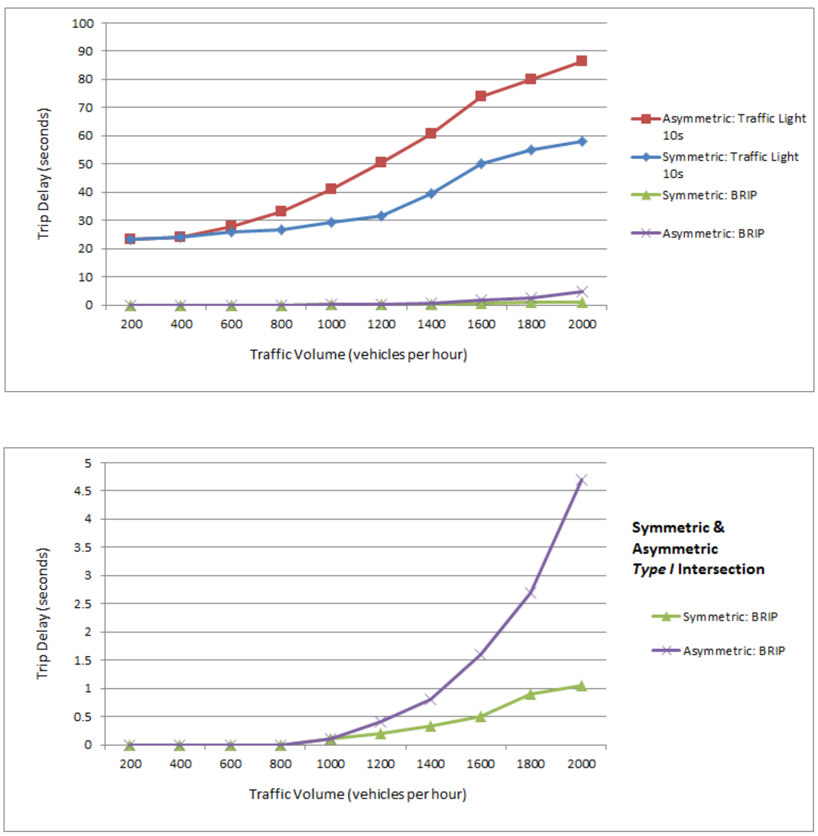


Figure 7-18: Delay comparisons for symmetric and asymmetric traffic at Type I intersections

In the example scenario of Figure 7.11, if there is a *maximum entrance flow*, we will reach the steady state at time slot t_2. All the 16 intersection cells are occupied at t_2, t_3 and the next time slots. This situation holds for all future time slots if no malfunctioning occurs. Since the number of occupied cells is equal to the total number of intersection cells during the steady state period, the ICU is equal to 100%. This is indeed the maximum intersection capacity utilization. The ICU for *Type II* and *Type III* intersections is respectively 75% and 56.25%.

In the case of intersections with stop signs, only one vehicle crosses at a given time and vehicles from all other directions should stop and wait for that vehicle's traversal. Therefore, only 1 intersection cell is utilized at any time slot. This decreases the intersection capacity utilization and increases the delays endured by each commuter significantly. Additionally, for a *Type I* intersection managed by traffic light, vehicles from perpendicular directions cannot cross simultaneously, and vehicles should stop and wait for the other directions. Therefore, even for the best-case scenario of allowing back-to-back entrance of vehicles during the green light for one direction, all intersection cells will be empty and not utilized before the transition phase, in which the perpendicular direction's light turns from red to green. Due to this fact, the traffic light's Intersection Capacity Utilization (ICU) does not exceed 50%. This leads to high amounts of delay especially with medium and large-volume traffics. These simulation results show that BRIP also provides substantially better intersection management for *Type I* intersections, by allowing the continuous entrance flow of the vehicles, and coordinated intersection crossing with constant speed while utilizing the maximum capacity of the intersection space.

7.4 Summary

The current technologies used for managing traffic through intersections, such as stop signs and traffic lights, are not very safe and efficient. The resulting high number of vehicle crashes and significant delays faced by commuters at intersections has motivated this work. In this chapter, our goal was to design a new intersection management method to manage traffic at intersections safely and efficiently by enforcing synchronized arrival of vehicles at intersections. Our method is independent of any type of V2X communications. The Ballroom Intersection Protocol (BRIP) also enjoys freedom from deadlock and allows all vehicles to cross the intersection grid with a constant speed without stopping before or inside the intersection area. The synchronous movement of approaching vehicles permits a continual traffic flow and significantly increases traffic throughput at intersections. Simulation results show that our proposed Ballroom Intersection Protocol (BRIP) avoids collisions and significantly increases the capacity utilization of the intersection comparing to other known techniques using V2I and V2V communications. BRIP outperforms the throughput of intersections managed by traffic lights. This method in fact provides an optimal solution and achieves the maximum possible capacity utilization of 100% for *Type I* intersections with any same number of entering lanes per each direction.

Chapter 8

Heterogeneous Traffic Management

Autonomous vehicles' full market penetration is considered to be the ideal scenario, in which all vehicles can benefit from a wide range of safety and traffic efficiency applications. However, this is not achievable in the near future due to the enormous number of existing manually-driven vehicles. Car manufacturers are introducing various Advanced Driver Assist Systems (ADAS) as the logical steps toward the ultimate goal of full autonomy, and more and more average vehicles will benefit from these systems in the near term. It is highly probable that the U.S. pursues a Dedicated Short Range Communication (DSRC) mandate for all new vehicles, and European carmakers have already committed to begin introducing DSRC systems in 2015. Therefore, not only autonomous vehicles but a wide range of human-driven vehicles will be equipped with DSRC On-Board Units (OBU), and will be able to transmit and receive safety messages and be a part of V2V, V2I and in general V2X communications.

In the near future, roads will be occupied by a mix of human-driven and autonomous vehicles. We refer to this type of traffic as heterogeneous traffic. It will be vital to manage the safe co-existence of manual and autonomous vehicles on the roads and specifically at road intersections. This chapter describes our methods which are designed to enable the safe and efficient passage of autonomous vehicles through intersections, while co-existing with human-driven vehicles in their surroundings. In contrast to V2V-Intersection Protocols which rely purely on the V2V communications, these protocols benefit not only from vehicular communications (V2X) but also from the on-board sensor system of the vehicle including cameras, radars and lidars.

In addition to our goal regarding the safe passage of autonomous vehicles through intersections in a heterogeneous traffic environment, we also aim to increase the safety of manually-driven vehicles. This goal is achieved by the use of warning systems in the shape of on-board or road-side units, as well as enhanced infrastructures. These warning systems allow the human driver to react quickly avoid collisions.

In this chapter, we also evaluate the performance of our protocols and study the challenges and effects of various destructive factors such as sensor inaccuracy, range limitations and road occlusion on them.

8.1 Assumptions and Requirements

First, we discuss the requirements and assumptions for our heterogeneous traffic management at intersections. Requirements include the on-board equipment for vehicles as well as the infrastructure tools to provide a safe passage for different vehicle types through cross-roads.

We believe that more equipped traffic lights can play an important role in increasing the safety and efficiency of signalized intersections. We define an Enhanced Traffic Light (ETL) as the traffic light which is equipped with a camera and a DSRC radio. An example of ETL is shown in Figure 8.1. ETL is capable of detecting the presence of vehicles at all intersection segments and inside the intersection box. The DSRC radio enables the ETL to participate in Vehicle-to-Infrastructure (V2I) communications with vehicles and infrastructures which are also equipped with these radios.

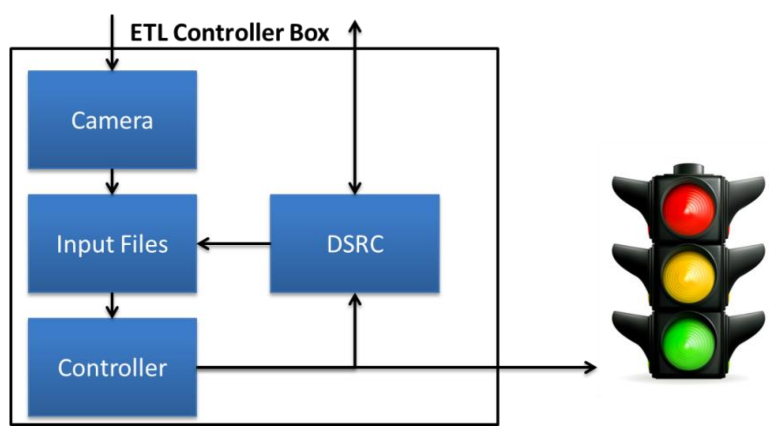


Figure 8-1: An Enhanced Traffic Light (ETL)

Various vehicle-infrastructure cooperation opportunities can be enabled using the real-time traffic Signal Phase and Timing (SPaT) information which is sent to vehicles approaching signalized intersections [107], [108][109]. SPaT describes the signal state of the intersection and how long this state will persist for each approach and lane that is active. Movements are given to specific lanes and approaches by use of the lane numbers present in the message. The real-time provision of SPaT information was originally conceptualized on the basis of equipping each signalized intersection with a

DSRC wireless transceiver that could broadcast information with low latency. SPaT's goal is to support not only safety, but also support enhanced mobility and improve traffic flow by reducing incidents at intersections. Reduced congestion further has a positive impact on the environment by reducing fuel consumption.

Using the SPaT safety messages, the ETL not only provides the exact cycle of the traffic light, it also offers the Geometric Intersection Description (GID) as a part of MAP information to all approaching vehicles. The MAP (GID) section of SPaT messages, describes the static physical geometry of the intersection; i.e., lane geometries and the allowable vehicle movements for each lane, and introduces the idea of "intersection data frame" which describes barriers, pedestrian walkways, shared roadways and rail lines that may affect vehicle movements. Within SAE J2735, this message is precisely defined as the *MSG_MapData* [8].

As shown in Figure 8.1, the DSRC box receives the SPaT information from the traffic light's controller box via Ethernet and broadcasts the related safety messages to all vehicles in its communication range.

For the sake of our heterogeneous intersection protocols, we assume that heterogeneous traffic consists of three different types of vehicles:

1) Human-Driven Vehicle (HDV): This category includes vehicles that are controlled by the human driver and are *not* equipped with any communication devices or on-board sensors. Therefore, they depend purely on the decisions made by the driver and have no means to interact with neighboring vehicles or infrastructure using V2V and V2I communications. We assume that human drivers will still follow the current technology rules at intersections, such as stop signs and traffic lights. When dealing with HDVs, visual warnings cannot be provided by an on-board system but as a part of the infrastructure such as road warning signs and enhanced traffic lights.
2) Enhanced Human-Driven Vehicle (EHDV): This type includes the vehicles that are still controlled by the human driver while benefiting from Advanced Driver Assist System (ADAS). These vehicles are assumed to be equipped with a GPS receiver and a map database which provides information such as positioning, heading and velocity. Being equipped with a DSRC radio gives EHDVs the capability to participate in V2V and V2I communications, and enables them to transmit/receive useful information to/from other equipped vehicles and road side units. Additionally, a warning system is used to warn the driver based on the received safety messages to avoid dangerous road situations

so that the driver can take actions in a timely manner and prevent collisions. This on-board warning system includes a display to provide visual warnings and appropriate movement instructions to the human driver.

3) Autonomous Vehicle (AV): These vehicles are equipped with autonomous steering controller and various information sources such as GPS receiver, digital road-map database, DSRC radio, and on-board sensors such as cameras, radars and lidars. As an example, Figure 8.2 illustrates the vehicle-resident sensor installation of CMU's autonomous vehicle platform. The on-board sensor system includes 15 sensors which are concealed and integrated into the vehicle for safety and appearance reasons [45].

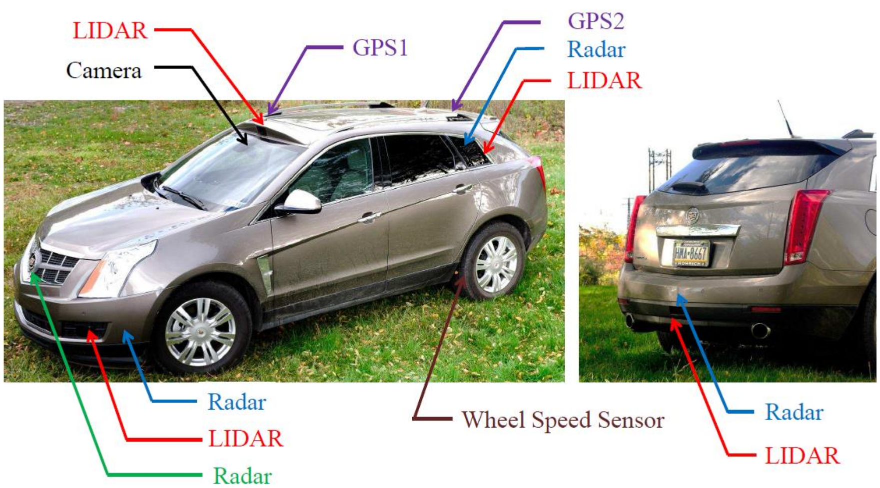


Figure 8-2: Sensor installation of CMU's autonomous vehicle

In an AV, the perception of the surrounding environment, including static and dynamic obstacles is provided by the vehicle-resident sensor system. Three main types of sensors are used by autonomous vehicle platforms: radar, LIDAR and cameras. Radar has the ability to detect obstacles' positions and speeds directly. However, radar outputs are usually not informative enough to estimate obstacle shape. The data provided by LIDAR are usually a cloud of 3D points dense enough for detecting the shape of cars, pedestrians, curbs and un-drivable areas. However, LIDAR's cost, sensing range, robustness to weather conditions and velocity measurement accuracy are not as good as radar's. Cameras are the most cost-effective sensor for automotive applications. Camera data are very informative, especially for detecting lane markings, signs and traffic lights with texture and color features. However, false-positive and recognition failure rates are much higher for vision than for LIDAR and radar. Figure 8.3 shows the sensors used by the CMU's automated SRX and their main specifications. There are multiple LIDAR and radar sensors installed, giving the vehicle 360-degree coverage around the car.

