Comprehensive Arterial Traffic Control for Fully Automated and Connected Vehicles

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Considering the environmental concerns and space limitations of urban infrastructure, construction of new roads and broadening of the existing ones are not accepted practices for managing the ever-growing traffic demand. The current traffic management methods (e.g., traffic signals) in urban networks focus on the resolution of traffic conflicts at urban intersections. However, such an approach sometimes turns intersections into bottlenecks resulting in loss of efficiency, increased risk of the traffic crashes, and negative environmental impacts. Connected and Autonomous Vehicles (CAVs) are seen to revolutionize urban transportation and bring efficiency and safety benefits to the transportation users. However, the full extent of CAV benefits will not be achievable unless the traffic control systems are rethought from the roots.

The goal of this Ph.D. research is to investigate the impact of flexible organization of traffic flows on efficiency and safety of urban networks, in a fully automated and connected transportation environment. This study proposes a robust control concept, called Combined Flexible Lane Assignment and Reservation-Based Intersection Control (CFLARIC) system, which allows vehicles in the traffic stream to utilize, when not endangering the other road users, any part of the paved road surface. The control strategy used in CFLARIC works through discretization of space and time in the entire network, which enables CFLARIC to resolve the conflicts both along the links between intersections and within intersection boundaries. A microsimulation tool called Flexible Arterial Utilization Simulation Modeling (FAUSIM) has been developed in NetLogo to model such flexibility.

The performance of various CFLARIC scenarios is evaluated through a comparison with Fixed-Time Control (FTC) and Full Reservation-based Intersection Control (FRIC) on both hypothetical and filed-like urban arterials, under various traffic demand conditions. Furthermore, delay and surrogate conflict predictive models are developed to examine the performance of a Reservation-based Control strategies in a flexible automated traffic network. Lastly, the flexible traffic lane assignment has been addressed as a network optimization problem, where an optimal lane assignment schema is achieved by using metaheuristic algorithms. Findings show that the CFLARIC brings significant benefits, in terms of efficiency and reduction of vehicular conflicts, for various traffic demands and infrastructure conditions.

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Preface

I would like to express my sincere gratitude to my advisor, Dr. Stevanovic, who always believed in me and helped me to move in the right direction. His expertise and constant support were invaluable. Working on such innovative and exciting research under his supervision was a great experience that pushed me to sharpen my thinking.

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I am extremely grateful to Dr. Nikola Mitrovic who has always been there with positive energy to provide advice and make constructive feedback. His rich knowledge of the subject and his continuous support made this research possible.

I also want to thank all of my friends and colleagues for their kind help and support.

A special thanks to my family for all of the sacrifices that they have made. Words cannot express how grateful I am to my parents and siblings. Not seeing them for more than five years was the most difficult part of this journey.

Also, I very much appreciate Dr. Issa Zakeri, my uncle, who has been an inspiration to me since I was in the first grade of elementary school.

Finally, I would like to acknowledge my dearest friend, my beloved husband Kaveh Barri, for his continued support. After a pause of over 20 years in my academic career, I renewed my effort to complete my research. Without his support in both the personal and professional aspects of my life, I could not follow my dreams and have achieved the goals that I set.

1.0 Chapter 1- Introduction

This chapter addresses the essential background of Automated Network Management (ANM) including the related traffic control systems. After a basic literature review of the most relevant studies on the topic, the research problem is defined. The research goal and objectives are stated in the next part of the chapter. The final part of the chapter provides an overview to guide readers through the remainder of the dissertation.

1.1 Traffic Congestion and Intersection Control Mechanism

Traffic congestion is a major issue in urban transportation systems, which does not only result in loss of efficiency by causing substantial delay (Iqbal et al., 2021), but it also generates many critical safety events such as crashes and near-crashes and leads to significant negative environmental impact (Alshayeb et al., 2021). Considering the environmental concerns and space limitations of urban areas, construction of new roads and broadening existing ones, to manage the growing traffic, are not accepted practices anymore. Therefore, there is a multifaceted need to advance control mechanisms to better manage traffic flows in urban networks.

With the latest advancement in Information Technology (IT) sector and the automotive industry, Connected and Autonomous Vehicles (CAVs) are promised to revolutionize urban transportation and bring significant efficiency and safety benefits to transportation users (Dhingra et al., 2021). Vehicles with advanced driving assistance systems and some levels of autonomy are already on the market and new technologies are paving the way to novel traffic management approaches (Erdağı et al., 2019; Fagnant and Kockelman, 2015). Therefore, it is imperative to advance intersection control mechanisms to better manage traffic flows. A fully connected and automated driving environment offers the potential to change the current restrictions and introduce new traffic control rules.

1.2 Problem Statement

The current methods for managing traffic flows in urban networks use a directional Right of Way (ROW) to organize traffic along urban roads and are focused on resolution of traffic conflicts at urban intersections. In these approaches, the traffic operates as directional (compressible) fluid on road stretches between urban intersections, while the intersections serve as the major 'containers' of conflicts between various traffic streams. Therefore, the resolution of conflicts between vehicles is always made at intersection boxes, which turns such intersections into bottleneck points wherever traffic demand exceeds intersection capacities.

Autonomous Intersection Management (AIM) systems are innovative traffic control mechanisms (Dresner and Stone, 2004) in Autonomous Network Management (ANM) that are responsible to coordinate movements of individual vehicles for collision-free passage through intersections. However, the core of such a concept remains the need to control traffic movements only at intersections. Our ability to leave behind this traditional directional Right of Way (ROW) approach for controlling traffic has been limited due to the inability to fully control human behavior, and lack of technological resources to enable full communication and interaction among vehicles, and between vehicles and infrastructure. However, a fully automated driving environment offers the potential to change the current restrictions.

In addition to the limitations that one faces when applying a novel traffic management in the field, there are some restrictions on traffic modeling side as well. In most of the existing microsimulation platforms (such as Vissim, Aimsun, and Sumo) the edges/links, representing street segments, are coded as unidirectional elements – where a road segment can be used only to carry directional traffic (Barcelo and Casas, 2005; Lopez et al., 2018; PTV Group, 2015). This approach imposes a limitation on the simulation of unconventional traffic management scenarios, where vehicles may need to use the same lane for both directions in bypassing situations. Although some attempts have been done to use special coding in the above-mentioned software to simulate a realistic overtaking process (Llorca et al., 2015), these tools still do not allow very flexible utilizations of the roadway. Therefore, not only there is a need to introduce novel traffic control systems for an autonomous environment, but it is also necessary to have flexible simulation platforms that can address deficiencies of the traditional microsimulation tools.

To address the above mentioned issue, Stevanovic and Mitrovic (2018) proposed a novel framework called Combined Alternate-Direction Lane Assignment and Reservation-based Intersection Control (CADLARIC) which models directionally unrestricted traffic flows in a fully connected and automated vehicle environment. However, despite its promising results, CADLARIC faces some limitations, due to heavy infrastructural expectations and lack of generality. Chapter 3 of the current dissertation provides more details about CADLARIC.

This research advocates a flexible organization of traffic flow where overall roadway infrastructure could be better utilized to improve efficiency and safety of traffic on urban networks in a fully automated and connected transportation environment. A major assumption made is that in such novel traffic organization, every vehicle in the traffic stream can utilize, when not endangering the other road users, any part of the paved road surface regardless of the direction of its movement or its current speed or position.

1.3 Research Goal and Objectives

The goal of this Ph.D. research is to investigate the impact of flexible organization of traffic flows on efficiency and safety of urban networks in a fully automated and connected transportation environment. For this purpose, this study introduces an advanced control framework, called Combined Flexible Lane Assignment and Reservation-Based Intersection Control (CFLARIC) system which offers more flexible lane-assignment possibilities to improve efficiency and safety of urban networks. The stated goal decomposed into the following objectives:

- Evaluate the impact of a CFLARIC on an urban arterial that has a counterpart in the real world.
- Evaluate benefits of CFLARIC in traffic conditions with near- or over-saturated traffic for certain traffic movements.
- Develop delay and surrogate conflict predictive models to examine the performance of a Reservation-based Control strategy in a flexible automated network.
- Address the flexible traffic lane assignment as a network optimization problem using metaheuristic optimization algorithms.

1.4 Dissertation Organization

This dissertation is divided into eight chapters.

1.4.1 Chapter 1 – Introduction

Chapter 1 introduces the reader to the essential background of Automated Network Management (ANM) and the related traffic control systems.

1.4.2 Chapter 2 – Literature Review

Chapter 2 provides a comprehensive overview of the related research. The literature review concentrates on three topics. The first subchapter reviews the studies on Reservation-based Intersection Control (RIC) as one of the advanced control systems in ANM. The second subchapter, Optimization-based Intersection control, discusses recent attempts at optimizing RIC based on various objectives. The last subchapter reviews literature on lane reversal. It should be mention that in Chapter 6, Estimation of Delay and Surrogate Conflicts in Automated Network, an independent literature review is conducted on delay functions.

1.4.3 Chapter 3 – Research Methodology

Chapter 3 describes the approach to conducting the research. The first and second sections of this chapter introduce the main control concepts (lane-changing process and time-space reservation at intersection) in the proposed flexible control framework (CFLARIC) as well as in the previously introduced novel control system (CADLARIC) (Stevanovic and Mitrovic, 2018). In the third part, the implementation framework has been discussed. The last subchapter, explains the efficiency and safety performance metrics that are used in the evaluation purposes.

1.4.4 Chapter 4 – Evaluation of CFLARIC in a Field-Like Traffic condition

Chapter 4 presents the results of implementing the proposed CFLARIC models in a 3-interscetion corridor in Utah. The efficiency and safety of the proposed CFLARIC models are compared with the two base control systems; Fixed-Time Control (FTC) and Full Reservation-based Control (FRIC) systems under various Level of Services (LOS).

1.4.5 Chapter 5 – Impact of Shared Lanes on Performance of the CFLARIC

Chapter 5 investigates the most beneficial strategy for reassigning extra through traffic to the turning lanes when through lane reaches ‘physical capacity’. This goal is decomposed into two objectives: 1. Identify which lanes should be shared, and 2. Find a close-to-optimal amount of through traffic that should be assigned to the identified shared lane. The proposed CFLARIC strategies are compared with Fixed-Time Control (FTC), Full Reservation-based Intersection Control (FRIC), and CADLARIC for multiple traffic demand scenarios.

1.4.6 Chapter 6 – Delay and conflicting request predictive models

This chapter has its own literature review, methodology, results, and discussion sections. The goal of this chapter is to develop delay and surrogate conflict predictive models to examine the performance of a Reservation-based Intersection Control strategy in a flexible automated network. Linear regression and Multigene Genetic Programming (MGGP) approaches are utilized to derive new prediction models for delay and number of conflicting requests.

1.4.7 Chapter 7 – Optimized Flexible Lane Assignment Using Metaheuristic algorithms

In this chapter, the flexible traffic lane assignment problem in CFLARIC has been solved as a network optimization problem, in which an optimal lane assignment schema is achieved using metaheuristic optimization algorithms. The output of the optimization process is the lane assignment that leads to a minimum total travel time for a given network and traffic volumes.

1.4.8 Chapter 8 – Conclusions and Future Research

This chapter consists of two sections. The first section presents the conclusions of the research. The second section provides the limitations of the research, as well as directions for future research.

2.0 Chapter 2- Literature Review

This chapter presents a comprehensive literature search over various advanced control systems in Automated Network Management (ANM). Special emphasis is given to the Reservation-based Intersection Control (RIC) system since it is one of the main control concepts of the proposed control framework in this study. Findings are grouped into three subchapters. The first section reviews Reservation-based Intersection Control (RIC) as one of the novel control concepts for urban traffic management in a CAV environment. The second section deals with the optimization-based intersection controls and the third section reviews the lane reversal concept.

2.1 Reservation-based Intersection Control

One of the novel urban traffic control concepts, that drew a lot of attention in the last two decades, is Reservation-based Intersection Control (RIC). The research about RIC started almost two decades ago when Kato et al. (2002) have shown the feasibility and potential of Vehicle-to-Infrastructure (V2I) technology for automated vehicle control and cooperative driving. Dresner and Stone (2004) proposed one of the first implementations of First Come First Served (FCFS) traffic control algorithms in reservation-based systems. Their control system relies on Dedicated Short-Range Communication (DSRC), for alleviating traffic congestions at intersections under the assumption that vehicles are controlled by intelligent agents. In their study, the intersection is divided into an n by n grid of reservation tiles and vehicles need to call ahead and reserve the required space at the intersection. This concept is also known as the Autonomous Intersection

Manager (AIM) – which, depending on the availability of space at a given time at the intersection, – either approves or denies vehicular the requests. If such a request is not approved, the vehicle driver agent slows down and transmits a new reservation request with an updated arrival time. Since then, the RIC has been addressed in different studies. While some evaluated the practicability of this algorithm (Baber et al., 2005), others used mathematical models (Tian et al., 2015) or simulation models (Huang et al., 2012; Li et al., 2013) to study the safety and efficiency benefits of the algorithm.

Another series of attempts have been done to enhance the efficiency of the RIC. For instance, using a more centralized approach to reservation requests approach, De La Fortelle. (2010) improved the efficiency in terms of flow by increasing the average speed of the vehicles at an intersection. Later, Lee et al. (2012) proposed a Cooperative Vehicle Intersection Control (CVIC) system that eliminates the potential overlaps of vehicles traveling in conflicting approaches at the intersection and as the result reduced delay and total travel time significantly. Hassan and Rakha (2014) reduced average and maximum delays by developing an algorithm that prioritizes traffic coming from lanes with the highest traffic demands.

One of the key issues that RIC faces is the adopted request control policy. Initial work in this area mostly focused on the protocol of the control system and used the First-Come-First-Served (FCFS) policy, where a vehicle first to arrive at the intersection is the first one being served (pass through the intersection). Fajardo et al. (2011) and Li et al. (2013) reported promising performance for the FCFS policy under various traffic demands. A study by Levin et al. (2016) also illustrated that FCFS policy has a great potential to reduce the congestion not only in a small group of intersections but also within a city. However, in the same study, paradoxes were observed when RIC was coupled with network dynamics. Accordingly, a number of studies have studied alternative priorities rules and how they affect the performance of RIC. For example, Carlino et al. (2013) proposed a market-based pricing mechanism to prioritize conflicting movements and showed that auctions can regulate traffic effectively only in some networks. Later, Levin and Boyles (2015) concluded that most of the benefits of intersection auction (over FCFS approach) can be attributed to the randomizing effects of auctions which results in greater shares of intersection capacity going to longer vehicular queues.