Sensor Type	Number	FoV (°)	Max Range(m) / Resolution
LIDAR	6	85-110	200
Radar1	1	12-30	250
Radar2	5	20(near) 18(far)	60(near) 175(far)
Video Camera	1	30	1360x1024
FLIR Camera	1	36	640x480

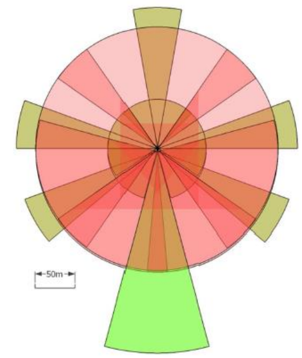


Figure 8-3: Installed Sensors' Specifications and Perception System Coverage

8.2 Heterogeneous V2V-Intersection Management

We first consider the traffic that consists of AVs (Autonomous Vehicles) and EHDVs (Enhanced Human-Driven Vehicles). All of these vehicles are equipped with DSRC radios and are able to transmit and receive safety messages to and from other vehicles in their communication range. We present a new scheme which enables the co-operative driving of AVs and EHDVS through intersections and increases the safety and throughput of their passage.

Both AVs and EHDVs broadcast Basic Safety Messages (BSM) which includes the information regarding their current position coordinates, velocity and heading. There is a fundamental difference between the messages generated by an AV and an EHDV. This difference corresponds to the *intersection intent*. Since the AV has already computed a route based on its source and destination points of travel, the vehicle's intent at the intersection is known. This means that the vehicle knows whether it will be going straight, turning right or left at an intersection. However, an EHDV does not have the intent information a priori. The human driver is still in charge of the EHDV and will make the decision upon its arrival at the intersection.

The information received from EHDVs is limited in the sense that it is not enough to make a certain prediction of the vehicle's behavior at the intersection box. Knowing the current lane of the EHDV and lane restrictions of the intersection would help in determining the probable behavior and trajectory of the vehicle but not with absolute certainty. We have developed a scheme that will benefit from all the available information and allow AVs to make the best and safest decision at an intersection and also provide EHDVs with a sophisticated warning system.

AVs are able to detect the potential collision among themselves and other AVs using the Collision Detection Algorithm for Intersections (CDAI) which runs on each autonomous vehicle (Chapter 3.3.2). Within the intersection safety messages, they broadcast the list of the cells they will occupy while crossing the intersection grid. Therefore, they can detect a potential collision by comparing the Trajectory Cells Lists (TCLs).

The collision detection between an AV and an EHDV is based on the available information encapsulated in the safety messages which are broadcast by all of these vehicles. EHDV is broadcasting periodic safety messages using the mandatory part I of BSM based on the SAE's J2735 standard. This message includes: Position information such as *Current Position Coordinates*, *Current Road Segment*, *Current Lane Number*, and the physical and controller information such as Current *Speed, Current Acceleration/ Deceleration and Vehicle Size.* If the EHDV is using the GPS device and Map database for route planning between its source and destination, then it can automatically provide the information regarding its *Next Road Segment*, which is the road that the vehicle exits to, after crossing the intersection box. In this case, it can also determine the cell numbers along its trajectory and encapsulate the TCL information within the intersection safety messages. But as mentioned earlier this information, which is dependent on the intent of the driver at the intersection, might not be available. Therefore, the AV should account for potential collision cases even with the basic set of information received from the EHDV.

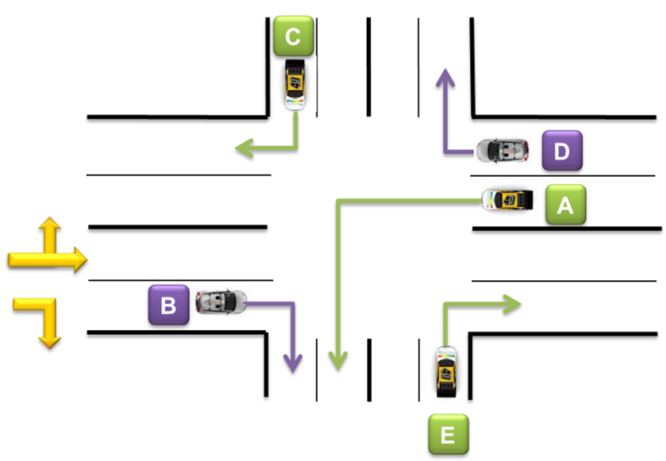


Figure 8-4: Example of an intersection scenario

Figure 8.4 shows an example scenario of a symmetric 2x2-lanes intersection with the following common turn restriction: vehicles in the right lane must turn right, and vehicles in the left lane must go straight or turn left. There is heterogeneous traffic present at the intersection, which consists of autonomous vehicles ***A***, ***C*** and ***E***, as well as the enhanced human-driven vehicles ***B*** and ***D***. The Collision Detection Algorithm for Intersections runs on all the vehicles. The EHDV ***B*** determines that there is no potential collision between itself and the AV ***A***, since it knows the *Current Road Segment, Current Lane, Next Road Segment* and *Next Lane* information of vehicle ***A*** within the received intersection safety messages.

On the other hand, vehicle ***A*** (AV) only receives the Current Road Segment and Current Lane but does not receive the Next Road Segment and Next Lane information from vehicle ***B*** (EHDV). However, based on its Map/GID information it knows that vehicle ***B*** will turn right due to its current lane and turning restrictions of the intersection. Even though both vehicles are going in the same direction, since they are on different lanes, there is no trajectory conflict between them, and they can cross the intersection simultaneously.

In the scenario of Figure 8.4, all approaching vehicles run the CDAI and determine that there are no potential collisions and therefore, they can cross the intersection box safely at the same time. This increases the parallelism at the intersection and leads to a high throughput.

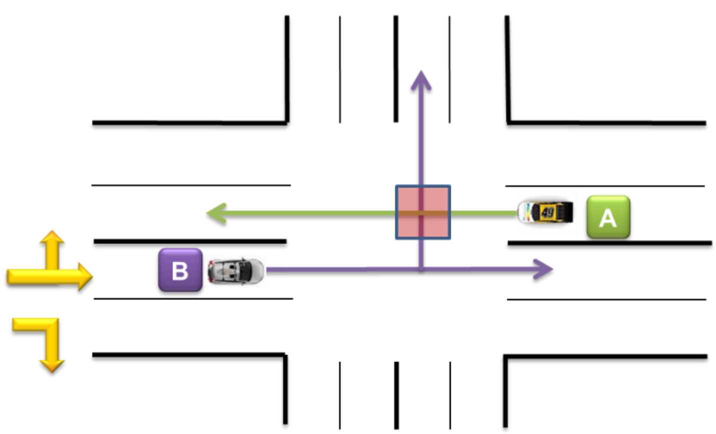


Figure 8-5: Example of an intersection scenario

Figure 8.5 shows another example scenario in which an AV ***A*** and an EHDV ***B*** are approaching a 2x2-lanes intersection from opposite directions and in the left lanes. Vehicle ***B*** receives the intent information from vehicle ***A*** and knows that vehicle ***A*** is intending to go straight. The CDAI running on vehicle ***B*** then predicts two possible cases: (1) There is no potential conflict if vehicle ***B***'s driver decides to go straight. (2) There is a potential conflict if vehicle ***B***'s driver decides to turn left.

These two possible options will be provided to the human driver using the on-board warning system and the decision is left in the hands of the driver. On the other hand, the autonomous vehicle ***A***, receives the limited information from vehicle ***B*** and therefore, which lacks the *intersection intent* information regarding vehicle B's turning decision at the intersection. In this case, due to the lack of information from the EHDV ***B***, the CDAI running on vehicle ***A*** acts cautiously and predicts the worst case scenario. The worst case scenario is that vehicle B decides to turn left and therefore, a potential collision will occur between ***A*** and ***B***, and the output of CDAI will be *potential conflict detected*. In the case that a potential collision is detected, priorities will be assigned to vehicles based on the priority policy described in Chapter 3.

In our method, both AVs and EHDVs make their decisions about their behavior at the intersection in a completely distributed manner and based on the information received from their neighbors through safety messages. . It is important to note that in EHDVS, in contrast to AVs, the current speed, acceleration and deceleration of the vehicle is in the control of the human driver and fluctuations in these parameters are unavoidable. Therefore, the intersection protocol families; High-Concurrency Protocols (HCP) and High-Concurrency Protocols with Enhanced Vehicle Dynamics (HCP-EVD), which require the fine granularity of intersection cells and high accuracy requirements for speed and cell arrival and exit time estimations, are not suitable for EHDVS. We believe that for managing the mixed traffic of AVs and EHDVs, the most appropriate category of V2V-Intersection Protocols is the Low-Concurrency Protocols LCP, as explained in Chapter 4.1. The reason is that these protocols require a more cautious behavior of vehicles and have more relaxed requirements regarding the positioning, timing and controller accuracy of the vehicles.

Figure 8.6 shows an example scenario in which, a mix of AVs and EHDVs are approaching a symmetric 2x2-lanes intersection. Vehicles ***A***, ***C*** and ***E*** are autonomous, and vehicles ***B***, ***D*** and ***E*** are manually-driven. All vehicles are following the Throughput Enhancement Intersection Protocol (TE-IP) rules, described in Chapter 4.1.1. Vehicles ***C***, ***D***, ***E*** and ***F*** have no potential trajectory conflicts with each other or with vehicles ***A*** and ***B***. Therefore, based on the TE-IP rules, they can cross the intersection at the same time. The interesting case, however, is between the AV ***A***, and the EHDV ***B***. From vehicle ***A***'s point of view, as explained earlier, due to the lack of intent information from vehicle ***B***, a potential collision is detected to deal with the worst case scenario in which vehicle ***B*** turns left. On the other hand, from vehicle ***B***'s point of view, there is a potential collision if it turns left, but there is no potential conflict if the driver decides to go straight.

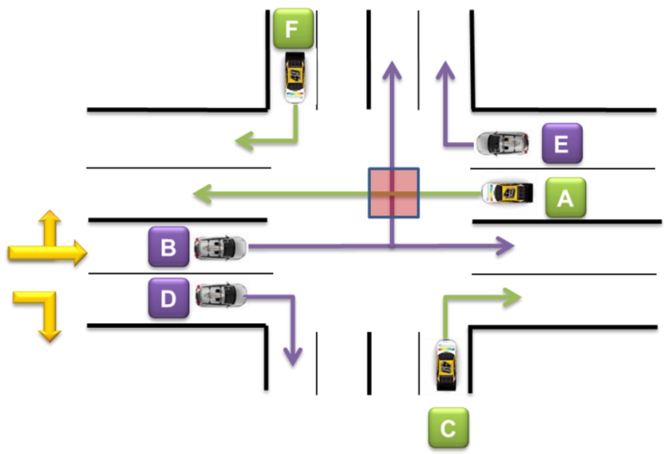


Figure 8-6: Example of TE-IP for AVs and EHDVs

We now examine two possible cases based on the priorities of these vehicles. First we assume that based on the *priority policy* vehicle ***A*** has a higher priority than vehicle ***B***; $P_A > P_B$. In this case vehicle ***A*** ignores the safety messages from the lower-priority vehicle ***B*** regardless of vehicle ***B***'s turning decisions, and cross the intersections without stopping or slowing down. If vehicle ***B*** decides to go straight, since there is no potential conflict, it can ignore the intersection safety messages from vehicle ***A*** and cross at the same time. Otherwise, since vehicle ***B*** has lost the competition, the on-board warning system displays a warning to inform the driver that turning left is not allowed. Figure 8.7(a) shows an example of this warning system display installed in the EHDV. Vehicle B has to wait until it receives EXIT safety messages indicating that the higher-priority vehicle ***A*** has exit the intersection, and only then it will be allowed to make a left turn and cross.

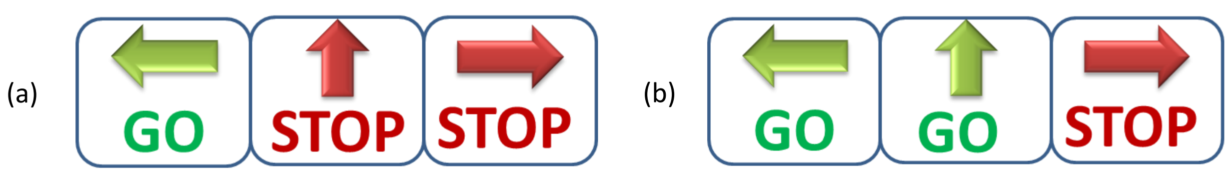


Figure 8-7: On-board Warning System Display; Intersection crossing permissions for EHDVs

Secondly, let's assume that vehicle ***B*** has a higher priority than vehicle ***A***; $P_B > P_A$. In this case, vehicle ***A*** behaves cautiously and prepares for the worst case scenario. Vehicle ***A*** assumes that vehicle ***B*** might turn left and therefore, there will be a potential collision. Vehicle ***A*** comes to a complete stop at the intersection and waits for vehicle ***B*** before crossing the intersection. Vehicle ***B*** has a higher priority than the *potentially conflicting* vehicle ***A***. Therefore, as shown in Figure 8.7 (b), regardless of its decision on making a left turn or going straight, the warning system displays the crossing permission for vehicle ***B*** and the driver can cross the intersection without stopping or slowing down.

A video clip from AutoSim for V2V management of mixed traffic of AVs and EHDVs:

- https://youtu.be/OBBY-rwEcWQ
- https://youtu.be/ntySuRGZULw

8.3 Heterogeneous Perception-Based Intersection Management

Human-driven vehicles (HDV) will be around for many years to come. Therefore, it is important to study the safe co-existence of autonomous vehicles (AVs) with HDVs as parts of the traffic flow. In contrast to the previous set of protocols, since HDVs are not equipped with DSRC radios, they are not capable of transmitting or receiving any messages including BSM (basic safety messages). This means that AVs cannot leverage V2V communications to gain information regarding the neighboring HDVs and must rely on other sources of information.

It is vital for the AVs to detect the presence of HDVs that are approaching the same intersection. AVs will mainly use their vehicle-resident sensors such as cameras, radars and lidars for the detection task. Using their on-board sensor system, they acquire important information such as the position and speed of the approaching HDVs. The accuracy and availability of the mentioned information strongly depends on the various sensor ranges and we will discuss it in Chapter 8.4. An important piece of information which cannot be inferred using the vehicle-resident sensing system is the *intersection intent* of the HDV. This means that due to the lack of communication between the AV and the HDV, the autonomous vehicle has no means of knowing the decision of the human driver at the intersection area. AV can benefit from the digital Map database and Geometric Intersection Descriptor (GID) to predict the behavior of the HDV based on its current lane and turning restrictions of the intersection. However AVs should also account for the human errors and driving misbehaviors which are explained in Chapter 8.4.

We now introduce Perception-Based Intersection Protocols (PB-IP) in which, AVs will mainly use their vehicle-resident sensors such as cameras, radars and lidars to detect the presence of HDVs at the intersection area. PB-IP protocols benefit from a distributed intersection management algorithm which runs on each autonomous vehicle and controls their behavior at the intersection. Current technology such as stop signs and traffic lights will be managing urban cross roads for many years to come, and human drivers will be obeying the current rules for these types of intersections. Therefore, it is important for our protocols to be adopted with the current infrastructure rules in order to provide the safety for both autonomous and human-driven vehicles. It is vital that these protocols are transparent to human drivers to prevent any panic situations that might lead to human errors and accidents.

We will now describe two intersection protocols, Perception-Based with Stop Sign Intersection Protocol (PB-SS-IP) and Perception-Based with Traffic Light Intersection Protocol (PB-TL-IP), respectively for managing the mixed traffic of AVs and HDVs, through intersections managed by stop signs and traffic lights. These protocols are designed to provide a safe and efficient passage of autonomous vehicles through intersections when the heterogeneous traffic consists of AVs and HDVs.

8.3.1 Perception-Based with Stop Sign Intersection Protocol (PB-SS-IP)

This protocol is designed to manage the behavior of autonomous vehicles when arriving at stop sign controlled intersections. All Human-Driven Vehicles (HDVs) must follow the infrastructure rules. Meaning that they have to come to a complete stop before entering the intersection boundaries and cross based on the Fist-Come First-Served (FCFS) *priority policy.* The sensor fusion of cameras, radars and lidars as parts of the vehicle-resident sensing system of the Autonomous Vehicles (AVs), enables them to detect the presence of HDVs at the intersection area. Additionally, vehicular communications enables AVs to detect other AVs and communicate with them using V2V-Intersection safety messages through DSRC devices.

The following rules apply to all AVs under PB-SS-IP:

Algorithm 8.1 PB-SS-IP for Autonomous Vehicle

Input: Received information from the fusion of vehicular networks and on-board sensors

Output: Vehicle's movement at the intersection

1. **Use** V2V to detect the presence of AVs
2. **Use** Perception to detect the presence of HDVs
3. **If** (no vehicle is detected), **then**
4. Cross the intersection
5. **Else if** (an AV is detected), **then**
6. Follow the assigned V2V-Intersection Protocol
7. **Else if** (an HDV is detected), **then**
8. FCFS Priority Policy

Figure 8.8 shows two example scenarios of a stop sign controlled intersection in which an AV is approaching the intersection box. A part of vehicle ***A***'s sensor plane is illustrated in this Figure. In Figure 8.8 (a), the AV ***A*** does not detect the presence of any other vehicles on the other legs of the intersection and therefore, can cross the intersection without stopping or slowing down. In Figure 8.8 (b), as the AV ***A***, approaches the intersection, it detects the presence of a vehicle on the West bund of the intersection using its on-board sensor system. Since no intersection safety messages are received from the detected vehicle ***B***, it concludes that vehicle ***B*** is of type HDV, and follows the PB-SS-IP rules. Based on the information inferred form vehicle ***B*** via the perception system, such as its speed and current distance to the intersection entrance, vehicle ***A*** determines if it has a lower or higher priority comparing to vehicle ***B***. If it has a higher priority then it will cross the intersection. Otherwise, it gets to a complete stop and waits till vehicle ***B*** crosses and exits the intersection box.

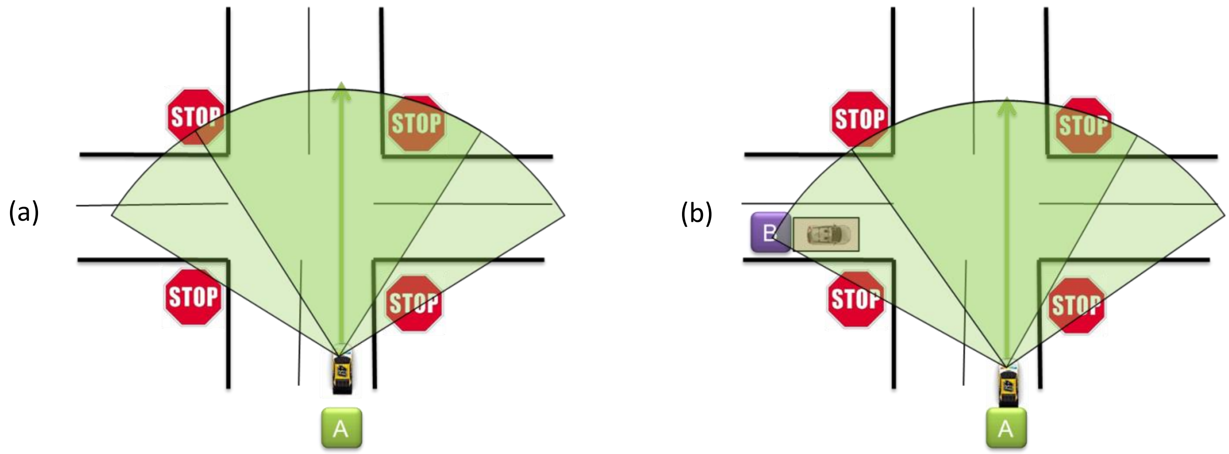


Figure 8-8: Example scenarios for PB-SS-IP

A video clip from AutoSim for PB-SS-IP:

- https://youtu.be/bOPNzsHB4xo
- https://youtu.be/nnOVgLfUoJE

8.3.2 Perception-Based with Traffic Light Intersection Protocol (PB-TL-IP)

This protocol is designed to manage the behavior of autonomous vehicles when arriving at stop sign controlled intersections. All Human-Driven Vehicles (HDVs) must follow the infrastructure rules. This means that they must get to a complete stop before the intersection box when facing the red light, and can only cross when there is a green light for the direction that they are intending to take. As mentioned previously, the autonomous vehicles use their on-board sensor system as well as their DSRC devices to infer information regarding their surrounding vehicles at the intersection box.

The following rules apply to all AVs under PB-TL-IP:

Algorithm 8.2 PB-TL-IP for Autonomous Vehicle

Input: Received information from the fusion of vehicular networks and on-board sensors

Output: Vehicle's movement at the intersection

1. **Use** V2V to detect the presence of AVs

```
Use Perception to detect the presence of HDVs
Use V2I to receive SPaT messages
If (no vehicle is detected), then
        Cross the intersection
Else if (an AV is detected), then
        Follow the assigned V2V-Intersection Protocol
Else if (an HDV is detected), then
        If (Green Light), then
                Cross the intersection
        Else if (Red light), then
                If (HDV faces Red light), then
                        Cross the intersection
                Else if (HDV faces Green), then
                        If (no potential Collision Detected), then
                                Cross the intersection
                        Else
                                Stop and Wait
```

Figure 8.9 illustrates two example scenarios of an intersection equipped with traffic lights. Figure 8.9 (a) shows three AVs ***A***, ***B*** and ***C***, as well as two HDVs ***M1*** and ***M2***. As the manually-driven vehicle ***M1*** approaches the intersection boundaries and faces the green light, it can cross the intersection without stopping or slowing down. However, the other HDV ***M2*** arrives at the intersection from the East direction and has to stop for the red light even though it has no trajectory conflicts with the surrounding vehicles.

On the other hand the AVs transmit and receive the intersection safety messages to detect the presence of other AVs and know their intent at the intersection. Additionally, they use perception via their on-board sensing system to detect the presence of ***M1*** and ***M2***. They also benefit from V2I communications to gain access to the traffic light cycle information which is encapsulated in the SPaT messages broadcast by the Enhanced Traffic Light (ETL). Even though they all face the red light upon their arrival at the intersection, no potential collision is detected among them. They have to detect potential collisions with HDVs now. AVs detect that ***M1*** is approaching on the right lane and based on the intersection's GID, the vehicles on the right lane must turn right, and there is no trajectory conflict between them. Using the SPaT messages, AVs infer that ***M2*** is facing the red light and since HDVs must follow the infrastructure rules, ***M2*** will stop upon its arrival and no potential conflicts will occur. Therefore, vehicle

A, ***B***, and ***C*** can cross the intersection at the same time as vehicle ***M1***, and vehicle ***M2*** must stop and wait till the light turns green.