2.2 Optimization-based Intersection Control

As the Reservation-based Intersection Control system does not guarantee optimality (Levin et al., 2016), several attempts have been done to utilize optimization-based methods to further improve the efficiency. Yan et al. (2009) proposed a dynamic programming algorithm to minimize the intersection evacuation time by assigning vehicles to an optimal passing order. Gregoire et al. (2013) defined a priority relation between the vehicles to classify the feasible trajectories and proposed an algorithm to construct an optimal trajectory for given priorities. Zhu and Ukkusuri (2015) introduced a linear programming formulation that minimizes total travel time by accounting for traffic dynamics in autonomous intersection control. Altche and De La Fortelle (2016) minimized the average intersection travel time of vehicles and thus maximized intersection throughput. Zohdy and Rakha (2016) optimized vehicle acceleration and deceleration rates to minimize trajectory overlap and consequently to minimize intersection delay. Levin and Rey (2017) improved the performance of RIC by developing a reservation protocol based on a conflict point separation model. Wu et al. (2019) proposed a decentralized coordination multi-agent learning approach to optimize the sequential actions of vehicles. Later, Zhao et al. (2019) proposed a centralized way to integrate an intersection control problem with vehicle trajectory planning. Their formulated bilevel optimization problem designed to minimize the total travel time by a mixed integer linear programming (MILP) model while maximizing the total speed entering the intersection using a linear programming (LP) model. Later, Olsson and Levin (2020) incorporated acceleration to form realistic vehicle trajectories and optimized vehicle acceleration and velocity through the intersection using a mixed-integer linear program. Recently, Ma et al. (2020) proposed a mixed-integer linear programming model to optimize vehicle trajectories at the intersection and consequently to reduce delay.

2.3 Lane Reversal

The Reversal Lanes is another concept utilized in advanced urban traffic systems to better utilize road capacity in response to significant variations in directional traffic demand. This approach, focusing on contra-flow lane deployment, has been applied to specific traffic patterns or conditions including Time of Day (TOD) tidal traffic flows and evacuation purposes. Williams et al. (2007) examined the benefits of lane reversal under the stress of mass evacuation using simulation. Hausknecht et al. (2011) proposed a Dynamic Lane Reversal (DLR) model that is capable of adapting the number of directional lanes to respond to the traffic fluctuations in an automated environment. In their proposed model, traffic saturation is used to determine lane directions, and then bilevel programming determines the optimal configuration of lanes. Later, Zhang et al. (2012) proposed a cell-based regional evacuation model and optimized the deployment of the contra-flow lane strategy. Similarly, Levin and Boyles (2016) proposed a dynamic lane reversal model, using the cell transmission formulation, to determine the optimal direction of lanes based on dynamic demand scenarios. Later, Chu et al. (2017) developed a traffic scheduling scheme for dynamic lane reversal management in which the optimal routes, schedules, and lane directions of CAVs are determined based on the collected travel requests. Recently, Gravelle and Martínez (2018) proposed a distributed lane reversal algorithm for minimizing delay and Levin et al. (2019) developed a throughput-optimal decentralized max-pressure policy that controls both Autonomous Intersection Management (AIM) and Dynamic Lane Reversal (DLR) using a stochastic queueing model.

Although the aforementioned studies bring significant contributions to the emerging field of urban traffic management, none of them addresses the potential to fully utilize road infrastructure without strong directional constraints. The presented control concept in this dissertation splits directional traffic into individual lanes (based on the desired movements at the downstream intersection) and combines the mid-block traffic control approach with the RIC to apply control and resolve conflicts over the entire roadway surface in order to improve the efficiency and safety of the transportation network by better utilizing road capacity.

3.0 Chapter 3- Methodology

3.1 Introduction

With the benefits of the novel embedded IT technologies, connected and autonomous vehicles (CAVs) provide opportunities to relax some of the existing traffic control requirements and restrictions. The increase in the level of connectivity between vehicles, and between vehicles and infrastructure, allows transportation designers to think beyond the existing Right of Way (ROW) models and design novel traffic control systems, with higher levels of flexibility to improve safety and efficiency, and enhance sustainability.

In what follows, various levels for road-use flexibility, at an intersection, are presented. Figure 1 shows a conventional lane assignment and common "conflict" zones for two control systems, Fixed-Time Control (FTC) and Full Reservation-based Intersection Control (FRIC). In this environment, most of the conflicts are grouped within the intersection zone and there are no intersection conflicts among the vehicles that travel in the same direction. In such systems, the intersection conflicts can be minimized if (like in the case of Fixed-Time control shown in the left intersection of Figure 1) the left turns are protected, and Right-Turn on Reds (RTORs) are prohibited.

There are three relevant variations of this scenario. In the first scenario, the conventional signal control logic (i.e., traffic signals) is replaced with a common "Intersection Manager" facilitator. This system is considered as the traditional reservation-based system (Dresner and

Stone, 2004) in which vehicles are “controlled agents” and they required to reserve space at the intersection before reaching the intersection (the right intersection in Figure 1).

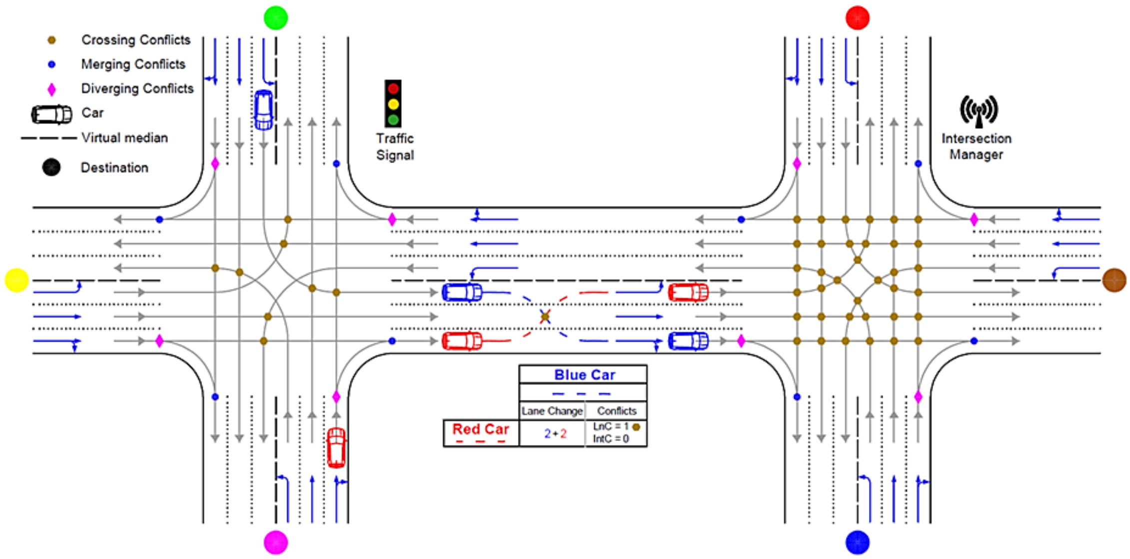


Figure 1 Conventional lane assignments (FTC at the right intersection- FRIC at the left intersection)

The second variation of the same concept refers to various types of intersections with alternative geometries intersection designs such as diamond interchange (DI) (Figure 2, right intersection) , median U-Turn (MUT) (Figure 2, left intersection), and J-Turn (Edara et al., 2015). In these alternative designs attempts are done to geometrically displace some of the conflicts from the intersection box, usually to facilitate the service of left-turning vehicles (FHWA, 2016).

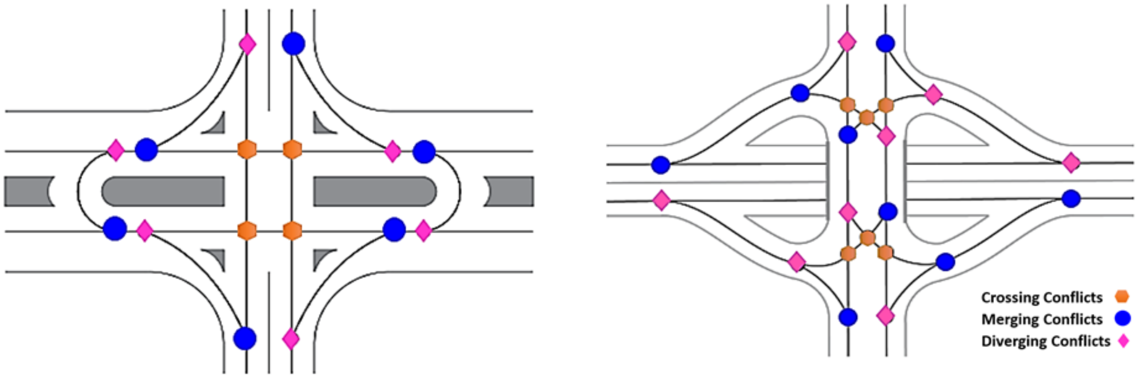


Figure 2 Conflict diagram for Median U-Turn (MUT) and Diamond Interchnage (DI)

Finally, the third variation includes reversible-lane designs (Levin and Boyles, 2016), focusing on contra-flow lane deployment , which provide great opportunities to adjust roadway capacity to meet the major diurnal fluctuations in traffic demand (Figure 3).

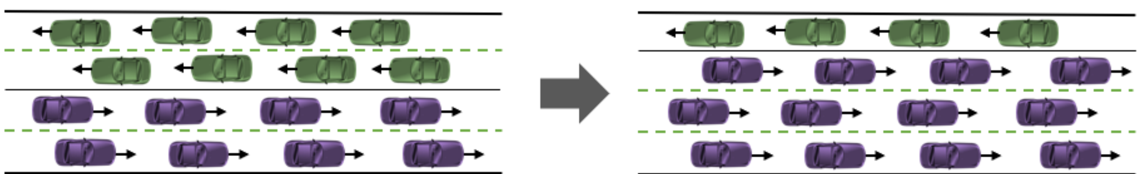


Figure 3 Dynamic lane reversal

Now, one should consider a fully connected and automated environment where vehicles communicate with each other (and with infrastructure) and every single user/agent in the system possesses relevant information about neighboring users (and their intentions). This condition will most likely be satisfied in the (medium to long-term) future considering all advances in communication technology. In such a rich IT environment, rules of traffic control, here inherently included as constraints of fixed lane assignments, do not have to be as restrictive as those in the traditional systems.

In an ultimately flexible scenario (100% autonomy and connectivity), with “virtual medians” between travel lanes, a vehicle can travel on any part of the road, as long as it is not endangering the other road users.

Figure 4 presents two possible traffic control systems for such a futuristic traffic control environment. At the left intersection, previously introduced (Stevanovic and Mitrovic, 2018) CADLARIC is shown, where vehicles can use lanes that are traditionally reserved for the opposite direction of travel. This approach allows left- and right-turning vehicles to align themselves in an appropriate lane before reaching the downstream intersection. In this way, vehicles, by the time they reach downstream intersection, can smoothly make a turn without facing any conflicts with vehicles from the other movements. The main control concepts of CADLARIC are described in the next subsections (sections 3.2 and 3.3). Now, consider if the flexibility of such a system is increased in a way that a vehicle traveling in a certain direction can take any of the lanes for the same direction, regardless if those lanes are dedicated to the same type of movement (right, left, or through) that the vehicle intends to make at the downstream intersection. Figure 4 shows two such vehicles (blue and red) heading to their destinations (shown by the circles with the same color as the corresponding cars). Imagine if traffic control rules were flexible enough to allow each of these two vehicles to travel in any relevant lane (this case Eastbound) with a possible path to their destinations. Obviously, in such a case there would be multiple combinations of paths (consisting of between-intersection links and within-intersection paths) that these two vehicles could take, each with a different number (and locations) of conflicts (both for lane-changing and within-intersection maneuvers), as shown in tabular formats within Figure 4).

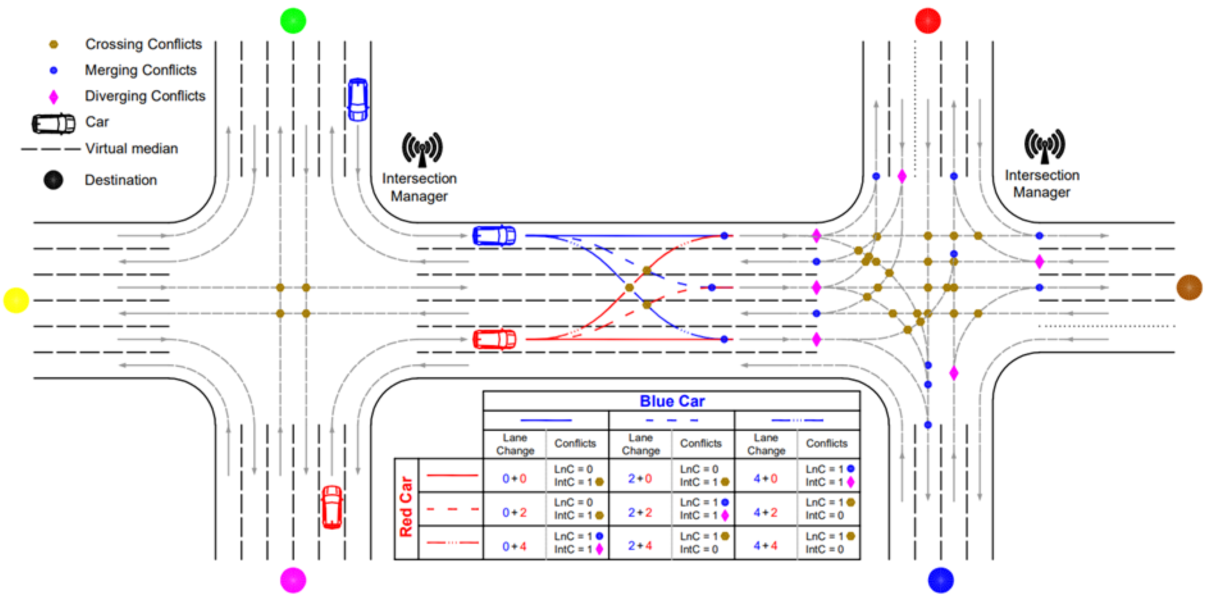


Figure 4 Potential lane assignments with CAVs

3.2 CADLARIC

Benefiting from opportunities offered by Connected and Autonomous Vehicles (CAVs), a concept called Combined Alternate-Direction Lane Assignment and Reservation-based Intersection Control (CADLARIC) was proposed recently for management of directionally unrestricted traffic flows in urban environments (Stevanovic and Mitrovic, 2018). In CADLARIC, resolution of vehicular conflicts is distributed between links and intersections to prevent intersections from turning into traffic bottlenecks.

CADLARIC assigns various turning flows to different lanes in an alternate fashion, as depicted in Figure 5, so vehicles can use lanes that are traditionally reserved for the opposite direction of travel. This approach allows left- and right-turning vehicles to align themselves in an appropriate lane before reaching the downstream intersection so that by the time they reach the intersection, they can smoothly (providing that there are enough lanes) go through the intersection without having to face any conflicts with vehicles of the other movements. In such a system, a RIC algorithm handles conflicts between the through movements. As shown in Figure 5, in CADLARIC each approach lane is dedicated only to a particular movement (through, left, or right) and as the result it requires at least 6 lanes per approach.

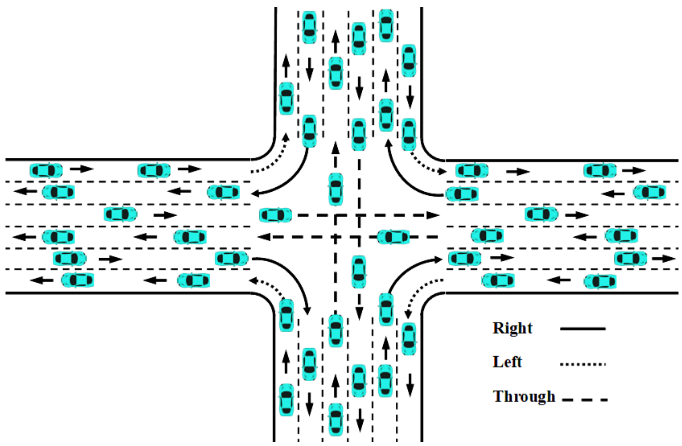


Figure 5 Lane assignment in CADLARIC

CADLARIC has been tested on a generic three-intersection network under Level of Service (LOS) B to LOS F (Stevanovic and Mitrovic, 2018). Figure 6 shows the results for the total delay comparison between CADLARIC, FTC, and FRIC. CADLARIC outperforms the FTC and FRIC under LOS B to LOS E. However, assigning only one dedicated lane to each movement at each approach, negatively impacts CADLARIC's performance in terms of total delay time in (over) saturated traffic conditions (i.e., LOS E and F), when the physical capacities of its single-lane movements are reached (Stevanovic and Mitrovic, 2018).

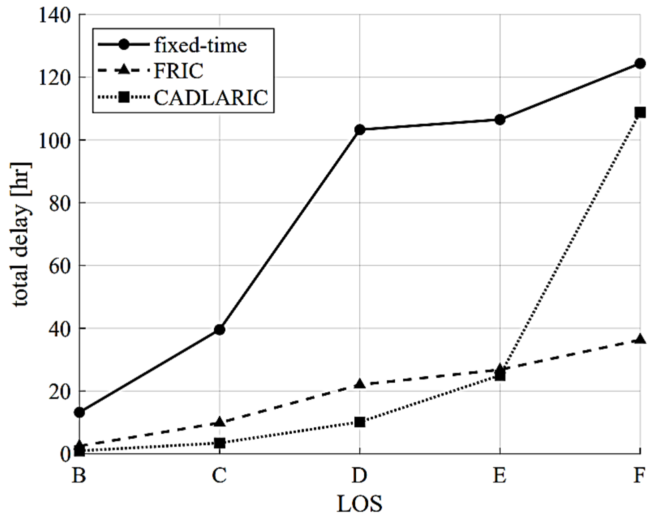


Figure 6 Total delay time comparision

3.3 CFLARIC

Combined Flexible Lane Assignment and Reservation-Based Intersection Control (CFLARIC) system, the generalized version of CADLARIC, is a robust control framework which allows every vehicle in the traffic stream to utilize, when not endangering the other road users, any part of the paved road surface. CFLARIC splits directional traffic into individual lanes (based on the desired movements at the downstream intersection) and combines the mid-block traffic control approach with the Reservation-based Intersection Control (RIC) to apply control and resolve conflicts over the entire roadway surface in order to improve the efficiency and safety of the transportation network by better utilizing road capacity.

While in the Reservation-based Control system introduced by Dresner and Stone (2004) only the intersection box is divided into space blocks (s), the control strategy used in Combined Flexible Lane Assignment and Reservation-based Intersection Control (CFLARIC) works with a discretization of space and time in the entire network. Discretization is done to enable space reservation at the intersections and for lane-changing processes along the inks, to resolve conflicts, and to evaluate performance of various traffic control scenarios.

In CFLARIC, vehicles are essentially "controlled agents" that communicate with the intersection manager (IM) to reserve the required time-space slots to guarantee their safe passage through the intersection (Figure 7) (See section 3.3.6: Time-Space Reservation at Intersections). The intersection manager (IM) collects all the information about vehicles including their turning intentions. The IM works as the brain of the entire system and controls when vehicles get permission to enter the intersection and how long they take to pass through the intersection. In this control framework, vehicles are not allowed to change their lanes within the intersection box, and thus they need to align themselves in the desired lane once they exit the intersection. To ensure a safety buffer during the cooperative lane-changing processes, vehicles communicate with each other (See section 3.3.7: Lane-Changing Process).

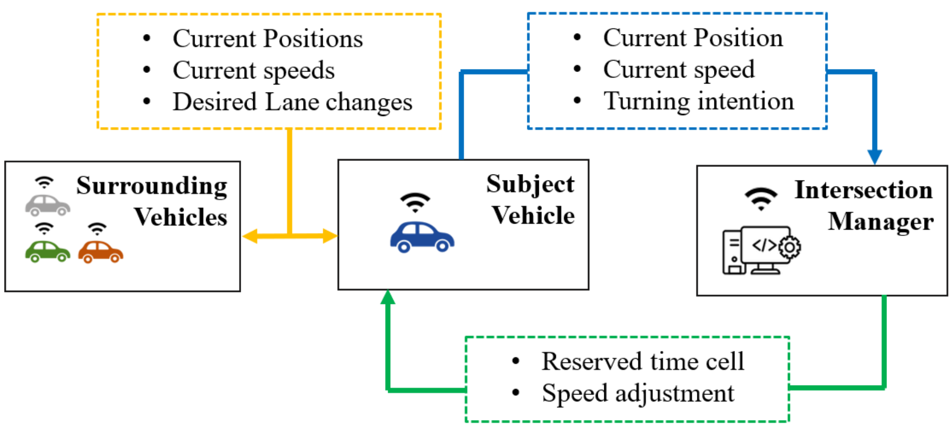


Figure 7 Architecture of the control strategy

Each CFLARIC strategy, where CADLARIC could be considered only one of the CFLARIC realizations, follows an identical set of control principles and regulations for resolving the conflicts within the links and intersections. The following sections describe the assumptions, the terminology, and the control components of CFLARIC, along with the constraints that are considered in the simulation.

3.3.1 Assumptions

The following assumptions are made when developing CFLARIC scenarios:

- Vehicles are fully connected and automated and they can exchange information with each other and with the intersection manager without any communication loss and latency.
- In the case that a vehicle requests to use a sharable road segment (e.g., opposite lane or areas within the intersection box), the decisions are made by a higher-level control logic such as Intersection Manager.
- At any time that the next-step maneuver of a vehicle in the network should be executed, a central control logic calculates appropriate action and transmits decision (approval or postponement of the requests) back to the vehicle.
- Pedestrians and other transportation modes are not part of current CFLARIC scenarios.

3.3.2 Definition of Intersection, Approach, and Lane

For a given urban network Figure 8, let us index intersections and lanes by η and l, respectively, where:

$\eta = 1, \dots, N,$

$l_{i,j}^{\eta}$ is a lane with an ID = j at arm i approaching intersection η,

$i = 1, \ldots, \eta_N$, where η_N is the number of approaches/arms at the investigated intersection,

$j = 1, \ldots, n$, where n is the number of lanes on the investigated intersection η_i and approaching arm i.

The traffic lanes are numbered (lane ID) consecutively from left to right (NS direction) and from top to bottom (EW direction). Therefore, for a vehicle traveling from an upstream to a downstream intersection, the lane ID is constant until the vehicle changes its lane.

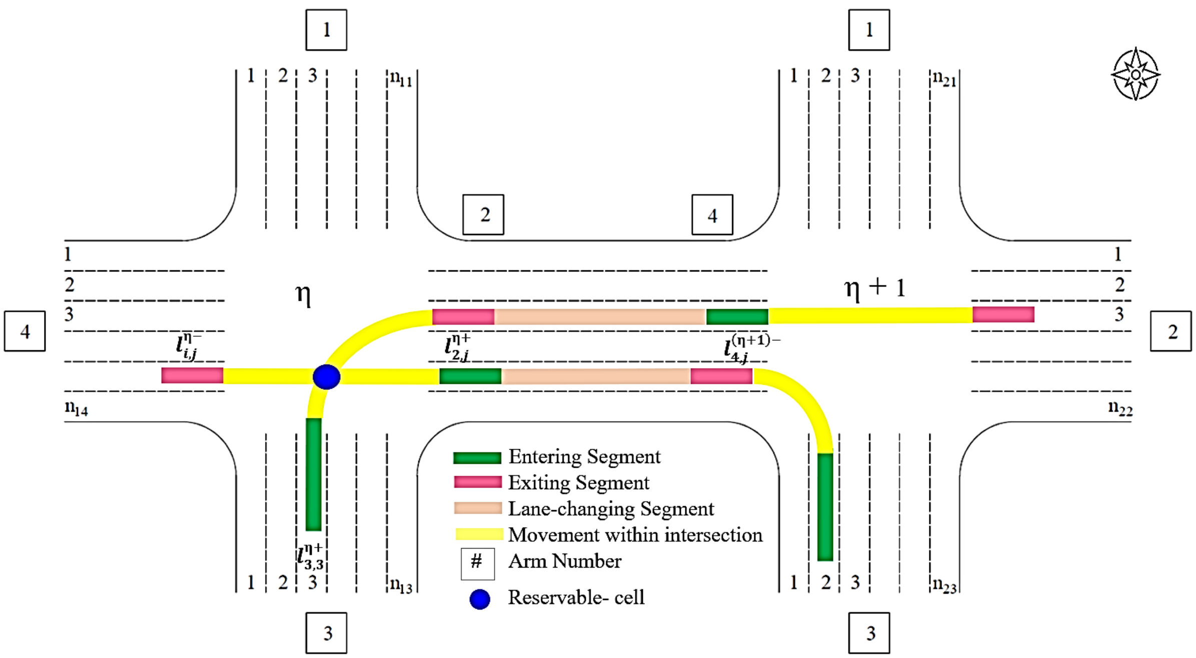


Figure 8 Illustration of different states of a movement between two intersections

To indicate traffic direction of a lane, a binary variable $P_{i,j}^{\eta}$ is introduced where:

$$P_{i,j}^{\eta} = \begin{cases} 1, & \text{if } l_{i,j}^{\eta} \text{ is entering lane} \\ 0, & \text{otherwise} \end{cases} \quad \textbf{(3-1)}$$

Also, to explore whether an approaching lane ($l_{i,j}^{\eta}$) to an intersection η is exclusive or shared a binary variable $\tau_{i,j}^{\eta}$ is defined where:

$$\tau_{i,j}^{\eta} = \begin{cases} 1, & \text{if } l_{i,j}^{\eta} \text{ is shared} \\ 0, & \text{otherwise} \end{cases} \quad \textbf{(3-2)}$$

A concept of a virtual median (VM) that places between any two adjacent lanes with different directions also is introduced. Therefore, for any two adjacent lanes with a virtual median in between:

$$P_{i,j}^{\eta} + P_{i,j+1}^{\eta} = 1 \quad \textbf{(3-3)}$$

For two lanes without a virtual median in between (both operating in the same direction):

$$P_{i,j}^{\eta} + P_{i,j+1}^{\eta} = \begin{cases} 2, & \text{if } l_{i,j}^{\eta} \text{ and } l_{i,j+1}^{\eta} \text{ are entering lanes} \\ 0, & \text{if } l_{i,j}^{\eta} \text{ and } l_{i,j+1}^{\eta} \text{ are exiting lanes} \end{cases} \quad \textbf{(3-4)}$$

As shown in Figure 8, each lane has three main segments. An exiting segment from an upstream intersection (shown by pink), a lane-changing segment (shown by orange), and an entering segment to a downstream intersection (shown by green). Therefore, an exiting segment from the intersection (for example η in Figure 8) leads to an entering segment (of the same lane) of the downstream intersection (for example η+1 in Figure 8). An entering segment is defined as $l_{i_E,j_E}^{\eta_E,P_E}$ and an exiting segment as $l_{i_x,j_x}^{\eta_x,P_x}$ where the signs of P_x and P_E define the directions of the traffic in the segment based on the η_x and η_E. For example, as shown in Figure 8, $l_{4,j}^{(\eta+1)-}$ is the exiting segment of the lane whose entering segment, to intersection η from arm 2, is $l_{2,j}^{(\eta)+}$.

3.3.3 Movement Permission

In the next step, a binary variable $(\delta^{\eta}_{i_e-j_e,i_x-j_x})$ is introduced to explore whether a movement from entering lane $l^{\eta_E, P_E}_{i_E, j_E}$ to an exiting lane $l^{\eta_x, P_x}_{i_x, j_x}$ is allowed:

$$\delta^{\eta}_{i_e-j_e,i_x-j_x} = \begin{cases} 1, & \text{if movement is allowed} \\ 0, & \text{otherwise} \end{cases} \tag{3-5}$$

The introduced flexible lane utilization allows the movement at the intersection from any entering to any exiting lane. The Condition [5] will be allowed only if $P^{\eta}_{i_e,j_e} = 1$ and $P^{\eta}_{i_x,j_x} = 0$. Therefore,

$$\delta^{\eta}_{i_e-j_e,i_x-j_x} = \begin{cases} 1, & \text{if } P^{\eta}_{i_e,j_e} - P^{\eta}_{i_x,j_x} = 1 \\ 0, & \text{otherwise} \end{cases} \tag{3-6}$$

3.3.4 Definition of Permitted Movements

In this step, the turning status (Left-turn, Right-turn, and Through) of permitted movements are defined. The equations are derived based on assumption that all approaches in the network have identical number of lanes (n). Conditions for the Left- turn, Right-turn and Through movement are presented in Equations (3-7) to (3-9), respectively.

$$P^{\eta}_{i_x,j_x} > P^{\eta}_{i_e,j_e} \wedge i_x - i_e \in \{1, (1 - \eta_N)\} \tag{3-7}$$

$$P^{\eta}_{i_x,j_x} > P^{\eta}_{i_e,j_e} \wedge i_x - i_e \in \{-1, (\eta_N - 1)\} \tag{3-8}$$

$$P^{\eta}_{i_x,j_x} > P^{\eta}_{i_e,j_e} \wedge |i_e - i_x| = 2 \wedge j_e = j_x \tag{3-9}$$

3.3.5 Movements' Conflict

After generating the movement permission matrix, it is explored whether two permitted movements (for which δ =1) have a conflict point at the intersection area (colored in yellow in Figure 8). For any movement, there is a single trajectory, $t^{\eta}_{i_e-j_e,i_x-j_x}$, associated with $\delta^{\eta}_{i_e-j_e,i_x-j_x}$. Two movements have a conflict when their trajectories intersect with each other. In a case that there is an intersection point for two trajectories, the corresponding "reservable-cell" at the intersection ($C^{\eta}_{i,j}$) has to be assigned to each one of the trajectories.

$$t^{\eta}_{*i_1\#i} \wedge t^{\eta}_{*j_1\#j} = C^{\eta}_{i,j} \text{, where :} \tag{3-10}$$

$$C^{\eta}_{i,j} = \begin{cases} (\mathrm{x,y}) \text{ of the reserved cell,} & \text{if trajectories are intersect} \\ \emptyset, & \text{otherwise} \end{cases} \tag{3-11}$$

For each movement, a set of reservable cells associated with that movement is computed and assigned. The total number of conflict points at each intersection is considered $\{C_{i,j}\}_{j=1}^{M}$ for $i = 1, \dots, \eta_N$, where $i \neq j$ and M is the number of permissible movements at the intersection.