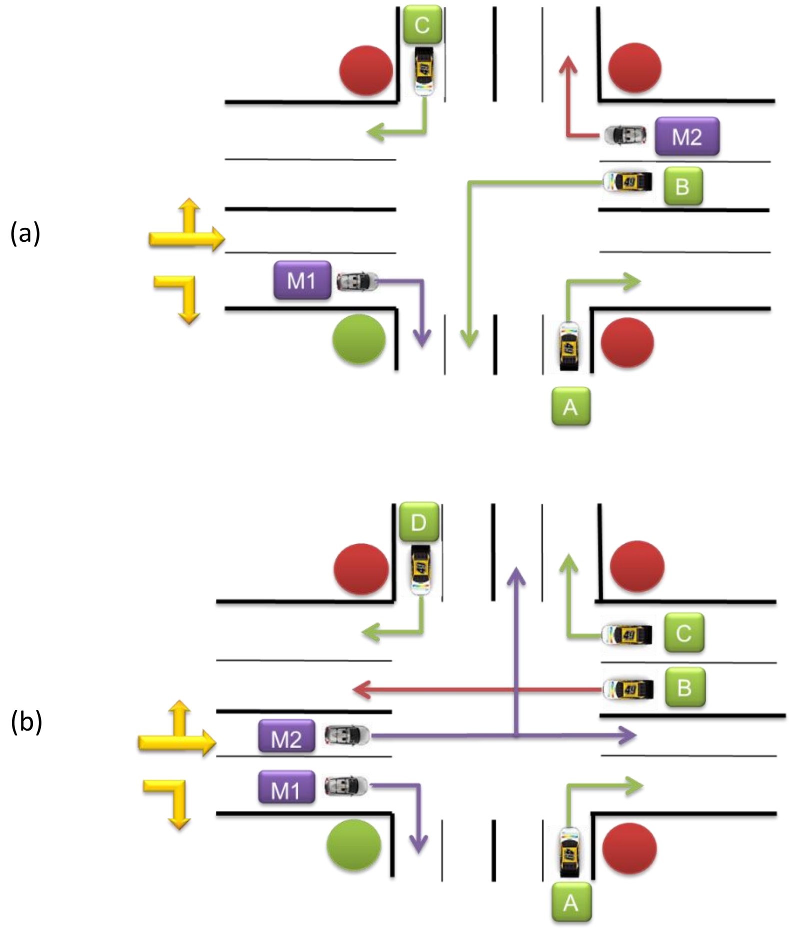


Figure 8-9: Example scenarios for PB-TL-IP

In Figure 8.9 (b), HDVs ***M1*** and ***M2*** are approaching from the West bund. Due to the turn restrictions, M1 must turn right, and ***M2*** must go straight or turn left. There are also four AVs ***A***, ***B***, ***C*** and ***D*** which are arriving at the intersection from the other directions. ***M1*** and ***M2*** are facing the green light, thus the can cross the intersection immediately. Despite the fact that the AVs ***A***, ***C*** and ***D*** are facing the red light, they detect no trajectory conflicts among each other, nor with the HDVS ***M1*** and ***M2***. However, this is not the case for vehicle ***B***. It detects that it has no potential collision with vehicles ***M1***, ***A***, ***C*** and ***D***. Due to lack of intent information from vehicle ***M2***, it should prepare for the worst case scenario in which vehicle ***M2*** decides to turn left and might get to a collision. As vehicle ***B*** is facing the red light and detects a potential collision with another vehicle, it comes to a complete stop and waits till ***M2*** has cleared the intersection and the light turns green.

We can conclude that the autonomous vehicle only stops for a human-driven vehicle only when the AV faces the red light and the *potentially conflicting* HDV faces the green light.

A video clip from AutoSim for PB-TL-IP

- https://youtu.be/b-toQJt_tvE

8.4 Challenges

To achieve the goals of managing the intersection using perception, we now study the limitations of this scheme and develop solutions to mitigate the shortcomings. One of the main challenges faced by the Perception-Based Intersection Protocols (PB-IP) is the sensors' accuracy and range properties. These parameters play an important role in the detection mechanism. Occlusion is the main source of range limitation and inaccuracies for the on-board sensor system mentioned in Chapter 8.1. In this Chapter, we determine the effects of occlusion on PBIPs and suggest solutions to guarantee the safe passage of autonomous vehicles through intersection despite the occluded environment.

As we are dealing with heterogeneous traffic flow which consists of both autonomous and manually-driven vehicles, it is curtail to account for human mistakes. Human errors play a significant role in car accidents and their effect in disrupting the traffic flow at intersections is not negligible. Therefore, we have designed a method for autonomous vehicles to detect scenarios such as red-light violations by manually-driven vehicles. These schemes will benefit from AV's on-board sensors as well as the received information from intersection Road Side Units (RSUs).

8.4.1 Sensor Occlusion

PB-IPs rely mainly on perception and information obtained through the on-board sensors, and their coverage range and precision play an important role in the efficiency of this method. Therefore, an important aspect of PB-IP would be dealing with occlusion at intersection areas. The presence of tall buildings at the corners of urban intersections prevents the detection of approaching HDVs from occluded legs of the intersections. The existence of occluded lanes and the possibility of not being able to detect the presence of Human Driven Vehicles (HDVs) approaching from other legs of the intersection, affects the behavior of the Autonomous Vehicles (AVs).

Each AV is able to detect the occlusion and modify its behavior in the presence of the occlusion by using the vehicle's perception system and its digital map database. The map database can be used to obtain information regarding the presence of buildings at the corners of the intersection. Most of the common used maps such as Google maps and Open Street Maps (OSM) and aerial maps, contain the location and shape information of structures on the sides of the roads and the corners of intersections [112]. In addition to the structure information, digital map databases provide AVs with the Geometric Intersection Description (GID), which is used in determining the geometry and the location of lanes on each segment of the approaching intersection. Despite the fact that some intersection legs might not be visible through the perception system due to occlusion, the information regarding their shape and position can be provided to AVs through digital map database with GID.

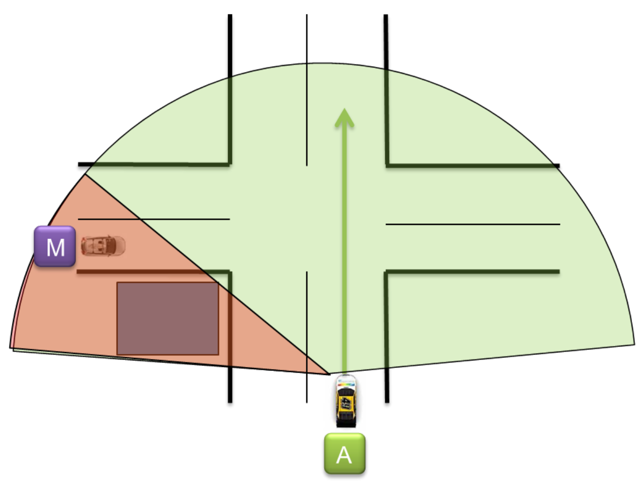


Figure 8-10: Sensor occlusion due to obstacles at intersection corners

As shown in Figure 8.10, when an AV A is approaching an intersection, it uses its perception system to detect the presence of HDVs at the intersection since V2V communications is not possible between them. Using its GPS and map information, the AV knows its current position and distance to the entrance of the intersection. It also uses the GID information to gather knowledge regarding the location of the other segments the intersection and specifically the occluded lanes behind the structures on the corners of the intersection. Vehicle's perception system cannot see beyond the structure's polygon and therefore, it is unable to detect the presence of the HDV B approaching from the West bund of the intersection.

In our method, the AV measures three polygons including the occluded segment of the intersection, its own sensor plane from the perception system and the obstacle structure. As illustrated in Figure 8.11, by calculating the intersection of these polygons, the vehicle determines how much of the occluded lane is visible, which we call $D_{visible}$. If this length is higher than a certain distance threshold $Th_{Occlusion}$: $D_{visible} > Th_{Occlusion}$, then the vehicle acts based on the PB-IP rules explained in Chapter 8.3. Otherwise, if the visible length is less than the occlusion threshold: $D_{visible} > Th_{Occlusion}$, to guarantee the safety of the vehicle, it must act cautious, and plans on coming to a complete stop before entering the intersection. This behavior continues until the vehicle can detect enough of the occluded lane and infer the necessary information from approaching vehicles which were previously occluded behind the structures.

To find out the intersection of these three polygons, we use the Separating Axis Theorem [74], [75]. The Separating Axis Theorem states that, for a pair of convex polygons that are not in a state of collision, there exists an axis perpendicular to an edge of one of the polygons that has no overlap between the projected vertices of the two polygons. This theorem can be simplified for our purposes since we are only dealing with two-dimensional rotated rectangles. Therefore, each polygon is tested against the four axes of the other polygon and if all projections overlap, a collision is detected. An optimization on this theorem exists for two-dimensional rotated rectangles, wherein, the polygon-under-test is rotated and centered on the intersection of the x-axis and the y-axis, and hence projections need to occur for only 2 axes[74], [75]. This solution works for any collision possibility, even for cross-collisions where a collision occurs between two polygons perpendicular to each other.

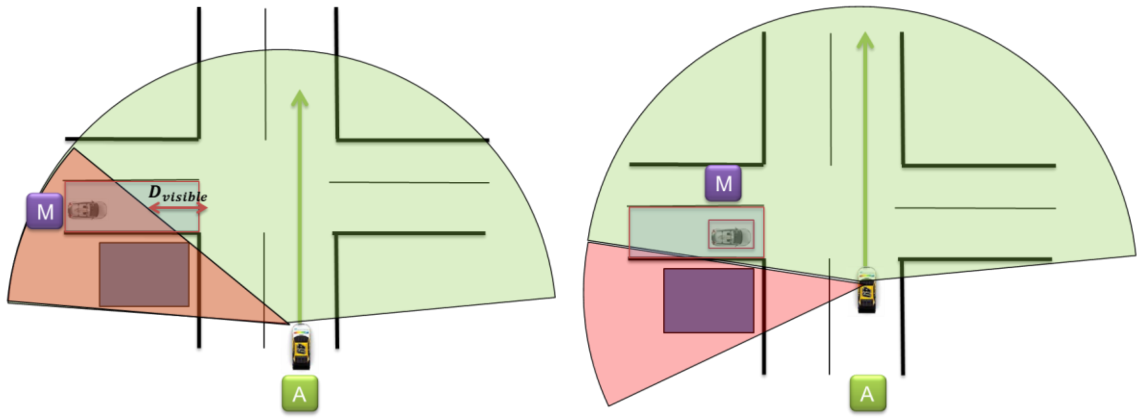


Figure 8-11: Detection of HDV on an occluded lane

A video clip from AutoSim of intersection behavior in the presence of occlusion

- https://youtu.be/j_N_k6-huWQ

8.4.2 Human Error

More than 95% of car accidents are caused by human error and as long as human-driven vehicles are part of the traffic flow, these errors are inevitable. Therefore, when designing our intersection protocols, we should consider scenarios in which human-driven vehicles might violate the intersection rules. Our goal is to detect these misbehaviors in a timely manner and prevent consequent collisions.

We first look at heterogeneous traffic which consists of autonomous vehicles and Enhanced Human-driven Vehicles (EHDVs). Despite the fact that EHDVs are equipped with ADAS and communication capabilities, as humans are in control, the previously mentioned errors might occur at intersections. In the case of stop-sign controlled intersections, we have developed a method which is implemented and running on all AVs and EHDVs, and enables them to detect potential violations of V2V-intersection rules by other approaching vehicles. It mainly relies on the periodic safety messages received from neighboring vehicles.

To detect a potential violation by an EHDV, each vehicle uses the other vehicle's information such as position, speed and deceleration to determine their distances to the entrance of the intersection. By using the received information from surrounding vehicles and simplistic Newton Kinematic rules, vehicle can predict if an approaching lower-priority vehicle might be violating the rules and not come to a complete stop before entering the intersection. In this case, the AV acts cautious and stops to prevent any potential collisions with the violating vehicle. It then continues to its normal operation when there no more potential violation is detected. Additionally, EHDVS will benefit from their on-board warning system. This leads to a fast reaction of the driver during the potential violation scenarios using acoustic and visual alert messages on their safety displays.

We now look at a heterogeneous traffic which includes Human-Driven Vehicles (HDVs) and AVs. HDVs have no communication medium and therefore, AVs have no way to transmit or receive periodic safety message to and from HDVs. Using their vehicle-resident sensing system, AVs can infer information such as positioning and speed of approaching HDVs which are in their sensor system range. When dealing with traffic light controlled intersections, in addition to previously mentioned information regarding the speed and position of vehicles, it is important to know the traffic light cycle and duration of green and red lights for each leg of the intersection. To obtain the traffic light cycle durations, we previously suggested using the smart Enhanced Traffic Lights (ETL).

ETLs are equipped with cameras and DSRC radios and after accessing the controller of the traffic light, they periodically broadcast their status via SPaT (signal phase and timing) messages to all approaching vehicles. SPaT message format has been standardized by SAE J2735 [8], [9], [107]. This information will be used by AVs to predict if an approaching vehicle will potentially run the red light and violate the traffic light rules.

Please note that as the ETL is aware of its cycle durations, cameras and DSRC devices. Therefore, it can also assist in predicting potential violation of vehicles approaching it. ETL can then broadcast warning messages to all approaching vehicles which are equipped with DSRC radios such as AVs and EHDVS. Additionally, ETL can benefit from visual warning signals such as blinking lights to warn the human drivers about the dangerous situation and decrease their reaction delay.

Video clips from AutoSim illustrating the traffic light violation scenarios and the corresponding behavior by autonomous vehicles, human-driven vehicles and enhanced human-driven vehicles:

- https://youtu.be/_36sR0TWzBQ

- https://youtu.be/L0Iq0YAAyZM

8.5 Evaluation

In this section, we will evaluate our intersection protocols which are designed for managing the heterogeneous traffic through intersections. All the mobility models for these protocols, as well as the perception models have been are implemented in our hybrid simulator-emulator AutoSim [0].

We use the *Trip Delay* as our metric to compare these intersection protocols with traffic light mobility models. As our intersection model, we have considered a perfect cross intersection with 2 entering lanes from each direction. Based on the Intersection Type, the turn restrictions are as follows. Vehicles on the right lane must go straight or turn right, and vehicles on the left lane must turn left. Traffic generation is through a random process which creates Poisson arrival of the simulated vehicles. On each step, we simulate 1000 vehicles and the simulation ends when the last car reaches its destination. We have looked at various traffic volumes and also different market penetration of Autonomous Vehicles (AVs), Human-Driven Vehicles (HDVs) and Enhanced Human-Driven Vehicles (EHDVs).