3.3.6 Time-Space Reservation at Intersections

As mentioned before, in CFALRIC, the entire network is divided into a grid of small space blocks (here called cells) used to identify conflicting areas. Each cell at the intersection is defined by its longitudinal and latitudinal coordinates (x_s, y_s), and a binary variable $\psi_s(t)$ which indicates whether the cell is reserved at a time t or not.

$$\psi_s(\mathrm{t}) = \begin{cases} 1, & \text{if cell s is reserved at time t} \\ 0, & \text{otherwise} \end{cases} \tag{3-12}$$

When a vehicle k approaches the intersection, it should reserve a group of cells, at which there is a possibility for a conflict between vehicle k and vehicles in other movements. Reservation is necessary for a safe travel across the intersection area. It should be mentioned that CFLARIC follows the First Come First Served (FCFS) ordering policy within its reservation process. A vehicle needs to satisfy three conditions to be eligible to reserve its path inside the intersection.

- Vehicle must be within the predefined communication distance (d_{res}) from the intersection.
- Vehicle needs to travel in the desired lane.
- The leading vehicle must have already reserved the path it must use.

For any reservation request at intersection η, the arrival time $\mathrm{t}_{k,s}^{arr}(t)$ and departure time $\mathrm{t}_{k,s}^{dep}(t)$, evaluated at time t, of the subject vehicle (k) located at the space cell s, can be, respectively, computed as:

$$\mathrm{t}_{k,s}^{arr}(t) = \mathrm{t}_{k,\eta}^{arr}(t) + \mathrm{t}_{k,\eta,s}^{trav}(t) \tag{3-13}$$

$$\mathrm{t}_{k,s}^{dep}(t) = \mathrm{t}_{k,s}^{arr}(t) + \tau^{buf} \tag{3-14}$$

where $\mathrm{t}_{k,\eta,s}^{trav}(t)$ is the travel time that vehicle k needs to cross a distance from intersection η to the cell s, evaluated at time *t*, and τ^{buf} is the safety buffer time that is needed for a vehicle to pass and clear the cell.

The arrival of vehicle k to intersection η depends on the scheduled arrival time of the leading vehicle ($\mathrm{t}_{k-1,\eta}^{arr}(t)$), in case a leading vehicle travels in front of vehicle k. If there is no leading vehicle the arrival time of vehicle k to intersection η depends on its current speed $v_k(t)$ and the predefined desired speed $v_{k,\eta}^{int}$. The desired speed of vehicle k when traveling across the intersection depends on its corresponding movement. The arrival of vehicle k to intersection η ($\mathrm{t}_{k,\eta}^{arr}(t)$) is defined as:

$$\mathrm{t}_{k,\eta}^{arr}(t) = \max\left\{\mathrm{t}_{k-1,\eta}^{arr}(t) + h\,, \mathrm{t} + \mathrm{t}_{k}^{acc}(t) + \mathrm{t}_{k}^{con}(t)\right\} \tag{3-15}$$

Where h is the time gap between vehicle k and its leader vehicle, and $\mathrm{t}_{k}^{acc}(t)$ and $\mathrm{t}_{k}^{con}(t)$ are two travel time components that are computed using the kinematic description of motion.

A vehicle can cross an intersection only if it reserves all of the requested cells, which are parts of its path within the intersection. If a vehicle can reserve all of its requested cells, it can be said that the requested path is assigned to that particular vehicle.

$$p_k(\mathrm{t}) = \begin{cases} 1, & \text{if path is assigned to vehicle k} \\ 0, & \text{otherwise} \end{cases} \tag{3-16}$$

Figure 9a) presents a possible lane arrangement scenario in CFLARIC with the corresponding conflicts between movements. Figure 9b) shows the reservation process for three vehicles moving in the NBT (red car), EBR (blue car), and WBT (green car) directions. If any of the cells that a vehicle needs to reserve is not free at the corresponding time (have been already reserved by another vehicle), the vehicle reduces its speed and repeats the reservation process until it can reserve all of the required cells. For example, the red car cannot get the ROW and reserve its requested path, before the green cell on its path, which has been already reserved by the green car, is cleared. It should be noted that cells in Figure 9 are not shown with the real resolution.

For any declined reservation request it is investigated whether the vehicle distance from the intersection is enough to maintain its speed, and repeat the request, or if the vehicle needs to start decelerating to stop in front of the intersection (Stevanovic and Mitrovic, 2018). For this purpose, the available and the required stopping distance for vehicle k are investigated. The binary variable in Equation (3-17) is defined to investigate the condition mentioned above.

$$\omega_k(\mathrm{t}) = \begin{cases} 1, & \text{if } d_{stop,k}(t) \geq \left| x_{\eta,k}(t) - x_k(t) \right| - d_{acc} \\ 0, & \text{otherwise} \end{cases} \tag{3-17}$$

Where $d_{stop,k}(t)$ is defined in a way that considers adequate distance in front of intersection for vehicle k to accelerate (d_{acc}) and reach the minimum speed before entering the intersection.

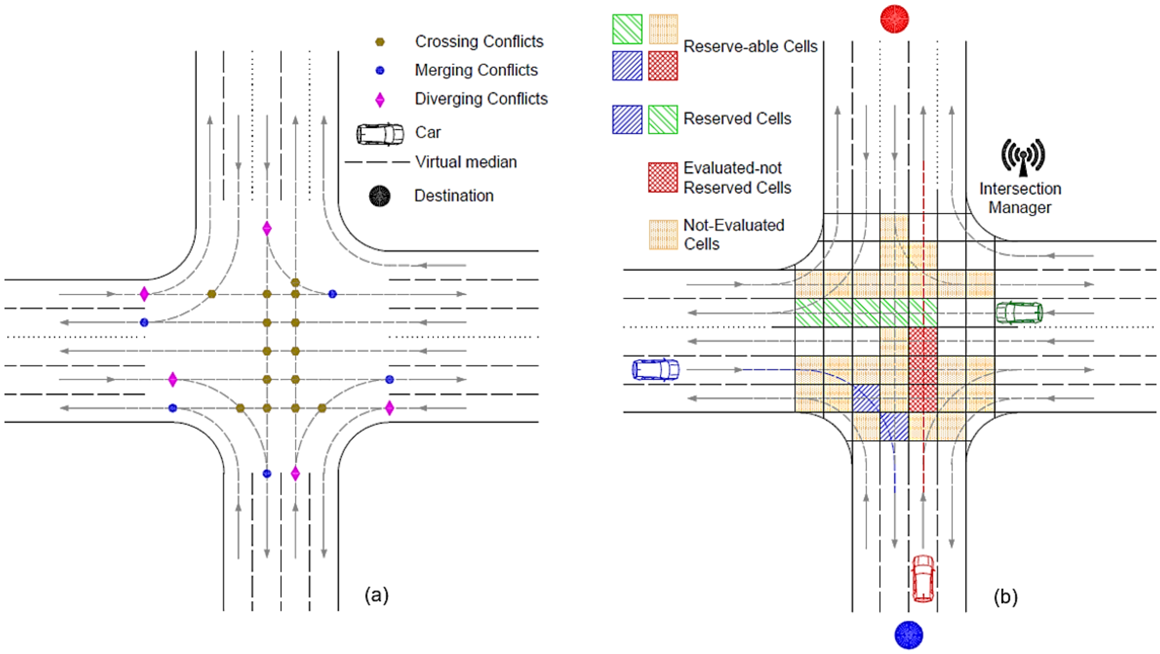


Figure 9 Time-Space reservation procedure in CFLARIC

3.3.7 Lane-Changing Process

In CFLARIC, vehicles are not allowed to change their lanes within the intersection box, and thus they need to align themselves in the desired lane once they exit the intersection. At that point selection of the desired lane depends on the movement a vehicle needs to make at the downstream intersection (based on its destination). Therefore, any vehicle exiting the lane $l_{i,j}^{\eta-}$ has to adjust its position to the most appropriate lane, $l_{i^*,j^*}^{\eta+1}$, that allows such a vehicle to perform the desired turning at the downstream intersection. For a vehicle that does not change its lane the condition in Equation (3-18) will be satisfied.

$$j^* = \mathrm{j} \wedge |i - i^*| = 2 \tag{3-18}$$

For other vehicles the number of lanes that should be changed is $|j^* - j|$ and the total number of crossed lanes during this maneuver is $|j^* - j| - 1$.

The process of lane changing, and resolution of the lane-changing conflicts is (to some extent) similar to resolving the conflicts within the intersection zone. In the fully automated and connected environment, the lane-changing is evaluated for the given position of all (conflicting) vehicles on the links and their intentions. The intention of an investigated vehicle for a lane change is defined by a binary variable $\alpha^{\eta}_{j_e,\, j_x^*}(t)$ which indicates if a vehicle k needs to change its lane at time t or not:

$$\alpha^{\eta}_{j_e,\, j_x^*}(t) = \begin{cases} 1 & \text{if} \quad j^* \neq j \\ 0 & \text{otherwise} \end{cases} \tag{3-19}$$

In a CFLARIC, a vehicle might need to change 1 lane to n -1 consecutive lanes with a single lane-changing maneuver, to get positioned in their desired lane. Also, unlike in the traditional environment where all of the crossed lanes have the same direction (which is a direction of travel of the investigated vehicle) in the proposed control environment, this is not necessarily the case. Therefore, a CFLARIC scenario may include various sequences of lane-changing configurations. Figure 10, for example, indicates two extremely different groups of lane-changing scenarios. In the top part of Figure 10, all lanes between the vehicle's current and desired lanes carry traffic that travels in the opposite direction of the subject vehicle. Each color in this figure indicates a specific lane-changing scenario in which the subject vehicle needs to cross one lane (green) to five (n -1) lanes (navy) to align itself in the desired lane. The bottom part of Figure 10 presents a scenario where traffic, in all lanes between the vehicle's current and desired lanes, travels in the same direction as the subject vehicle.

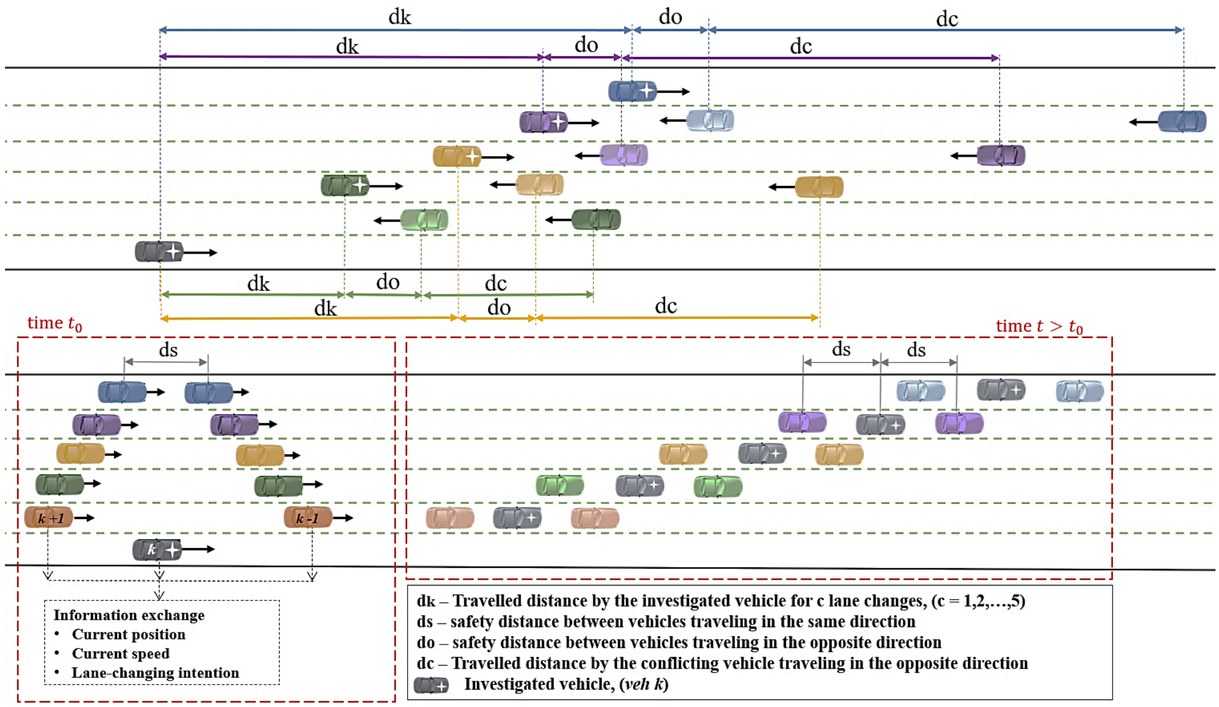


Figure 10 Lane-changing procedure in CFLARIC

Two main constraints are defined to guarantee a safe lane-changing maneuver in this control system. Whether only one or both of these constraints should be fulfilled before a lane-changing maneuver is performed, depends on the specific lane arrangement. First, for any lane-changing condition, where a vehicle needs to cross the opposing lane (lanes) to reach its desired lane, there should be sufficient space between the vehicle that wants to change its lane (k) and the vehicle (vehicles) in the adjacent lane (lanes) (k_o) traveling in the opposite direction.

$$\beta_k(\mathrm{t}) = \begin{cases} 1, & if \left|x_{k_o}(t) - x_k(t)\right| \geq d_{req,k}(t) \\ 0, & \text{otherwise} \end{cases} \tag{3-20}$$

Where $x_k(t)$ is the longitudinal coordinate of the subject vehicle k at time t, and $x_{k_o}(t)$ is the longitudinal coordinate of the vehicle k_o in the adjacent lane.

The minimum required distance that allows a vehicle to safely merge in its desired lane, $d_{req,k}(t)$, is a function of the number of lanes that the vehicle should cross during the maneuver (c), the time required to move to the adjacent lane (τ), and the speeds of the vehicles (v). This distance can be estimated as Equation (3-21), where d_s is the safety distance (headway) between two neighboring vehicles.

$$d_{req,k}(t) = d_s + c \times \tau \times (v_k(t) + v_{k_o}(t)) \tag{3-21}$$

Second, there should be enough space between the given vehicle and the leading or following vehicles, in the desired lane, to allow a vehicle to safely merge in its desired lane.

$$\gamma_k(\mathrm{t}) = \begin{cases} 1, & \text{if} \left\{ \begin{array}{c} \left|x_k(t) - x_{k-1}^{des}(t)\right| \geq ds \\ \wedge \\ \left|x_k(t) - x_{k+1}^{des}(t)\right| \geq ds \\ \wedge \\ v_{k+1}^{des}(t) \leq v_k(t) \leq v_{k-1}^{des}(t) \end{array} \right\} \\ 0, & \text{otherwise} \end{cases} \tag{3-22}$$

Where $x_{k+1}(t)$ and $x_{k-1}(t)$ are the longitudinal coordinates of the leader $(k-1)$ and follower $(k+1)$ vehicles, respectively.

The two lane-changing constraints are necessary for a safe lane-changing maneuver. During the lane-changing process, there should be communication between the subject vehicle k, vehicle $k+1$ (follower), and vehicle $k-1$ (leader). In a situation where the second condition (Equation (3-22)) is not satisfied, vehicles $k-1$ and $k+1$ can adjust their speeds to provide more space for vehicle k to merge to its desired lane safely.