We first look at the case that the heterogeneous traffic consists of autonomous and enhanced human-driven vehicles (AVs and EHDVs). Therefore, all the vehicles are equipped with DSRC radios and are able to broadcast and receive intersection safety messages. In this case, the Heterogeneous V2V-Intersection management is used to manage the intersection. Collision Detection Algorithm for Intersections (CDAI) is running on all approaching vehicles and they use the intersection safety messages to interact with each other and make movement decisions in a completely distributed manner.

Figure 8.12 shows a comparison between traffic light models with green light durations of 30 seconds and 10 seconds, and three different traffic scenarios:

- Scenario 1: Traffic consists of only AVs. They follow the V2V-Intersection Protocol rules [0].
- Scenario 2: Traffic consists of 50% AVs and 50% EHDVs. *Intersection Intent* information of EHDVs is available to the AVs through intersection safety messages. Therefore, all vehicles know about each other’s intention and turning decision at the intersection and can follow the V2V-Intersection Protocol rules for a safe passage through the intersection area.

- Scenario 3: Traffic consists of 50% AVs and 50% EHDVs. *Intersection Intent* information of EHDVs is not available to the AVs. This means that if an EHDV is approaching from a left lane, the AV knows that it will turn left, but if the approaching lane of the EHDV is on the right, it might go straight or turn right. Therefore, based on the Heterogeneous V2V-Intersection Management, the AV must consider potential conflicts in both possible turning cases of the EHDV, act cautious and prepare for the worst case scenario.

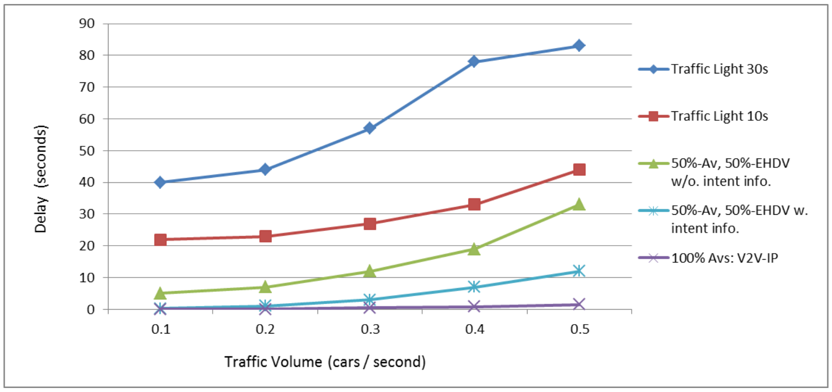


Figure 8-12: Delay Comparison between different traffic scenarios.

Our simulation results show that the heterogeneous V2V-intersection management methods decrease the delays faced by both AVs and EHDVs and significantly increase the overall performance of the system. It can be seen that the delay is very negligible when there are only AVs present at the intersection and the delay values are increased when 50% of the traffic flow consists of EHDVs. In the case that the intent information of EHDVs is available to AVs, our V2V-IP has 77.65% overall performance improvements over traffic light with green light duration of 10 seconds. The improvement is much less when the intersection intent information is not available and therefore AVs should act more cautious. This impacts the average delays faced by all approaching vehicles. Despite this delay increase, heterogeneous V2V-IP still outperforms the traffic light models. This improvement is 26.21% and 66.37%, respectably comparing to the traffic light model with green light duration of 10 seconds and 30 seconds.

Next, we look at traffic scenarios consisting of AVS and Human-Driven Vehicles (HDVs). As mentioned earlier in this chapter, for managing the safe co-existence of autonomous and manually-driven vehicles when not all vehicles are equipped with DSRC radios, we have designed the Perception-Based Intersection Protocols (PB-IPs). AVs leverage V2V to communicate among each other and use their on-board sensor system for detect the presence of HDVs at the intersection and acquire some information regarding their position, direction and speed.

Figure 8.13 illustrates the comparison between the traffic light models and the case that the traffic includes 50% AVs and 50% HDVs. The intersection is equipped with traffic light signals. In this case, the HDVs are following the traffic light rule and AVs are following the Perception-Based with Traffic Light Intersection Protocol (PB-TL-IP) rules. As HDVs are following the infrastructure rules, the delays faced by them are similar to the delays results illustrated for stop sign or traffic light models. In contrast, AVs face significant less delay values while crossing the intersection area since they do not have to get to a complete stop for the red light when no potential conflict is detected. Our results indicate that PB-TL-IPs have 25.16% and 30.87% overall performance improvement over the related traffic light models with green light durations of 30 and 10 seconds respectively.

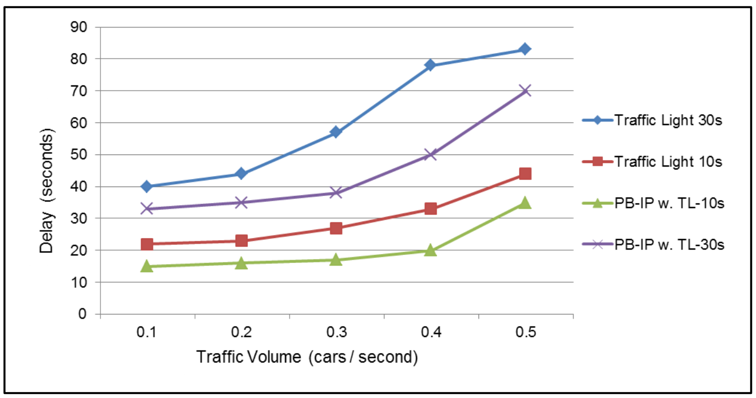


Figure 8-13: Delay Comparison between different traffic scenarios.

Finally, we have looked at the delay comparison for Perception-Based at Traffic Light Intersection Protocol (PB-TL-IP) when dealing with different market penetration of autonomous vehicles. Figure 8.14 shows this comparison for low traffic volume of 0.1 and medium traffic volume of 0.5 cars per second in each direction. As expected in the extreme case that there are no autonomous vehicles and the HDVs are following the traffic light rules, the PB-IP's performance is similar to the traffic light model. The average delay values decrease when the percentage of autonomous vehicles increases. For higher traffic volumes, even a small portion of HDVs impact the performance of PB-IP and higher delays are faced by AVs.

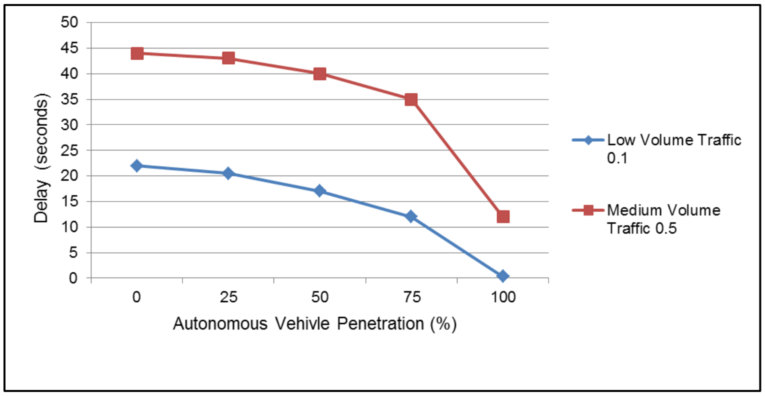


Figure 8-14: Delay Comparison of PB-TL-IP for different market penetration of AVs.

8.6 Summary

With the advances in cyber-physical systems and the rapidly growing autonomous driving technologies, it will not be too long before having a mix of autonomous and manually-driven vehicles on the roads. This motivated our intent to design a system which can provide a safe co-existence of this mixed traffic through the bottlenecks of urban transportation which are cross-roads and intersections.

In this chapter, we proposed the fusion of vehicle-resident sensing and vehicular communications (V2X) to increase the safety and throughput of the intersections. We looked at the benefits of having vehicular communication capability with DSRC radios. We proposed protocols which purely depend on vehicle-to-vehicle communications to manage the intersection when all vehicles including human-driven and autonomous vehicles are equipped with DSRC devices. Approaching vehicles to an intersection interact with one another using the intersection safety messages and follow our protocol rules to safely and efficiently cross the intersection. Our simulation results indicate that these protocols can significantly decrease the delays faced by both AVs and EHDVs while avoiding any collisions inside the intersection box.

As 100% market penetration of DSRC radios is not achievable in the near future, we proposed other solutions which incorporate the usage of current infrastructure such as traffic light and vehicle's on-board sensor system. Even when DSRC is widely is use, when dealing in extreme environment scenarios where the channel is congested and the packet loss rate is very high, local sensing technologies such as cameras, radars, lasers and thermal images can be combined with V2V and V2I communications to avoid any potential collisions. Therefore, connected autonomous vehicles use their perception system and follow the PB-IP rules even when facing other AVs. As these protocols strongly depend on the perception system, we looked at challenges such as occlusion which impact sensors' range and accuracy. We proposed methods for obstacle/structure detection and implemented a safe behavior for autonomous vehicles in the presence of occluded lanes at the intersection.

Chapter 9

AutoSim: Hybrid Simulator-Emulator

In order to test our intersection protocols, we have designed a tool called AutoSim. AutoSim is a hybrid emulator-simulator for vehicular communication and interaction. This emulator is a next generation version of GrooveNet [25], [26]. It facilitates protocol design as well as in-vehicle deployment and uses real street-map-based topography. This enables city-wide simulations using different types of trip and messaging models. The simulator uses a model-based approach where different models interact with each other resulting in vehicular movement. Each simulated vehicle is made up of several types of models. The core individual modules are Control, Communication, Mobility, Localization and Path-Tracking.

AutoSim also has real-time emulation capability wherein real and simulated cars can co-exist and interact with each other. The communication interfaces for DSRC communication as well as peripheral sensory interfaces are implemented to enable real cars instrumented with DSRC to react in real-time with simulated cars. The communication protocol uses Basic Safety Messages (BSM) [8] that are broadcast as part of the WAVE mechanism.

AutoSim consists of the following core entities:

1. Simulation Engine
2. World Model
3. Visualization
4. Vehicle Models

These entities are described in detail below.

9.1 Simulation Engine

This is the main class/thread for the simulation, which acts as the main simulation event loop within AutoSim. The *Simulation Engine* runs and updates all the cars, adds new cars and removes them from the simulation. This class actually runs the complete simulation and controls its various parameters. The event loop does the following (in order):

1. Update all vehicle models currently active for each vehicle
2. Log any status updates for vehicles
3. Remove inactive vehicles from update list
4. Add new vehicles to the update list
5. Update vehicle generators
6. Log trips and collisions for vehicles
7. Broadcast and receive messages using DSRC interface, if enabled
8. Update internal simulation time

The *Simulation Engine* can be run in real-time, or in specified increments of time. This is configurable through scenario configuration. The simulator runs as a separate thread from the GUI to enable GUI updates to happen separately from simulation. Also, the simulator stop vehicles from being generated too close to each other and queues up vehicles that cannot be added immediately, and adds them to the loop once there are no vehicles within a specified distance on that segment and lane.

9.2 World Model and Visualization

AutoSim's *World Model* contains the files related to the map database. *World Model* is responsible for parsing the information from the Road Network Definition File (RNDF) and extracting all the necessary information to build the map's geometry.

RNDF specifies accessible road segments and provides information such as waypoints, stop sign locations, lane widths, checkpoint locations, and parking spot locations. By building a RNDF for a specific road or intersection, we are able to generate the related path for vehicles. RNDF and Path files can then be loaded to AutoSim, and *World Model* classes will extract and parse the information. This information is used to build the map in the GUI and also to simulate vehicle's movement along different paths.

We have used the open source map database called Open Street Maps (OSM). It provides the basic road network information and includes the structure to add more auxiliary data to the map. We have created a system to convert an Open Street Map to a RNDF which will be used by AutoSim-OpenDS. Here is a brief description of this map generation process:

1. The region of interest is selected from the www.openstreetmap.org and an XML file of this map is extracted.
2. OSM filtering is performed to extract road network information and to remove unrelated information
3. Creation of RNDF
    a. Parse the information from OSM. OSM road network is consisted of a set of nodes and ways.
    b. Create RNDF road structures such as segments, lanes and waypoints
    c. Create Intersections, including entry and exit points
4. Output to AutoSim and RoadWorldModel uses the RNDF to generate the map

Figure 9.1 shows snapshots from OSM and AutoSim provides an example of this conversion from a real map from OSM to a generated map from RNDF in AutoSim.

Figure 9-1: RNDF conversion. Snapshots from OSM and AutoSim

The following snapshots in Figure 9.2 are from AutoSim show the road network created from OSM-RNDF and it also includes the created intersection with the appropriate entry-exit markings.

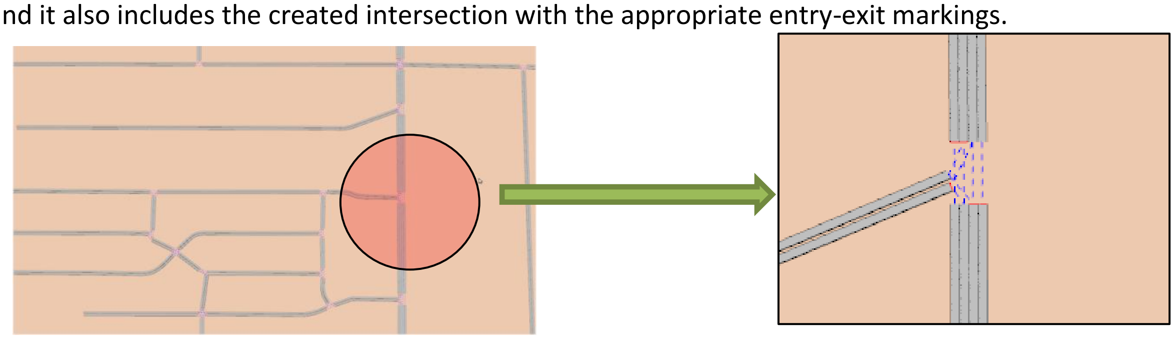


Figure 9-2: The road network and intersection entry-exits in converted RNDF

This demo shows a simulation from AutoSim, in which a map is built from a realistic OSM map and converted to RNDF, which is then used to build and display the map in AutoSim and run vehicles on it.

- http://youtu.be/7XA744R7F5w

The *Visualization* includes classes to constructs the main window of the simulation, draws the roads on the map and generates 3D car models. This is the main class for building the simulator's GUI and visualizing the simulations. This visual effects help to better understand different scenarios and effects of different models in various situations. To achieve this goal, we have used the Qt4 software [98]. Map navigation is also possible using the mouse buttons.

9.3 Vehicle models

The vehicle models are what describe the movement and behavior of vehicles within the simulator. Each vehicle has a list of associated models, which have periodic update rates, and are executed as part of a vehicle update. Each model class derives from the base *Model* class. The models have been categorized into the following:

1. GPS Model
2. Control Model
3. Communication Model
4. Communication Interface
5. Perception Model
6. Mobility Model
7. Path Model

9.3.1 GPS Model

GPS Model calculates the current location coordinates of the car. In real vehicles, it updates the vehicle coordinates using Global Positioning System (GPS) information from the vehicle itself. In simulated cars, it updates the coordinates based on the type of *GPS Model* being used. These models also include useful conversions from longitude, latitude to UTM coordinates which are used in formatting the information received from the vehicle. Various models inherit from the main GPS Model class. A simplistic model, which calculates and sets the current position coordinates of the vehicle based on different parameters such as vehicle's speed and heading information. Additionally, to model localization of the vehicle that can incorporate errors and inaccuracies, other GPS models have been designed to inject position inaccuracy into the GPS coordinates used by each vehicle. The level of positioning error is configurable, and will affect the decisions made by vehicles at and around intersection areas.

9.3.2 Control Model

These models are responsible for controlling the movement of the vehicle along its trajectory. They measure and set the kinetic characteristics of the vehicle. They use the parameterized kinetic characteristics of the vehicle to follow commands from higher level logic. The main parameters are velocity, acceleration and deceleration capability of simulated vehicles. These models are used to define different types of vehicles based on their kinetic characteristics as well as modeling more complex vehicle models.

9.3.3 Communication Model

The *Communication Model* classes are used to communicate information between vehicles and infrastructure. They create messages that can be transmitted using a *Communication Interface* as well as processing and information received. The base model contains two queues: *Transmit-Queue* and *Receive-Queue*. These models can be used to model communication variables on the vehicle side such as packet loss and interference. This information can be used to process messages in the transmit and receive queues.

We have also added various communication models which inherit from the main class. For example, a Propagation Model, which is the implementation of Nakagami-m model, which is proved to be a realistic model for estimating the Packet Reception Probability (PRP) when using Dedicated Short Range Communication (DSRC) radios as the communication medium. By using this model, we can simulate various scenarios in which, vehicles are facing different degrees of packet loss due to fading, and we are able to study how this affects vehicle's behavior.

9.3.4 Communication Interface

This serves as the way for AutoSim to enable communication with external entities. Interfaces for different networks can be attached to the simulator, enabling vehicles to communicate with real or simulated entities. DSRC interfaces can be added to enable actual DSRC communication using DSRC hardware.

Communicationinterface is the base class for the Communication Interface. This is the class which deals with external communication with the world. There is no communication done in this base class but in the classes which extend this model. *Simdsrccomminterface* class extends the communication interface for simulator and DSRC Communication. This class is meant to be used on the simulator for the DSRC communication. It actually runs transmission and receiving on separate threads and does the actual communication. Note that this class sends the message to a particular IP address (DSRC box), and that box does the DSRC broadcast. Also it receives message from the DSRC box and sends it to communication models to extract the received information and use it in other models.

There are two types of messages that are used:

1. Basic Safety Message (BSM): As defined in the SAE J2735 Dedicated Short Range Communications Message Set Dictionary. This message is broadcast by vehicles at fixed intervals.
2. Signal Phase and Timing (SPaT): These messages are broadcast by traffic light controllers.

The DSRC specification uses the Abstract Syntax Notation revision One (ASN.1) for expressing the messages that are defined in the standard. The encoding of messages is defined using the Distinguished Encoding Rules (DER) which serves as the payload for communicating over the DSRC network.

9.3.5 Perception Model

To study the perception-based intersection protocols and the challenges faced by them, we have developed new perception models by extending our simulator-emulator AutoSim. The perception models benefit from configurable parameters such as range, accuracy and field of view. We have also encoded structures within Map and WorldModel to study the effects of sensor inaccuracies such as occlusion on PB-IPs.

9.3.6 Mobility Model

Mobility Model is the base class for all mobility models. These classes are responsible for the decisions and actions taken by vehicles in different scenarios at intersections and manage their safe passage through the intersections.

Using the *Stop Sign Model,* when a simulated vehicle approaches an intersection managed by stop-signs at each entrance, it comes to a complete stop regardless of the situation of any other vehicle at the intersection. In other words, the velocity of the vehicle becomes zero even if there is no other car trying to cross the intersection. In discussions, police recommend 3 seconds of complete stopping even at an empty intersection. This stop delay will increase in proportion to the number of cars that arrived earlier at the intersection.

Traffic Light Model is a mobility model in which vehicles are obeying traffic light rules at the intersection. Same as in real world, vehicles are allowed to pass the intersection only when facing a green light, and in the case of the red light, they have to get to a complete stop before the intersection stop lines.

We have designed and implemented numerous mobility models which are the implementation of all our V2V-Intersection Protocols, which are intersection management methods designed based on V2V communications. BallRoom Intersection Protocol (BRIP) and Perception-Based Intersection Protocols (PB-IP) are also implemented in their related mobility models which benefit from V2V, V2I and Perception.

9.3.7 Path Model

Path Model is used to plan the trip of the vehicle and track the vehicle using map information. This model is responsible to determine the current state of the vehicle regarding to the next intersection on vehicle’s trajectory. It measures different parameters such as vehicle’s distance to the next intersection and updates vehicles current road and lane information.

A Path-Generator is also designed to generate paths for vehicles trajectories on the map. A path can be generated offline or by choosing starting and ending points on a map to generate paths for vehicles. The trip route for each car is calculated using the Dijkstra Trip Model in AutoSim which calculates the shortest route between two points using Dijkstra algorithm [13]. The route is chosen with a waypoint at the intersection forcing the route to pass through the intersection. A logging mechanism has been added to AutoSim to enable logging of start and end times of cars to measure their trip times.

In addition to mentioned models AutoSim benefits from various other models and new models can simply be added to existing base classes. We have also added the capability to easily generate new tests through the Test Generator Model which enables the configuration of all related parameters to design a realistic testing environment. This model is used to generate different test scenarios. Various parameters such as the number of simulated vehicles, their trajectories and inter-arrival times can be configured in this class. This model also contains a Poisson Random Distributer function to generate the simulated vehicles following this random distribution. This traffic generation method is commonly used since the traffic at intersections has the memory-less property which is covered by Poisson random distribution.

9.4 Testing Platforms

As mentioned previously, our AutoSim is a hybrid emulator-simulator which enables the communication of real and simulated vehicles through DSRC radios. Figure 9.3 shows the interaction among these two vehicle types.

Figure 9-3: AutoSim: Interaction of Real and Simulate vehicles though DSRC.

In order to test these capabilities, we have used various platforms and scenarios. Figure 9.4 illustrates how the real (green) and simulated (red) vehicles are participating in the Car-Following mobility model and perform leader following and path tracking using the received safety messages through DSRC.

Gaurav Bhatia has implemented our protocols on PowerWheels platform which includes HCS12(X) controllers, FlexRay & Interfaces added to controller and sensors over CANBus. It is equipped with a DSRC radio and uses the same codebase as our AutoSim simulator.

Figure 9-4: PowerWheels platform and Car-Following among real (green) and simulated (red) vehicles.

A video clip of AutoSim running on the PowerWheels platform can be seen at:

- https://youtu.be/w9YO3ThSqxY

Next we have used Segway RMP200 (loaned by GM) as a platform for prototyping. This Segway has the maximum speed of 10mph, equipped with GPS w/RTK corrections with 900Mhz Long Range Radio for RTK corrections, an AMD Geode Platform w/ DSRC radio, 802.11g router (for test & debug) and Control using USB-CAN interface. Figure 9.5 shows the Segway RMP200 and testing of our V2V-Intersection Protocols using them. The implementation is done by RTML members Gaurav Bhatia and Jarrod Snider.

Figure 9-5: Segway RMP200. V2V-IP testing in Robot-City, Pittsburgh, PA.

A video clip of V2V-Intersection Protocols running on Segway can been seen at:

- https://youtu.be/9ducwGKBs-o

Finally, we have used the autonomous driving platform Cadillac SRX developed at CMU [45]. We ran a scenario with the layout of our test track located at Robot City in Hazelwood, Pittsburgh, PA, where we test the vehicle at intersections. We have used the automated SRX to test various V2V and V2I safety applications at the intersection area. Figure 9.6 shows the automated SRX and a manually-driven vehicle equipped with DSRC.

Figure 9-6: CMU's autonomous vehicle platform and an Enhanced Human-Driven Vehicle.

Figure 9.7 shows the testing of V2V Distance-Keeping (Chapter 3.1) between the Enhanced Human-Driven Vehicle (EHDV) as the leader and the Autonomous Vehicle (AV) as the follower.

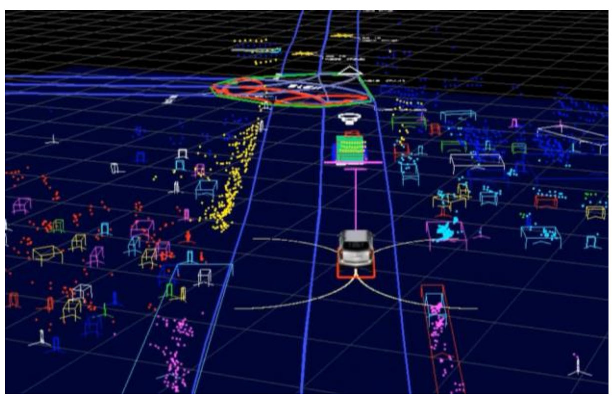


Figure 9-7: V2V Distance Keeping between the EHDV and the AV.

Figure 9.8 illustrates the test for V2V-Intersection protocols. All vehicles including the real autonomous and simulated cars follow the V2V-IP rules. The AV receives the intersection safety messages from the simulated vehicles and the Collision Detection Algorithm for Intersections (CDAI) that runs on it detects the potential collisions with neighboring simulated vehicles. Therefore, it stops for higher priority vehicles. It then receives the CLEAR messages from the higher-priority vehicles and crosses the intersection while lower-priority simulated vehicles are waiting for it.