It can be noted that intersection spacing is an important factor in the efficiency of cooperative lane changing. In this study, the distance between intersections is considered long enough so that all vehicles are able to change their lanes (if required) successfully and align themselves in their desired lane before reaching the downstream intersection.

3.4 Implementation Framework

As mentioned in the literature, most of the commercial tools cannot properly simulate flexible bi-directional utilization of the entire road pavement. Therefore, to simulate the proposed control concept, in which every vehicle in the network can utilize any part of the road surface (regardless of its direction, speed, and position) a microsimulation tool called Flexible Arterial Utilization Simulation Modeling (FAUSIM) (Stevanovic and Mitrovic, 2020, 2019) has been developed in NetLogo, an agent-based modeling platform, (Tisue and Wilensky, 2004) through a series of custom-made codes which were written in Scala. The entire network, in the NetLogo platform, is discretized into cells, each of which is 0.7m x 0.7m. To overcome the challenges associated with cell-based models and deploy more advanced car-following models, the discrete space within NetLogo is converted into a continuous one by relaxing some of the vehicle's parameters (e.g., speed, position) to non-integer values (Wilensky, 2015) . In FAUSIM, time intervals are discrete, and each simulation step is 0.2 seconds. The vehicle's desired speed is uniformly distributed around the speed limit (50 km/hr) within 5 km/hr on each side of the limit. However, the desired speed of each vehicle can vary for each random seed that is used to generate traffic inputs. The overall scheme of FAUSIM with corresponding modules is presented in Figure 11. Details of FAUSIM's algorithms are provided in (Stevanovic and Mitrovic, 2019).

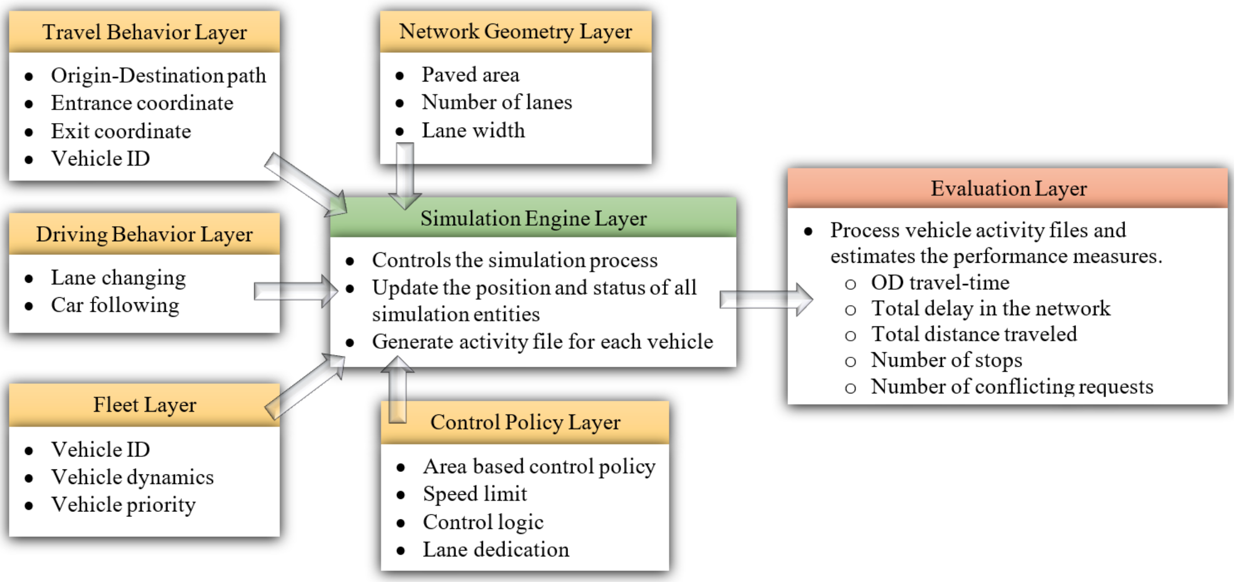


Figure 11 Basic architecture of FAUSIM

3.4.1 Validation of FAUSIM

For the development of any new microsimulation model, validation is a critical step before one can trust its simulation results. For this purpose, CFLARC have been modeled both in the Vissim (PTV Group, 2015) and FAUSIM with fixed-time signals. The vehicular inputs, turning proportions, lane assignments, and the signal timing logic (FTC) are identical in both tools. Figure 12 shows scatterplots and correlation between the delays generated for FTC in FAUSIM and Vissim in OD and Node levels for a generic 3-intersection network (Stevanovic and Mitrovic, 2019). The results show very high degree of similarity between the two simulations.

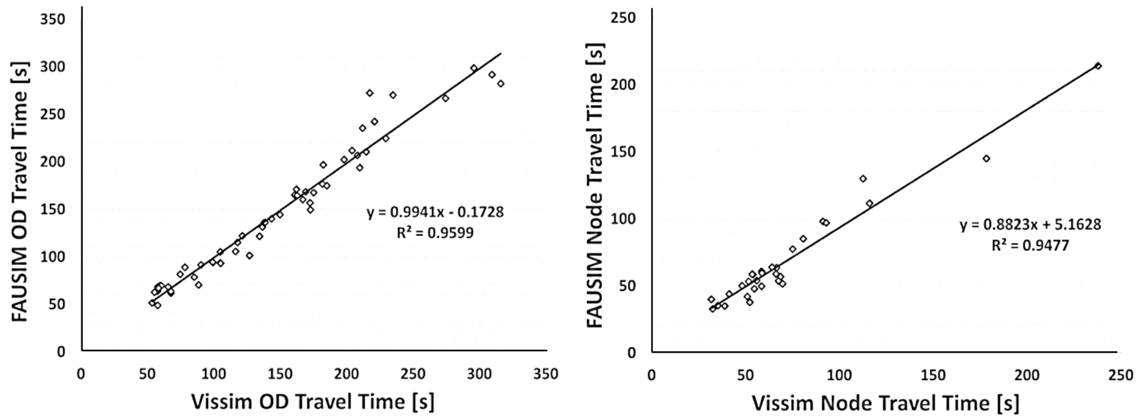


Figure 12 Correletaion between FAUSIM and Vissim for the generic netwrok

Figure 13 illustrates scatterplots and correlation between the OD level travel time and the number of vehicles in Vissim and FAUSIM for a field-like 3-intersection network. As shown in Figure 13, the result from both simulation tools are highly correlated.

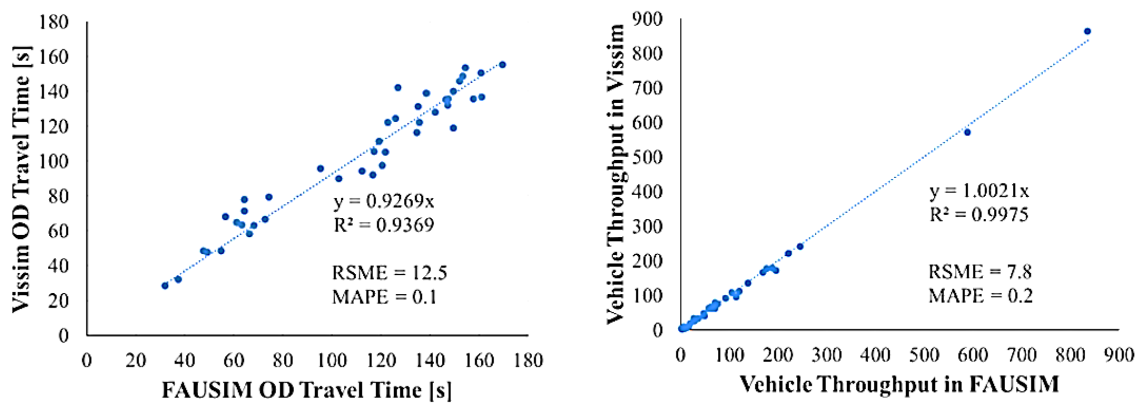


Figure 13 Correletaion between FAUSIM and Vissim for the field-like netwrok

In general, the results of validation represent the similarity of the vehicle interaction models (e.g., car-following, and lane-changing) in both of the simulation tools and for both of the tested networks. Similar results were obtained in the previous study by (Stevanovic and Mitrovic, 2019) for, acceleration/ deceleration vehicle dynamics, and durations of lane-changing maneuvers.

3.5 Performance Metrics for Evaluation Process

Vehicle reports its status that contains multiple attributes at each simulation time step (i.e., 0.2s). Those attributes are static (such as origin and destination) as well as dynamic (such as speed and position). The traditional attributes such as (but not limited to) vehicle lateral and longitudinal position, speed, and acceleration are used to assess the common efficiency-based performance metrics including delay and number of stops. In addition, the non-traditional attributes such as vehicle desire to change the lane and/or reserve the path within the intersection are also recorded on a high temporal resolution and used to evaluate safety-based indicators. This section describes the performance metrics used in this study to evaluate the CFLARIC's performance, including how they are calculated from the vehicle status information.

3.5.1 Efficiency Performance Metrics

In order to evaluate traffic efficiency characteristics of each CFLARIC scenario, total delays and number of stops for all the vehicles in the network were calculated as two of the most commonly used parameters for evaluating the performance of traffic control systems (Dobrota et al., 2022). Delay is an important travel time-based performance measure that is widely used to assess the efficiency of arterial roads. It is also used as an indicator of the Level of Service at intersections (FHWA-HOP-15-033). Number of stops is chosen to evaluate the efficiency of the control system, since it is a well-known measure for arterial congestion level which is not only an indicator of the travelers’ experience (FHWA-HOP-15-033), but also one of the main components to evaluate energy (e.g. fuel) consumption and vehicular emissions (Stevanovic et al., 2009) (Al Shayeb et al., 2021).

3.5.1.1 Travel time and Delay

Let assume that vehicle k, with the desired speed v_k enters the network at time t_o and at node o (origin) and leaves the network at time t_d and at node d (destination). This vehicle k spends in the network $tt_k^{\mathrm{o,d}}$, traveling from node o to node $d,$ where:

$$tt_k^{\mathrm{o,d}} = t_d - t_o \tag{3-23}$$

The total and average travel time of all $(k_{o,d})$ vehicles traveling from given origin node o to the given destination node d are given as:

$$TT_{k_{o,d}}^{\mathrm{o,d}} = \sum_{k=1}^{k_{o,d}} tt_k^{\mathrm{o,d}} \tag{3-24}$$

$$\widehat{TT}^{\mathrm{o,d}} = \frac{TT_{k_{o,d}}^{\mathrm{o,d}}}{k_{o,d}} \tag{3-25}$$

Where $k_{o,d}$ is the total number of vehicles traveling from origin node o to destination node d. Therefore, the average and total travel time of all vehicles in the network with ζ nodes is given as Equations (3-26) and (3-27). It should be noted that $k_{o,d} = 0$ if $o = d$.

$$TT = \sum_{o=1}^{\zeta} \sum_{d=1}^{\zeta} \sum_{k=1}^{k_{o,d}} tt_k^{\mathrm{o,d}} \tag{3-26}$$

$$\widehat{TT} = \frac{TT}{\sum_{o=1}^{\zeta} \sum_{d=1}^{\zeta} k_{o,d}} \tag{3-27}$$

For any given vehicle k , time $tt_k^{\mathrm{o,d}}$ that vehicle spends in the network contains two components: (i) free-flow travel time $ftt_k^{\mathrm{o,d}}$, which is the time that vehicle k would need if travels alone in the (identical) network without signals; and (ii) the delay time $dt_k^{\mathrm{o,d}}$.

To record $ftt_k^{o,d}$ a simulation model was used in which vehicles are neither impacted by other vehicles in the network nor by signals. In such a case, the only reduction in vehicle speed (from desired speed) might be due to associated left/right movements when the vehicle needs to slow to perform safe turning maneuvers. Having the $ftt_k^{o,d}$ and $tt_k^{\mathrm{o,d}}$ for each subject vehicle k , the delay of vehicle k is computed as:

$$dt_k^{\mathrm{o,d}} = ftt_k^{\mathrm{o,d}} - tt_k^{\mathrm{o,d}} \tag{3-28}$$

Total and average delay time for a given OD pair is computed in analogy with Equations (3-26) and (3-27) respectively, by replacing the $tt_k^{\mathrm{o,d}}$ in Equation (3-26) with the delay $dt_k^{\mathrm{o,d}}$. Similarly, average and total delay in the network are computed.

3.5.1.2 Number of Stops

Single stop event (sse) is defined as the event when a vehicle's speed drops and stays for a predefined time interval below the threshold speed (v_t). A single stop event is assigned to vehicle k, traveling from node o to node d, at time t_{st} if:

$$sse_{k,t_{st}}^{\mathrm{o,d}} = \begin{cases} 1 & \text{if } v_{t_{st}-1} \geq v_t \wedge \max\left(v_{t_{st}}, v_{t_{st}+1}, \dots, v_{t_{st}+n_{st}}\right) < v_t \\ \emptyset & \text{otherwise} \end{cases} \tag{3-29}$$

Where for this study $v_t = 5\,mph$ (Stevanovic and Mitrovic, 2018) and $n_{st} = 4$. Therefore, $sse_{k,t_{st}}^{\mathrm{o,d}}$ is equal to 1 if the speed of vehicle k remains below 5mph for 5 consecutive simulation steps (equivalent to 1 sec). The total number of stops made by vehicle k is computed using Equation (3-30).

$$\mathrm{ts}_k^{o,d} = \sum_{t_{st}=t_o}^{t_d} sse_{k,t_{st}}^{\mathrm{o,d}} \tag{3-30}$$

Total and average number of stops for a given OD pair is computed as:

$$TS_{k_{o,d}}^{\mathrm{o,d}} = \sum_{k=1}^{k_{o,d}} ts_k^{\mathrm{o,d}} \tag{3-31}$$

$$\widehat{TS}^{\mathrm{o,d}} = \frac{TS_{k_{o,d}}^{\mathrm{o,d}}}{k_{o,d}} \tag{3-32}$$

In analogy to Equations (3-31) and (3-32), total and average number of stops in the network are given as:

$$TS = \sum_{o=1}^{\zeta} \sum_{d=1}^{\zeta} \sum_{k=1}^{k_{o,d}} ts_k^{\mathrm{o,d}} \tag{3-33}$$

$$\widehat{Ts} = \frac{Ts}{\sum_{o=1}^{\zeta} \sum_{d=1}^{\zeta} k_{o,d}} \tag{3-34}$$

It should be noted that the spatial aggregation of stops, where stops need to be assigned to one of the intersections in the network, can be done by analyzing the destination (d) of vehicle k and the position of the subject vehicle (x_k^{st}, y_k^{st}) at time t_{st} when the stop is recorded, and then mapping this position to a corresponding intersection approach.