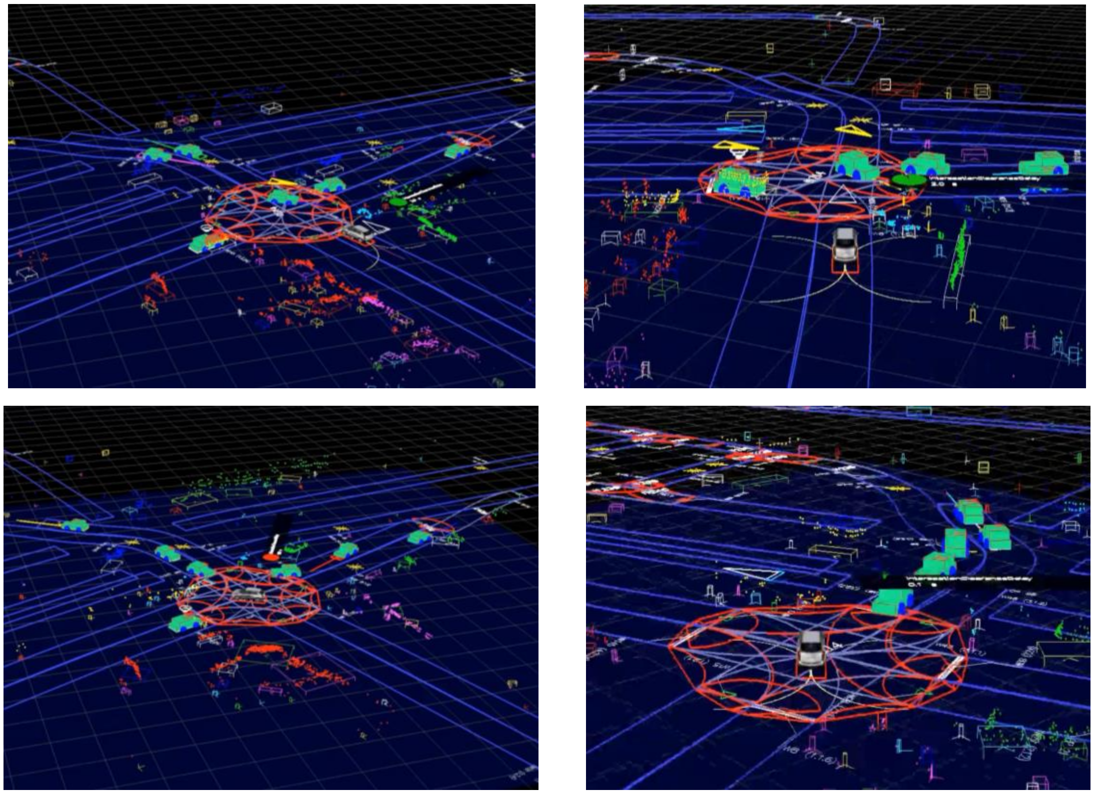


Figure 9-8: V2V-Intersection Protocol. An autonomous real vehicle and a few simulated vehicles interacting between each other and follow the V2V-IP rules.

Figure 9.9 shows leveraging the Vehicle-to-Infrastructure (V2I) Communications at the intersection area. The AV is approaching an intersection which is equipped with an Enhanced Traffic Light (ETL). The ETL is broadcasting the SPaT messages and the AV receives this information regarding the traffic light cycle, stops for the red light and crosses only when the light is green.

A video clip of various testing scenarios can be seen at:

- https://youtu.be/ifdLx_y-qZU

Figure 9-9: Intersection behavior using V2I. Enhanced Traffic Light equipped with DSRC.

9.5 Summary

We have designed a hybrid simulator-emulator, called AutoSim, as a testing tool for our intersection protocols and other vehicular communications based safety applications. AutoSim is model-based and benefits from a wide range of modules such as Control, Communication, Mobility, Localization and Path-Tracking. AutoSim's 3D graphics capability provides visualization of real street-map-based topography and accelerates the development of V2X safety applications. Additionally, AutoSim enables the real-time interaction among real and simulated vehicles. The DSRC communication and the peripheral sensory interfaces in AutoSim, enable real cars instrumented with DSRC to react to simulated cars.

Chapter 10

Conclusions and Future Work

With the recent advances in Cyber-Physical Systems (CPS), the future of road transportation is expected to include autonomous vehicles. An important component of urban transportation infrastructure is intersections and cross-roads. Current technologies such as traffic lights and stop signs are not suitable for autonomous driving. They are not very safe in managing the through traffic and inject significant delays due to their inefficiency. We consider this to be a major opportunity to introduce new methods which are suitable for autonomous driving at intersections and roundabouts, and provide solutions to problems that hamper current traffic management technologies at intersections.

In this dissertation, we have studied the problem of managing traffic through intersections. We have designed and implemented new decentralized, reliable and efficient active safety methods to provide safe and efficient passage through intersections and roundabouts. Our framework called STIP (Spatio-Temporal Intersection Protocols) is designed and developed to enable co-operative driving at intersections using vehicular networks. This cyber-physical system will allow vehicles to traverse safely by avoiding vehicle collisions at intersections, and increase traffic throughput.

Our Spatio-Temporal Intersection Protocols (STIP), shown in Figure 10.1, incorporates vehicle-to-vehicle (V2V), vehicle-to-infrastructure (V2I) communications and vehicle-resident sensor systems to enable co-operative driving of autonomous and manually-driven vehicles at intersections. STIP safely and efficiently manages the traversal of autonomous vehicles through intersections and roundabouts, and guarantees deadlock-freedom of the system. It also enables the safe co-existence of autonomous and manually-driven vehicles at cross-roads. The functionality of our methods was evaluated using our vehicular networks emulator-simulator, called AutoSim. The enabled co-operative driving technology will be applicable and beneficial to a wide range of active safety applications for various driving scenarios such as lane-changing and highway merging. However, in this dissertation, our focus has been on driving at intersections and roundabouts as the bottlenecks of urban transportation.

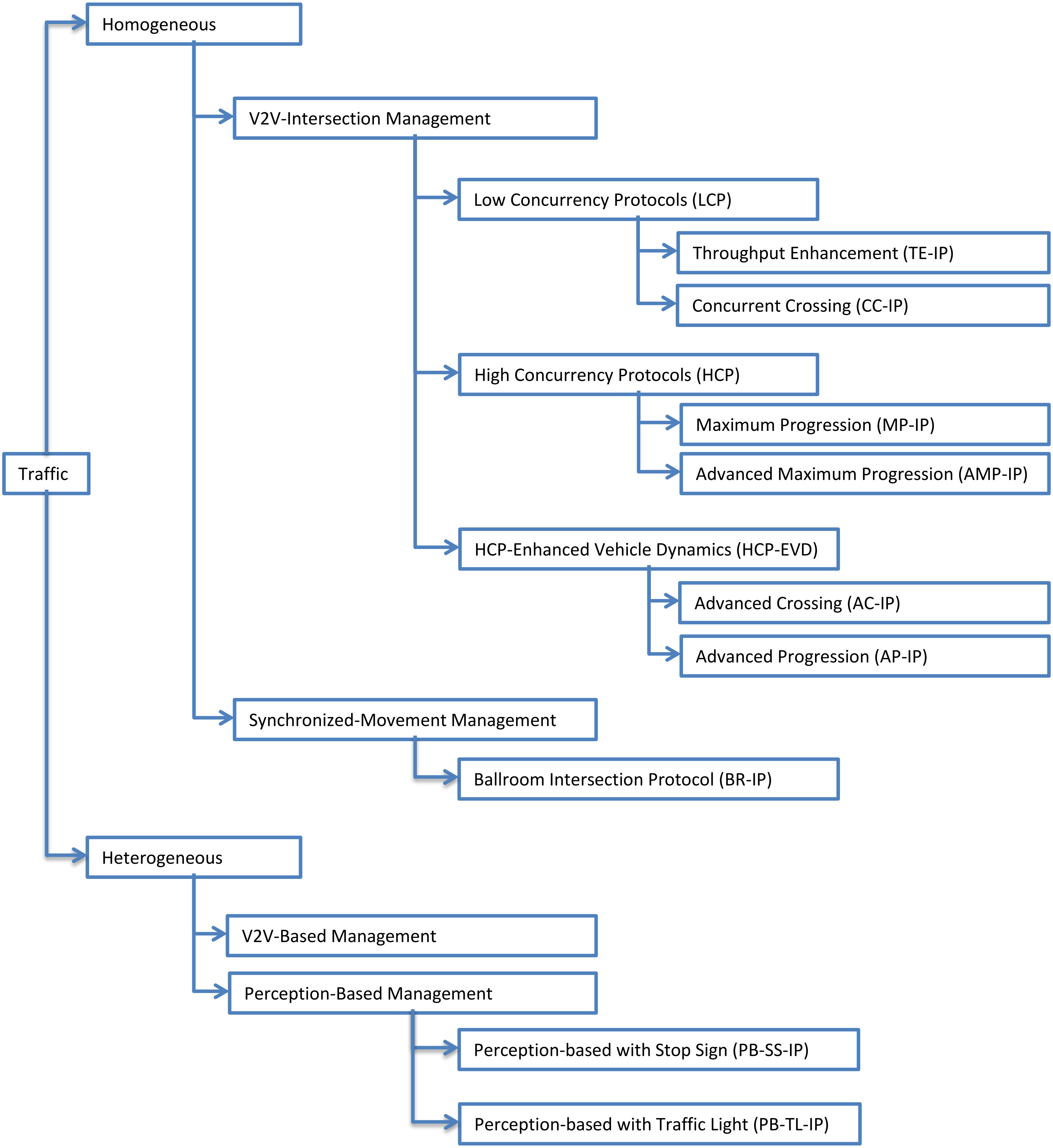


Figure 10-1: Spatio-Temporal Intersection Protocols (ST-IP)

10.1 Research Contributions

The major contributions of this dissertation are as follows:

- V2V-Intersection Management
- Vehicular Networks Intersection Management Challenges
- Synchronization-based Intersection Management
- Vehicular Networks and Perception fusion Intersection Management
- Hybrid Simulator-Emulator AutoSim

The details of the contributions are presented below.

10.1.1 V2V-Intersection Management

We have designed a family of distributed intersection management protocols to provide safe and efficient traversal of vehicles through road intersections and roundabouts. These Intersection Protocols incorporate vehicular networks and specifically V2V communications to enable co-operative driving of autonomous vehicles. We have developed and implemented three generations of V2V-Intersection Protocols (V2V-IPs). Our simulation results showed significant increase in traffic throughput. For example, our latest V2V-IP yields over 85% overall performance improvement over the common traffic light models. In addition, minimal dependency on static infrastructure is a significant benefit of using these intersection management protocols.

The first generation of our protocol family, the Low-Concurrency Protocols (LCP) includes the Throughput Enhancement Intersection Protocol (TE-IP) and the Concurrent Crossing Intersection Protocol (CC-IP). LCP is the most suitable one when dealing with low positioning accuracy levels. In these protocols, vehicles consider the whole intersection grid as one big cell. They make appropriate decisions to come to a complete stop before entering the intersection boundaries to avoid potential collisions inside the intersection box. The second generation is called the High-Concurrency Protocols (HCP) and includes the Maximum Progression Intersection Protocol (MP-IP) and the Advanced Maximum Intersection Protocol (AMP-IP). Comparing to the LCP, the HCP requires a more accurate positioning system and a digital map for vehicles. These requirements enable each vehicle to know the cell geometry of an approaching intersection, cell positions and vehicle position relative to the intersection cells. Vehicles are then able to update their Trajectory Cells List (TCL) while entering and leaving each cell along their trajectories. And, finally, we introduced the third generation of V2V-IPs, called the High-Concurrency Protocols with Enhanced Vehicle Dynamics (HCP-EVD). In addition to constraints and requirements mentioned for the HCP, the HCP-EVD requires tight time synchronization among vehicle agents and highly accurate timing calculations based on each vehicle's specific physical parameters. These provide each vehicle with the capability to accurately calculate their arrival and exit time to each cell inside the intersection box, as well as setting the desired speed and appropriate acceleration/deceleration parameters to achieve that goal in a timely manner.

In addition to V2V-Intersection management for roundabouts and isolated intersections, we have modified our V2V-IPs to be compatible with the characteristics of cascading intersections where traffic through consecutive intersections interact with and impact one another. Our simulation results showed that our intersection protocols are also suitable for cascading intersections and can avoid congestion propagation to other intersections. We also proposed a method to detect road congestions due to vehicle break-downs, road construction, etc., and avoid road blockage and congestion propagation by informing the approaching vehicles about the existing congestion situation.

10.1.2 Vehicular Networks Intersection Management Challenges

We analyzed potential deadlock conditions which could affect our distributed cyber-physical system. We have defined a set of rules as a part of our V2V-Intersection Protocols to avoid deadlock in the system. We have proved the deadlock-freedom property for a series of our intersection protocols and presented mathematical proofs

To incorporate the DSRC/WAVE V2X communications in the STIP framework, we have implemented realistic communication models. Additionally, we have studied the impact of imperfect communication and channel impairments such as packet loss on our V2V-intersection protocols and leverage the use of realistic DSRC channel propagation models such as the *Nakagami-m* model [17, 18]. We have also leveraged empirical models to study the effects of packet collision on our V2V-IP since multiple vehicles around the intersection area are attempting to broadcast the safety messages. Additionally, we analyzed the communication reliability of our proposed active safety applications. Our results indicate that our protocols benefit from high application reliability even in harsh NLOS environments such as intersections with tall buildings at all corners.

Localization and positioning accuracy play an important role in safety applications such as ours. In this dissertation, we have studied the effects of position inaccuracy on our STIP framework by implementing realistic GPS models. We have designed and implemented methods leveraging the use of dynamic distance buffers to deal with high position inaccuracies to guarantee the safety of our intersection protocols.

10.1.3 Synchronization-based Intersection Management

We have introduced a new synchronization-based method to enforce the synchronous and staggered arrival of vehicles at intersection. Our Ballroom Intersection Protocol (BRIP) is independent of any type of V2X communications and enjoys freedom from deadlock. BRIP allows all vehicles to cross the intersection grid with a constant speed without stopping before or inside the intersection area. The synchronous movement of approaching vehicles permits a continual traffic flow and maximally increases traffic throughput at intersections. Simulation results show that our proposed Ballroom Intersection Protocol (BRIP) avoids collisions and significantly increases the capacity utilization of the intersection comparing to other known techniques using V2I and V2V communications. BRIP vastly outperforms the throughput of intersections managed by traffic lights. This method in fact provides an optimal solution and achieves the maximum capacity utilization for Type I intersections with any same number of entering lanes per each direction. This method can be also beneficial for a wide range of non-vehicular applications, such as in storage warehouse, that has been discussed in the thesis.

10.1.4 Vehicular Networks and Perception fusion Intersection Management

We have designed and implemented a series of protocols for managing the mixed traffic of human-driven and autonomous vehicles through intersections. Leveraging V2V, V2I and on-board sensor systems, we have designed communication-based and perception-based protocols which enable the safe co-existence of manually-driven and autonomous vehicles. We have shown the benefits of the fusion of vehicular networks and sensor systems for these safety applications. We have also evaluated these protocols using our emulator-simulator AutoSim. Our simulation results demonstrate the improvements obtained in safety and throughput at intersections. Additionally, we have studied the effects of sensor inaccuracy and occlusion on our perception-based intersection protocols and have proposed simple solutions to deal with these shortcomings.

10.1.5 Hybrid Simulator-Emulator AutoSim

To evaluate our Spatio-temporal Intersection Protocols (STIP), we have created a model-based emulator-simulator, AutoSim. This simulator is the next generation of GrooveNet [25], [26]. This tool is used to implement and evaluate our STIP framework. AutoSim provides a hybrid emulation and simulation environment for vehicular communications. The communication interfaces for DSRC communication as well as on-board sensory interfaces have been implemented to enable real cars instrumented with DSRC to react in real-time with simulated vehicles. We also support the modeling of different aspects of mobility protocols. The architecture consists of several models such as the Control, Communication, Mobility, Localization and Path Tracking. Additionally, AutoSim supports modeling of Vehicle-to-Vehicle (V2V) and Vehicle-to-Infrastructure (V2I) communications.

10.2 Future Work

As CPS represents a relatively new area, there are still many possible research directions for future work relevant to this dissertation. We discuss below some of research topics that need to be studied in depth.

10.2.1 Improved Intersection Protocols

Our current V2V-intersection protocols can be further improved in various aspects. As explained in Chapter 4, dynamic intersection cell geometry can replace the current static geometry. To accommodate the crossing of larger vehicles or in order to enable the crossing of back-to-back vehicles on high traffic volume roads, intersection cells can also be virtually merged. This would be also beneficial in the case of odd-shaped intersections which do not allow the intersection grid to be divided into uniformly sized intersection cells.

In our intersection protocols, we discussed assigning higher priorities to vehicles approaching from the major roads comparing to vehicles arriving from the minor roads. This static priority assignment can be replaced by a dynamic method in which the priority assignment can change depending on the current traffic volume on each segment of the intersection. In the case of homogeneous traffic, which includes only autonomous vehicles, a distributed algorithm can run on all approaching vehicles. This method benefits from the received messages from neighboring vehicles to determine the traffic volume along each segment of the intersection, enabling dynamic priority assignment based on the traffic volume of the entering lane. This, in turn, would allow the passage of more vehicles from the high-traffic volume directions.

For heterogeneous traffic, where there is a mix of autonomous and human-driven vehicles present at the intersection, we propose benefiting from smart infrastructure to improve the efficiency of our protocols when dealing with asymmetric traffic volumes at the intersection. This can be achieved using an Enhanced Traffic Light (ETL), which is equipped with a camera and a DSRC device. ETL can estimate the traffic volume along each segment of the intersection using its perception system and also through the received safety messages from the approaching autonomous or enhanced human-driven vehicles. The traffic light state and the duration of green/red lights can be then dynamically changed depending on the current traffic volume to avoid congestion of high-volume traffic roads.

Both from research and practical points of view, it would be beneficial to determine the robustness of our Spatio-Temporal Intersection Protocols (ST-IP). As in any other cyber-physical system, our proposed system also faces various challenges that we discussed about and provided some solutions. For example, the GPS positioning error can be substantially high, and, in extreme cases, no GPS signal would be available. Additionally, the communication medium might suffer from various channel impairments. Channel congestion and a bursty nature of packet loss will affect the application reliability of our V2V-intersection protocols. Additionally, on the physical side of this CPS, vehicle breakdowns and mechanical failures might occur at any time a vehicle traverses through the intersection area. Therefore, it is advantageous to consider all failure cases and provide recovery plans for these extreme situations to avoid vehicle collisions and, despite the failure of a vehicle, manage the efficient crossing of other vehicles through the intersection.

Our V2V-intersection protocols explained in Chapter 4 exhibit inherent robustness. Specifically, they avoid collisions even in scenarios where a vehicle breaks down inside the intersection box and is not able to broadcast appropriate safety messages to its neighboring vehicles. For example, let’s consider a scenario in which the intersection is managed by the Throughput Enhancement Intersection Protocol (TE-IP) rules. In the case that a vehicle breaks down in the middle of the intersection, it broadcasts the ENTER safety message periodically. This indicates that this vehicle is still inside the intersection boundaries. Therefore, potentially conflicting vehicles remain stopped before entering the intersection box and wait to receive the EXIT safety message as an indication that the higher-priority vehicle has safely crossed and exited the intersection grid. In a more extreme case, we can consider that the vehicle breaks down inside the intersection box and stops broadcasting the safety messages. As no EXIT safety messages are received from the sender of ENTER messages, there is no indication that the higher-priority vehicle has crossed yet and, therefore, potentially conflicting vehicles must act conservatively and remain stopped before entering the intersection box. This continues till this transient has passed and EXIT safety messages from the same sender of the ENTER messages are received by the potentially-conflicting vehicles, indicating that they can now safely cross the intersection area.

The same idea applies to the HCP and the HCP-EVD protocols. For example, under the Maximum Progression Intersection Protocol (MP-IP), vehicles broadcast the updated Trajectory Cells List (TCL) which includes their current cell and next cells. Let's consider a case in which a vehicle breaks down inside the intersection box broadcasting CROSS safety messages. Since the vehicle is not able to move, its current cell does not change and no cells are being deleted from the TCL. Therefore, other approaching vehicles correctly assume that the Trajectory Conflicting Cell (TCL) is still occupied by that vehicle and do not progress into that cell. If the vehicle breaks down and also is not able to broadcast the TCL within the CROSS safety messages, robustness needs to be improved.

10.2.2 Pedestrian and Bicyclists

Focusing on road intersections, other than vehicles, there are other agents present in the intersection environment. Pedestrians and bicyclists are also parts of this equation and it is important to look at methods to guarantee their safe passage through intersections. The goal would be avoiding any collision among various types of crossing agents including vehicles, pedestrians and bicyclists, while trying to increase the throughput of the intersection and decrease the delays faced by these agents.

Pedestrians and bicyclists can be equipped with communication devices such as their smart phones and they can participate in various distributed active safety applications. Traffic rule violations by these entities will be detected using V2V, V2I or perception systems and approaching vehicles will be warned about the dangerous situation.

10.2.3 Non-Vehicular Applications

In addition to collision avoidance at cross-roads, we believe that our Spatio-Temporal Intersection Protocols (STIP) will be beneficial for a wide range of real-world applications in different domains. Based on our discussions with experts in these fields, a form of our methods can be implemented for the following applications to assist with their goals of high safety and high efficiency.

Our Ballroom Intersection Protocol (BRIP) is applicable to a variety of intelligent applications. There is a significant need for more efficient setup and management of manufacturing lines and distribution centers. We believe that BRIP can be quickly deployed in manufacturing lines of companies to reduce the required physical space, avoid any potential collisions of moving products and significantly increase the throughput of these lines. Additionally, it is beneficial for distribution systems. An example of these methods is the Kiva systems of Amazon.com [99]. Kiva robots have been deployed to reduce labor requirement and increase efficiency by smart transportation of boxes in distribution facility centers. BRIP is suitable for managing the movement of Kiva robots. Our intersection management protocol can be implemented to increase the safety and efficiency of these low-speed robots.

Our V2V-Intersection Protocols (V2V-IP) can be beneficial for various military applications specifically for collision avoidance of automated military vehicles on the battlefields. Additionally, these protocols can be implemented on heavy and giant-sized machineries such as Caterpillar machines used in the mining and construction sectors. Safety has the highest priority for these applications and, due to the harsh environment conditions, centralized solutions are not as attractive as our proposed distributed systems [100].

Similar to road intersections, rail-road intersections are also suffering from collisions including Train-to-Train, On-Track-Vehicles and Train-to-Car conflicts. Over 10,000 railroad incidents lead to more than 700 fatalities every year in the United States. Based on the statistics collected by the Federal Railroad Administration (FRA), an average of 2100 Train-to-Car crashes occur per year in the U.S which leads to over 200 fatalities and 1000 injuries [101], [102], [103], [104].

Obviously, each of the mentioned applications is in very different environments and has different requirements in communications, positioning and sensing and can tolerate different levels of inaccuracies. Therefore, an in-depth study of the requirements and environmental challenges is necessary.

10.2.4 Cascading Intersections

We discussed managing the traffic through cascading intersections in Chapter 5.2, and explained the problem of congestion propagation to neighboring intersections. One alternative candidate to consider is route change. This means that in the case of a congested exit-lane at an intersection, the vehicles which were previously intending to exit toward the congested lane will now change their route to get to their destinations. Each vehicle will use its GPS and digital Map database information to find alternative routes from its current position towards its destination.

Another solution would be benefiting from the existence of the smart infrastructure. In this case, the intersection infrastructure will be involved in detecting the congestion and relaying the information to all neighboring intersection which may get affected by the current traffic situation. The receiving intersection infrastructure can then broadcast the information regarding the congestion at neighboring intersections, and may even suggest alternative routes using visual instruments such as arrows. Vehicles will receive these traffic warnings and decide by themselves in a distributed manner about their action at the intersection regarding their route intentions. In the case that human-driven vehicles are also part of the traffic flow, smart intersection infrastructure with a traffic light can change the light condition and the duration of green and red lights to avoid further congestion toward the already congested route.

Additionally, for synchronous movement intersection management, it is important to study the BRIP challenges for *intersection cascading*, in which multiple intersections are connected in a row through connecting road segments as found in urban areas. By looking at examples of different *Intersection Types* in Figures 7.11, 7.13 and 7.15, one can see that the exit pattern of the vehicles from each direction of the intersection is exactly the same as the arrival pattern of that direction. Therefore, in the case that intersection cascades are of the same type, vehicles will have the same arrival pattern from the first intersection to enter the next intersection. In this case, the vehicle can maintain the same speed and arrive at the second intersection at an eligible time slot, without any speed adjustments.

In other cases, when the connected intersections are not of the same type, the exit pattern of one is not similar to the arrival pattern of the next intersection. Thus, each vehicle is required to adjust its velocity to adapt to the arrival pattern of the upcoming intersection and enter each intersection at that intersection's eligible time slot and *Desired Speed*. It must be noted that the value of the *Desired Speed* is tightly dependent of the distance between two intersections and each vehicle's physical characteristics such as acceleration and deceleration parameters. This might be problematic when the road length between two consecutive intersections is too short. To solve this problem, the desired speed for vehicles to enter the first intersection should be compatible with its value for the second intersection. This allows each vehicle to adjust its speed before entering the first intersection and then enter the following intersection without drastic changes in speed.

10.2.5 Topology-based Channel Congestion Avoidance

The presence of structures such as tall buildings at intersection corners causes fading and shadowing effects. This affects the reliability of Vehicle-to-Vehicle (V2V) communications used for safety applications. It is vital to increase the reliable communication's range without causing congestion, so that the occluded vehicles successfully receive V2V safety messages despite the presence of large obstacles and structures at intersections. We propose a method of congestion control in vehicle-to-vehicle (V2V) communications by controlling the transmit power based on the structure topology of the vehicle's environment. Such structures like buildings and natural barriers are detected using map information and a vehicle's onboard sensors such as cameras, lidars and radars.

The goal is to reduce network congestion and improve the probability of successful packet reception by dynamically changing the power at which packets are transmitted. Additionally, it is desirable to increase the awareness of a vehicle about its surrounding environment to determine the appropriate fading model for use during transmissions.

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