3.5.2 Surrogate Safety Performance Metrics

The reported non-traditional attributes for vehicle status allow to run complex safety-related analyses, related to lane changing and intersection crossing conflicts along with the links and at intersections, respectively. It is important to mention that in this study a conflict refers to a "conflicting request" where multiple vehicles request the same time-space block(s) and it does not represent an actual conflict between trajectories (near-miss) of the two vehicles. Therefore, a higher number of conflicts does not necessarily imply an unsafe situation, as in an automated vehicle environment these conflicting requests are handled safely by the resolution algorithms. However, the magnitude of the conflicting requests may have an impact on the efficiency of IM algorithms or how quickly a vehicle will get permission to continue along its intended path.

3.5.2.1 Lane-Changing Conflict

Let's assume that vehicles k_a with the origin o and the destination d travels at time instant t_{ch} in the lane l_{k_a} while its desired lane $l_{k_a}^{\text{des}}$ is different from the current lane. A lane-changing conflict is an event when a vehicle k_a , approaching an intersection in a non-desired lane, needs to change its lane (($\alpha_{j_e, j_x^*}^{\eta,k_a}(t) = 1)$, see Equation (3-19)), however, it is not allowed (by the control mechanism) to change the lane due to the presence of another vehicle (k_b) in one of the lanes (l_{k_b}) that vehicle k_a needs to cross or merge (Equations (3-20) to (3-22)), where $l_{k_a} < l_{k_b} < l_{k_a}^{\text{des}}$ (or $l_{k_a} > l_{k_b} > l_{k_a}^{\text{des}}$). This condition can be explained mathematically as:

$$\alpha_{j_e, j_x^*}^{\eta,k_a}(t_{ch}) = 1 \ \wedge \ \beta_{k_a}(t_{ch}).\gamma_{k_a}(t_{ch}) = 0 \quad \textbf{(3-35)}$$

A single lane changing conflict event ($lcce$) of vehicle k_a traveling from origin node o to destination node d is defined as:

$$lcce_k^{\mathrm{o,d}} = \begin{cases} \{k_a, k_b, l_{k_a}, l_{k_b}\} & \text{if vehicle } k_b \text{ traveling in lane } l_{k_b} \text{prevents} \\ & \text{vehicle } k_a \text{to adjust its position} \\ & \text{before the downstream intersection} \\ \emptyset & \text{otherwise} \end{cases} \quad \textbf{(3-36)}$$

The total number of lane-changing conflicts made by vehicle k ($lCC_k^{o,d}$) is number of unique quadruples $\{k_a, k_b, l_{k_a}, l_{k_b}\}$. The number of lane-changing conflicts associated with a particular OD path can be obtained by summing all lane-changing conflicts of those vehicles ($k_{o,d}$) traveling from origin node o to destination node d as shown in Equation (3-37).

$$LCC_{k_{o,d}}^{o,d} = \sum_{k=1}^{k_{o,d}} lcce_k^{\mathrm{o,d}} \quad \textbf{(3-37)}$$

3.5.2.2 Intersection Crossing Conflict

A crossing conflict at an intersection is when a vehicle wants to reserve a time-space block at an intersection that has already been reserved for another vehicle. Let assume that vehicle k_a (that already position itself in the appropriate lane) wants to reserve the set of cells – $\{c_1, c_2, \dots, c_n\}$ to cross the intersection η. Let also assume that this reservation request cannot be approved because reservable cell c_r (where *1 <= r <= n*) is reserved by vehicle k_b traveling in a conflicting movement. In other words, based on Equation (3-12), $\psi_s(\mathrm{t}) = 1$ for the requested cell and at the requested time. A single cross conflict event (cce) associated with the vehicle k_a is defined as:

$$cce_k^{\mathrm{o,d}} = \begin{cases} \{k_a, k_b, \mathrm{r}, \eta\} & \text{if vehicle } k_b \text{ has already reserved cell } c_r \\ & \text{at intersection } \eta \text{, thereby prevents} \\ & \text{vehicle } k_a \text{ to reserve the path} \\ \emptyset & \text{otherwise} \end{cases} \tag{3-38}$$

The total number of crossing conflicts made by vehicle k ($CC_k^{o,d}$) is number of unique quadruples $\{k_a, k_b, \mathrm{r}, \eta\}$. The number of crossing conflicts associated with a particular OD path is obtained by summing all crossing conflicts of those vehicles ($k_{o,d}$) traveling from origin node o to destination node d as shown in Equation (3-39).

$$CC_{k_{o,d}}^{o,d} = \sum_{k=1}^{k_{o,d}} cce_k^{\mathrm{o,d}} \tag{3-39}$$

It should be mentioned that a maximum of one crossing conflict can be assigned to an investigated vehicle at a single time instant. For reporting and visualization purposes, positions of the vehicle of interest (k_a) and the conflicting vehicle (k_b) are also recorded.

4.0 Chapter 4- Evaluation of CFLARIC in a Field-like Traffic Condition

The presented objective in this chapter is under second-stage review for publication in Transportmetrica A: Transport Science.

Azadi, F., Mitrovic, N., & Stevanovic, A.; Combined Flexible Lane Assignment and Reservation-based Intersection Control in Field-like Traffic Conditions.

4.1 Overview

A concept, called Combined Alternate-Direction Lane Assignment and Reservation-based Intersection Control (CADLARIC), was recently proposed for better management of directionally unrestricted traffic flows in an automated vehicle environment. In CADLARIC, vehicles must position themselves in a proper lane before they reach the downstream intersection, which enables resolution of vehicular conflicts both between intersections and, as traditionally, within the intersection boxes. The proposed concept has shown very promising results but it is quite infrastructurally demanding, requiring six lanes per intersection approach. To overcome this problem, a more robust concept called Combined Flexible Lane Assignment and Reservation-based Intersection Control (CFLARIC) is proposed here, that offers a full spectrum of lane assignment possibilities in combination with the appropriate reservation-based intersection control. CFLARIC does not have any restrictions on required number of lanes per traffic movement and thus it has a higher potential for field-like network geometries. Three distinctive CFLARIC strategies have been tested on a three-intersection corridor in West Valley City, Utah.

The efficiency and safety performance of the proposed CFLARIC scenarios are evaluated through a comparison with Fixed-Time Control (FTC) and Full Reservation-based Intersection Control (FRIC), both with conventional lane assignments. All scenarios are evaluated using the customized simulation platform FAUSIM that allows simulations of the conventional (FTC and FRIC) and unconventional types of traffic control (CFLARIC). The results illustrate that CFLARIC scenarios: (i) outperform FTC and FRIC in terms of the efficiency (delay and number of stops), and (ii) improve overall safety (by reducing number of conflicting situations) when compared to FRIC.

4.2 Introduction

A concept, called Combined Alternate-Direction Lane Assignment and Reservation-based Intersection Control (CADLARIC), was recently proposed by Stevanovic and Mitrovic (2018) for better management of directionally unrestricted traffic flows in an automated vehicle environment. CADLARIC is described in detail in subsection 3.2.

Despite its promising results (Stevanovic and Mitrovic, 2018), one of the limitations of CADLARIC is that it is considered an infrastructurally-demanding concept, because it requires, under an ideal setting, six traffic lanes on each of the intersection approaches. Moreover, CADLARIC has not been envisioned as a lane-sharing system and thus each approach lane is dedicated only for a single particular movement (through, left, or right). This approach impacts CADLARIC's performance in congested traffic conditions (e.g., Level of Service (LOS) E and F), when physical capacity of its single-lane movements is reached (Stevanovic and Mitrovic, 2018).

This chapter addresses this CADLARIC's limitation by implementing Combined Flexible Lane Assignment and Reservation-based Intersection Control (CFLARIC) on a common layout of field conditions. As discussed in subsection 3.3, in CFLARIC, the number and location of the lanes assigned to a certain traffic movement are flexible variables and so are directions of individual lanes. So, the CFLARIC can be considered a more flexible version of CADLARIC, where the latter one could be considered only a special case of the former one. Thus, this chapter aims to investigate how this approach performs, in terms of efficiency and safety, on an urban arterial that has a counterpart in the real world. The road network analyzed in this study is a three-intersection segment of 3500 S in West Valley City, Utah. Unlike with the CADLARIC, where all of the movements at each intersection had a dedicated lane, field conditions often require that some of the movements (for the lack of dedicated lanes) are shared with the others. To address this issue, few alternative scenarios, developed heuristically, are proposed. The decision on how to share the lanes under CFLARIC in the proposed scenarios have been made considering some logical constraints and priorities. Then, the performances of these CFLARIC scenarios were compared with base-case scenarios of Fixed-Time Control (FTC) and Full Reservation-based Intersection Control (FRIC), as defined in previous chapter.

The relevant studies are reviewed in Chapter 2 and the underlying methodology of CFLARIC scenarios is explained in detail in Chapter 3. In the following sections, Experimental Setups describes the study area, the proposed CFLARIC scenarios and the traffic demand scenarios. Results presents a comparison of the proposed scenarios in the field conditions, and under various traffic demands (LOSs). Finally, the concluding remarks are presented.

4.3 Experimental Setup

4.3.1 Study area

This study implements the CFLARIC concept to field-like roadway conditions to show that such concepts which advocate flexible utilization of road infrastructure can bring significant benefits even in existing field conditions (e.g., no extra lanes, like in CADLARIC, are required). The arterial network analyzed for that purpose, shown in Figure 14, is composed of three intersections on 3500 South arterial in West Valley City, Utah. As observable from Figure 14, the arterial has two lanes in each direction and a middle two-way left turn lane (TWLTL), which provides an extra capacity for potential utilization by either direction. The TWLTL presence on arterial roads is a common feature on many corridors in the US. It should be noted that this lane configuration is asymmetrical at some intersections. The original field conditions operate approximately at the congestion level described by LOS C. Origins and destinations of this arterial network are represented as encircled numbers next to each network entrance/exit. Also, Figure 14 shows all of the turning movement flows (in veh/hour). The traffic volumes represent field traffic counts collected at the time when this network was modeled in Vissim in another study (Zlatkovic et al., 2012). It should be mentioned that small access roads, driveways and similar have not been included in the test network of this study. However, future research should add these elements to explore how utilization of the middle two-way left-turn lane impacts experience of the travelers who need to have access to those commercial areas that are accessed by using such small driveways. This can be done by simply adding more origin and destination points to the studied network.

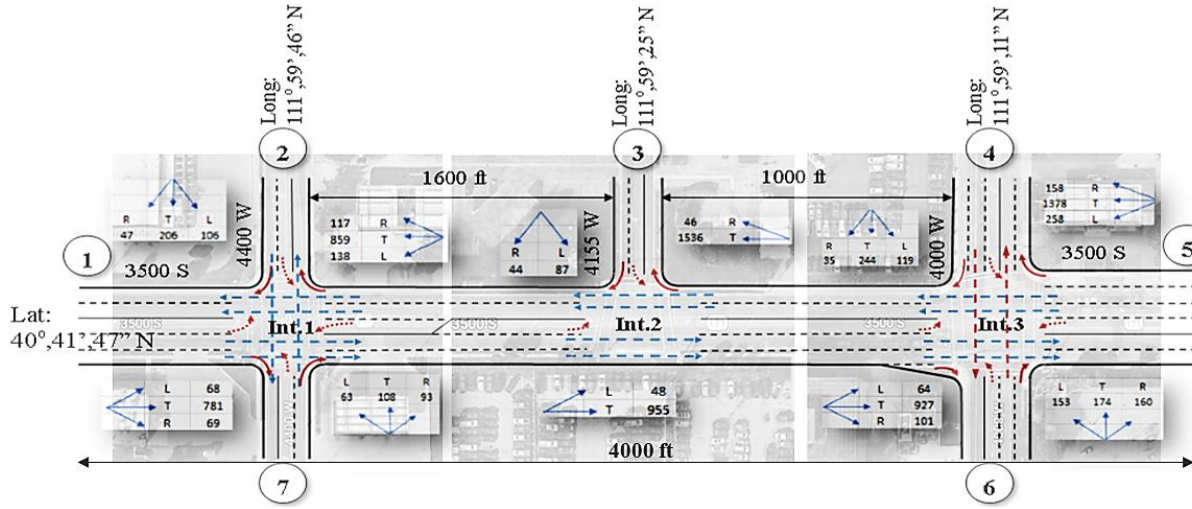


Figure 14 Schematic representation and traffic volumes of the field-like test network

4.3.2 Proposed CFLARIC Scenarios

CFLARIC has the potential to provide a whole spectrum of possible lane assignment scenarios where the number of such scenarios is a function of existing geometry (number of lanes and distance between intersections). FRIC with its conventional lane assignment (with one virtual median on all links) could be considered the most simplistic CFLARIC scenario where all conflicts are controlled, at the intersections, by the reservation-based system. CADLARIC is also a simplified CFLARIC scenario with the five virtual medians in which case the left and right turn traffic does not face any conflicts, while the reservation-based control system handles only conflicts between the through movements. The true potential of CFLARIC lies in its ability to deploy the described control algorithms in any transportation network. The number of virtual medians in CFLARIC on each approach can be any number from 0 to $n-1$ where n is the number of lanes. Therefore, this study proposes only three of many CFLARIC scenarios that are found to be logical for given field-like conditions. In the following sections, the underlying principles of the three chosen CFLARIC scenarios and two base-case scenarios are described. By comparing lane assignments in the proposed CFLARIC scenarios (Figure 15, Figure 16, and Figure 17) one can notice that CFLARIC implies various numbers of virtual medians (VM) in each scenario (shown next to each link). This capability makes this control system flexible enough, in contrast to CADLARIC, to be applied in various infrastructural environments.

It should be mentioned that for the proposed CFLARIC models, as well as for the base-case scenarios, the lane assignment restrictions remain fixed throughout the simulation. However, the logic for conflict resolutions (both for lane changing and intersection-crossing situations) was applied in an online manner during the simulation experiments.

4.3.2.1 Alternating Lanes (AL:2E&3WA)

The alternating lanes scenario (shown in) preserves the main rules of the CADLARIC, by alternating directions of the adjacent lane. Where possible, the leftmost lane is used for all lefts turns, and the rightmost lane is assigned to all right turns, while the through movements are shared between all lanes traveling in relevant directions (initial proportions of through traffic on various lanes can be chosen arbitrarily and then adjusted as needed). In a case when it is not possible to assign an equal number of lanes to movements in both directions (e.g. total number of lanes is odd), more lanes are assigned in the favor of the direction with the highest traffic demand. As shown in Figure 15, three lanes are assigned to WB direction with heavier traffic, while two lanes are given EB direction where traffic is lighter. Under this scenario, some extra conflict points are tolerated in order to investigate the performance of CFLARIC under the field-like geometries and traffic flows.

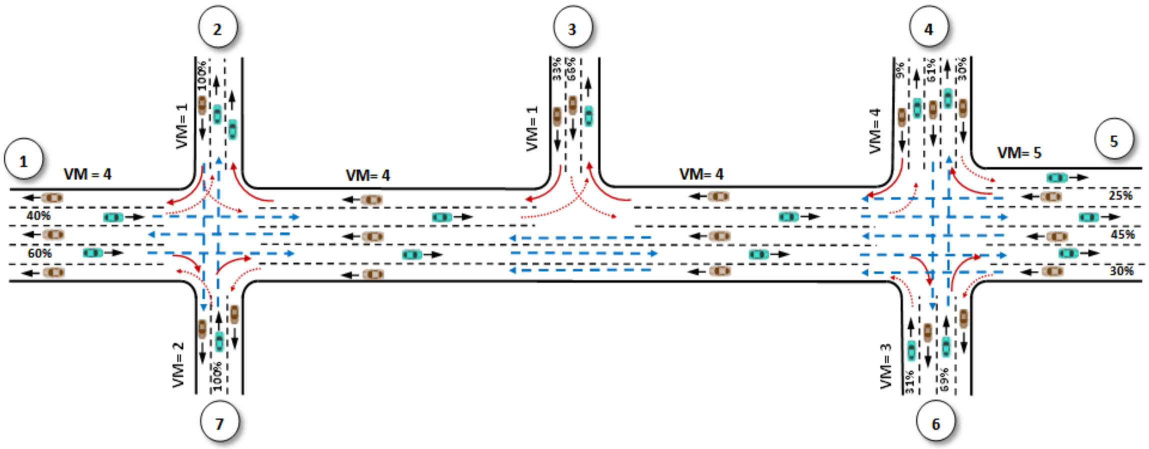


Figure 15 Alternating 2E and 3W Approach (AL:2E&3WA)

4.3.2.2 Minimum Conflicts for Left-Turn Movements (MCLTM)

Under Scenario 2, shown in Figure 16, the objective is to arrange use of traffic lanes in such a way to minimize the conflicts between the left-turn movements and the other traffic movements. To accomplish this, a dedicated lane is given to each of the major-street left turns. Moreover, the relevant lanes on the main street, which receive left-turn traffic from the side roads, are made exclusive, wherever possible and where the side-street conditions are allowed. In the cases when such exclusivity (of the main-street receiving lane for side-street left turns), the main-street lanes were shared with the other incoming movements. The remaining lanes on the main street were distributed for through and shared right-turn movements. By assigning exclusive lanes (usually also inner lanes with smaller radii) to the left-turn movements the authors intended to reduce the number of 'more dangerous' conflict points inside an intersection. This lane assignment could be a good option for intersections with heavy left-turn traffic.

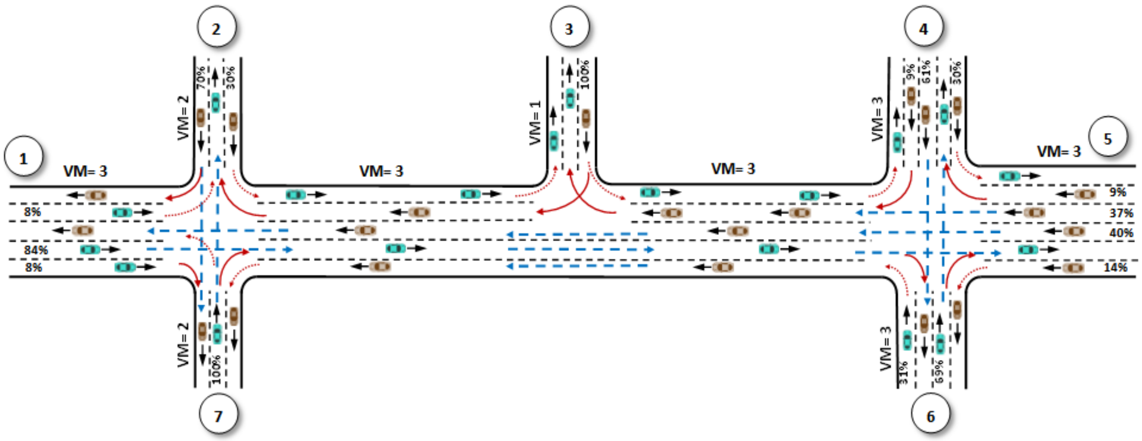


Figure 16 Minimum Conflicts for Left-Turn Movements (MCLTM)

4.3.2.3 Minimum Conflicts for Turning Movements with Higher Volumes (MCTMHV)

The main factor considered in MCTMHV (Figure 17) is the magnitude of traffic volume for each of the turning movements. Traffic lanes have been assigned to various movements in such a way that conflicts of the turning movements with higher traffic volumes are minimized first. For this purpose, volumes of relevant left-turns are compared with their opposite right-turns (e.g., NBR and WBL); whichever turning movement has a higher volume gets a lane with a lower potential for conflicts (smaller radius). This process continues until all turning lanes with the smallest radii are assigned to heavy turning movements. The process is repeated for all intersections in the corridor. As this strategy tries to minimize turning conflicts locally, some adjustments are needed when the same lane is assigned different directions on two ends (near intersection). This lane assignment could be a good option for traffic conditions where left or right turning movements carry high proportions of traffic.

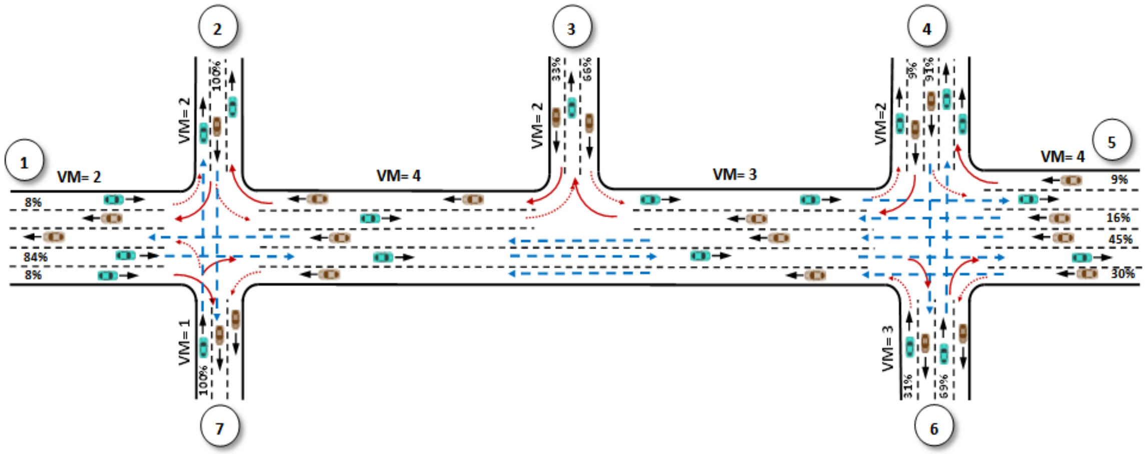


Figure 17 Minimum Conflicts for Turning Movements with Higher Volumes (MCTMHV)

4.3.2.4 Base-case Scenarios

Performances of the proposed CFLARIC scenarios are evaluated in comparison to the two base-case scenarios Fixed-time Control (FTC) and Full Reservation-based Control (FRIC). FTC scenario is implemented (as in the field) with permissive left-turn phasing and right-turn-on-red (RTOR) operations. These features make the FTC scenario more efficient than if all of the movements were fully protected (Mitrovic et al., 2020) . It is important to mention that the signal timings of the FTC scenarios (for all LOSs) were optimized by VISTRO (Vistro, 2014), which ensures near-optimal signal timings for each of the traffic movements/phases.

The Reservation-based control concept developed in this study is called "full" because, unlike CADLARIC/CFLARIC, it does not reserve time slots only for certain movements (e.g. CADLARIC does reservation only for through movements), but for all movements.

The lane arrangements for the two base-case scenarios are the same as for the field conditions. As is shown in Figure 18, both FTC and FRIC have only one virtual median and they maintain the traditional directional restrictions.

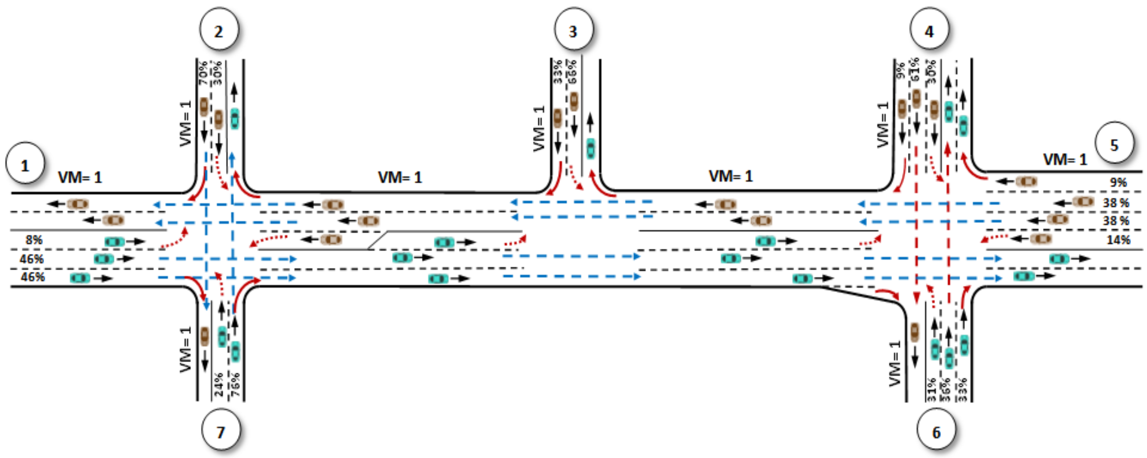


Figure 18 Lane arrangements in the base-case scenario

4.3.3 Traffic Demand Scenarios

To compare the performance of the proposed CFLARIC lane-assignment scenarios, three traffic demand cases are considered for each of the five control regimes (3 CFLARIC, FTC, and FRIC). These traffic demand cases are characterized by various overall LOSs, ranging from LOS B to LOS D. While the traffic volumes for each turning movement are different, the distribution is the same as in the field conditions, shown in Figure 14.

Table 1 shows the traffic volumes of each turning movement for various LOSs for the entire network. For each of the experiments, the traffic demand patterns of various LOS loads were preloaded before each simulation.

Table 1 Traffic volumes for turning movements for LOS B to LOS D

Movements		LOS B			LOS C			LOS D		
		Vol (veh/hr)		LOS	Vol(veh/hr)		LOS	Vol(veh/hr)		LOS
Intersection 4000*	NBL	147	44	B	490	147	D	540	162	D
	NBT		59	C		196	D		216	D
	NBR		44	C		147	D		162	D
	SBL	120	36	B	400	120	C	440	132	D
	SBT		72	C		240	D		264	E
	SBR		12	C		40	D		44	D
	EBL	367	18	B	1015	51	B	1112	56	C
	EBT		312	C		863	D		945	D
	EBR		37	C		101	D		111	D
	WBL	540	81	B	1800	270	C	1980	297	C
	WBT		405	B		1350	C		1485	C
	WBR		54	B		180	B		198	B
LOS for Int.4000		**B**			**C**			**D**		
Intersection 4155*	SBL	131	85	B	131	85	D	143	93	D
	SBR		46	B		46	D		50	D
	EBL	293	15	B	974	49	B	1083	65	B
	EBT		278	B		925	A		1018	A
	WBT	456	433	B	1522	1445	A	1690	1589	B
	WBR		23	B		77	A		101	B
LOS for Int.4155		**B**			**A**			**B**		
Intersection 4400*	NBL	80	20	B	271	68	C	297	74	C
	NBT		32	C		108	D		119	D
	NBR		28	C		95	D		104	D
	SBL	107	32	B	360	108	C	396	119	D
	SBT		59	C		198	E		218	E
	SBR		16	C		54	E		59	E
	EBL	277	21	B	920	69	B	1012	76	B
	EBT		235	B		782	C		860	C
	EBR		21	B		69	C		76	C
	WBL	484	73	B	1495	224	B	1640	246	B
	WBT		363	B		1121	C		1230	C
	WBR		48	B		150	C		164	C
LOS for Int.4400		**B**			**C**			**C**		

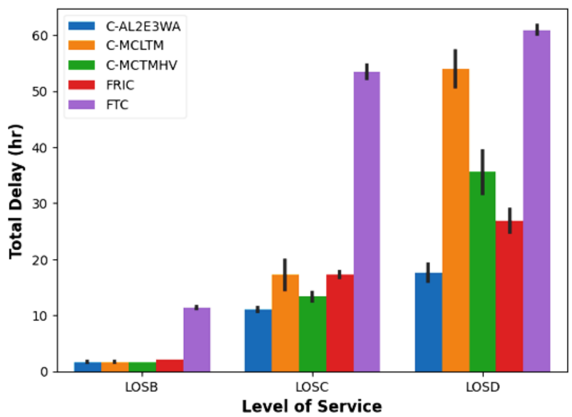
* Location of the intersection is shown in Figure 14.

4.4 Simulation Results

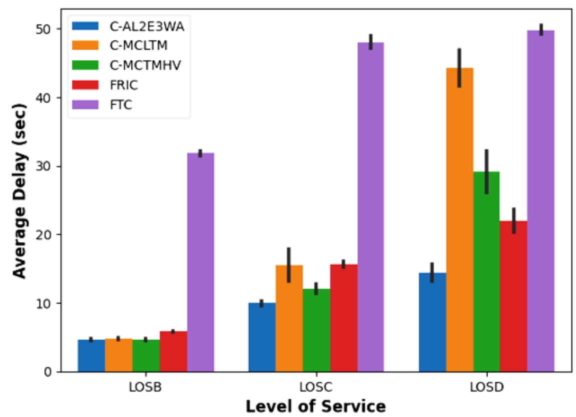
The CFLARIC scenarios are compared with FTC and FRIC traffic control regimes in terms of traffic efficiency and surrogate measures of safety. Simulations for each of the scenarios were performed for 60 minutes, with 5 extra minutes as a warm-up time. Five simulation runs were performed for each scenario using different random seeds to include stochasticity within the microsimulation model. As mentioned before, the qualities of the three proposed CFLARIC scenarios are comparatively assessed with two conventional scenarios (FTC, and FRIC) in terms of four performance measures: delays and number of stops – representing measures of efficiency, and number of intersection lane-changing conflicts – representing potential conflict indicators as surrogate measures of safety.

4.4.1 Network Efficiency Comparison for Various LOSs

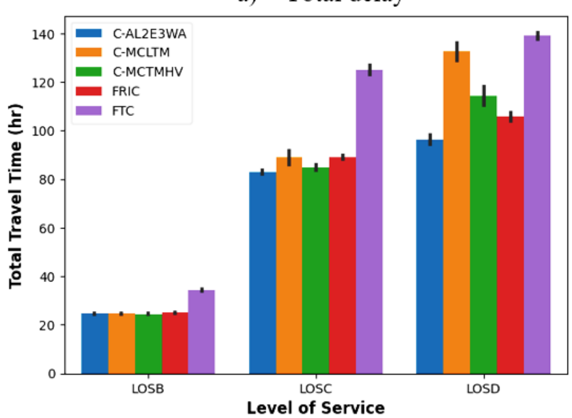
In order to evaluate performance reliability of the various CFLARIC scenarios, they are tested under three LOSs (B to D). The results for average delay (in seconds) and total delay (in hours) are presented in Figure 19. As shown, all three CFLARIC scenarios outperform the FTC scenario in terms of delay. Furthermore, scenario AL:2E&3WA outperforms the FRIC scenario for the same performance measure. However, out of the three CFLARIC scenarios, MCLTM is the worst as it cannot maintain its performance under LOS D, when heavy through traffic creates severe congestion (clearly indicated by high delay and travel time in Figure 19). One can notice that, under LOS B, all unconventional scenarios perform very similarly (CFLARIC scenarios are just slightly better than the FRIC in terms of delay). However, when traffic volumes increase some of the traffic control scenarios perform much better than the others. It seems that out of the three proposed CFLARIC scenarios, AL:2E&3WA is the most reliable as it can maintain the best performance for all LOSs, which leads to average reductions of 30% and 80% in the delay time, when compared to FRIC and FTC, respectively.



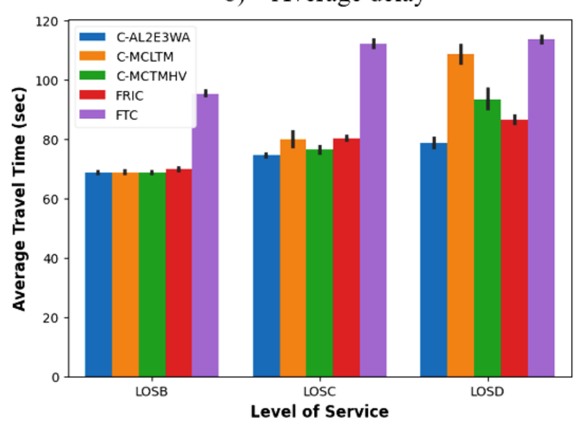
a) Total delay



b) Average delay



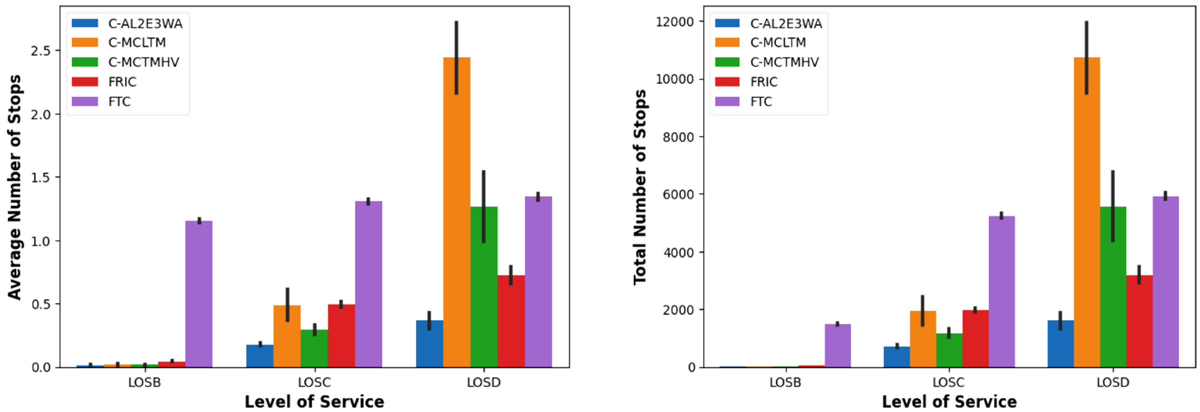
c) Total travel time



d) Average travel time

Figure 19 a) Total delay time, b) Total travel time, c) Average delay time, and d) Average travel time

Figure 20 shows performance of various scenarios in terms of average and total number of stops. Out of the three proposed CFLARIC scenarios, the AL:2E&3WA again performs best as it reduces number of stops by 63% and 86%, when compared to the FRIC and FTC, respectively.

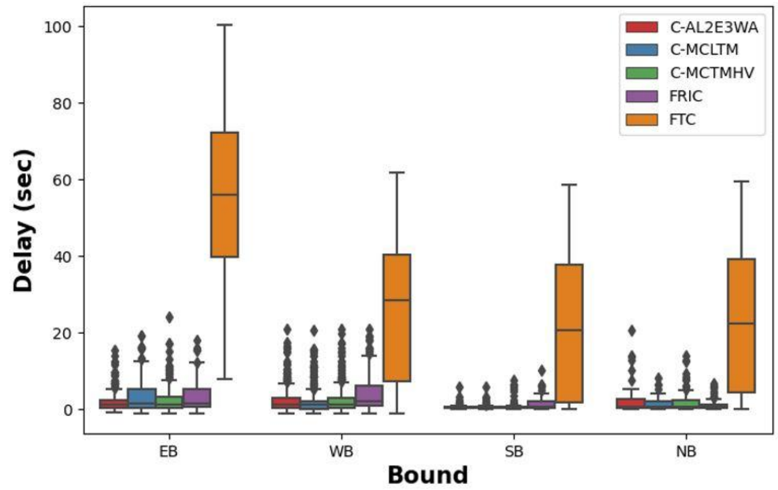


a) Average number of stops b) Total number of stops

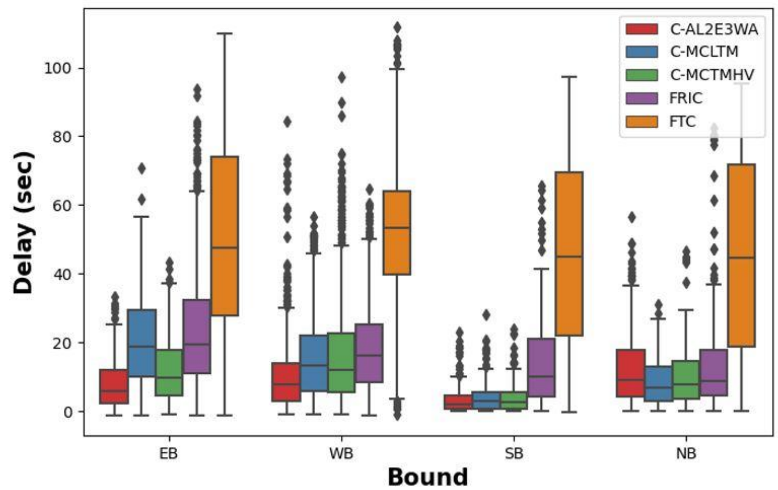
Figure 20 a) Average number of stops, and b) Total number of stops

4.4.2 Comparing Arterial Performance for Various LOSs

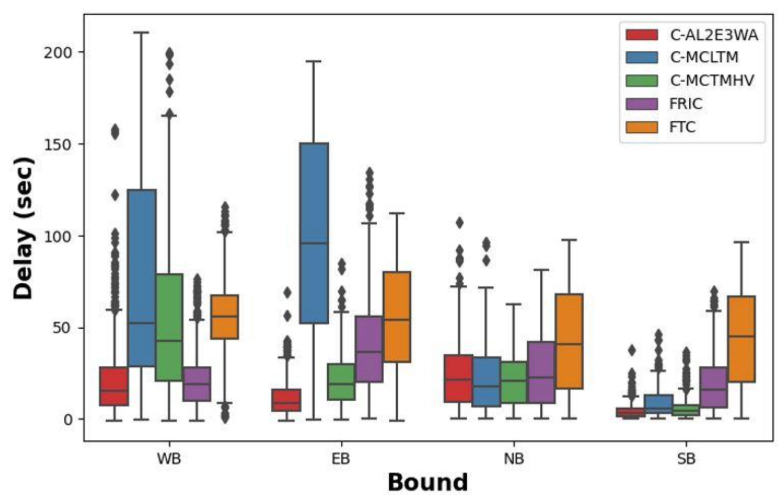
So far, the results have shown that the non-conventional CFLARIC control scenarios outperform the FTC. To take a closer look at the performance of the investigated control strategies they have been compared in terms of delay on the main and side streets. Figure 21 shows boxplots for the delay for each LOS, separately on the main street (EB and WB directions) and the side street at intersection 3 (SB and NB direction). Among the evaluated strategies AL:2E&3WA has the lowest delay for each of the tested LOSs, whereas MCLTM shows the highest variation in delay. The reason for the relatively poor performance of MCLTM could be that left-turn traffic volumes were not high enough to justify this strategy.



a) Delay- LOSB



b) Delay- LOSC



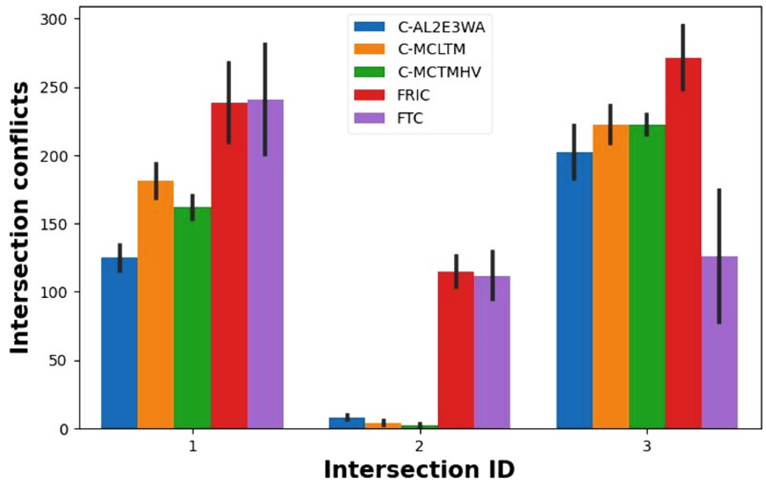
c) Delay- LOSD

Figure 21 Box plots showing variation in delay time under three LOSs

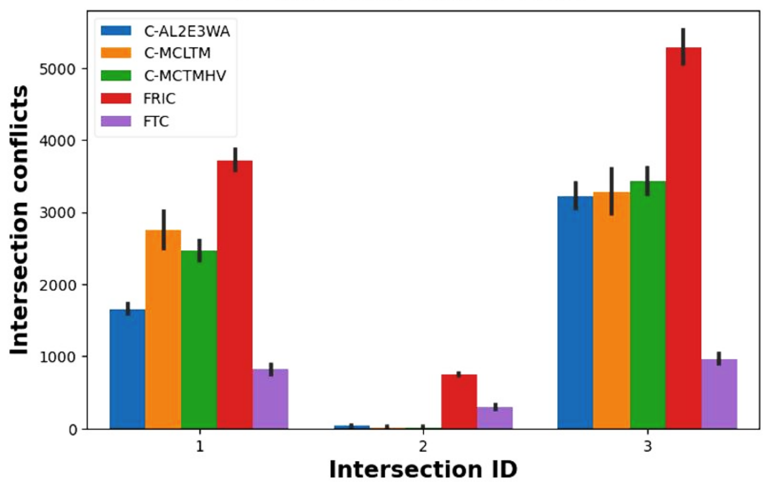
4.4.3 Comparing Conflict Resolution for Various LOSs

Total number of crossing conflicts at intersections and lane-changing conflicts between intersections are presented in Figure 22 and Figure 23, respectively. Figure 22 indicates that the proposed CFLARIC scenarios perform better than the FRIC model in terms of intersection conflicts. However, one can observe that CFLARIC scenarios experience a higher number of lane-changing conflicts compared to the FTC and FRIC models (Figure 23). This outcome is a consequence of the fact that CFLARIC scenarios require many more lane changes to align vehicles in proper lanes before entering the intersections, which in turn reduces number of conflicts inside of the intersection boxes.

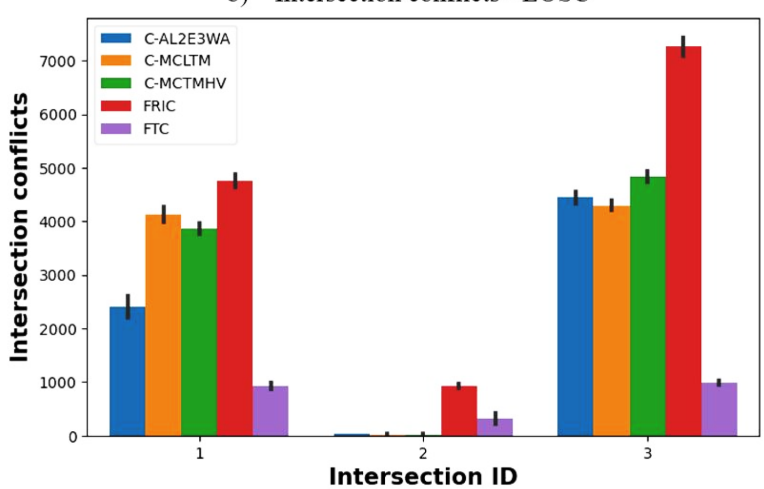
In order to evaluate the overall performance of the investigated traffic control scenarios, when handling resolution of vehicular conflicts, Figure 24 presents combined lane-changing and within-intersection-box conflicts under various LOSs. The results from Figure 24 show that the total number of conflicts is much lower for all of the CFLARIC scenarios than for FRIC.



a) Intersection conflicts - LOSB

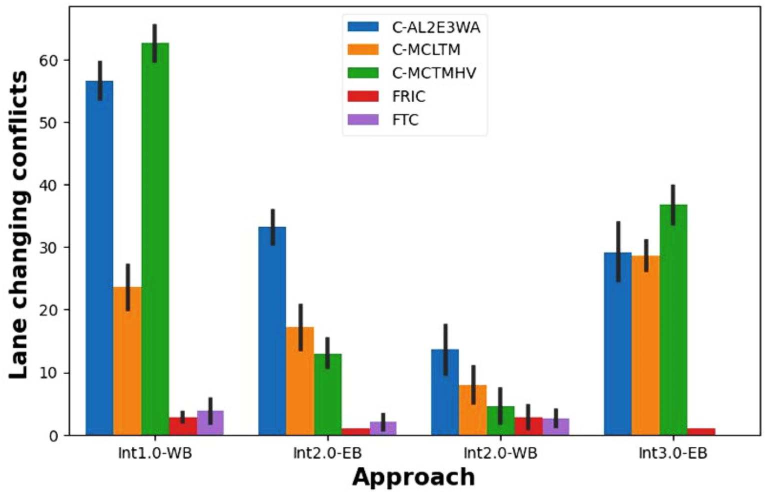


b) Intersection conflicts - LOSC

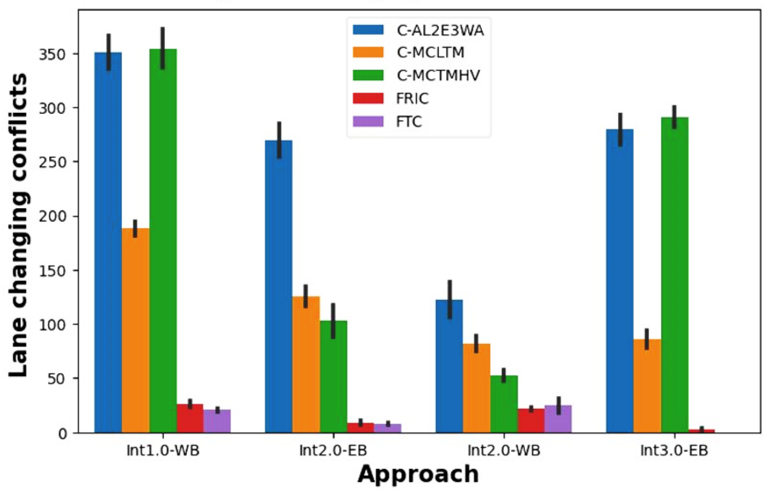


c) Intersection conflicts - LOSD

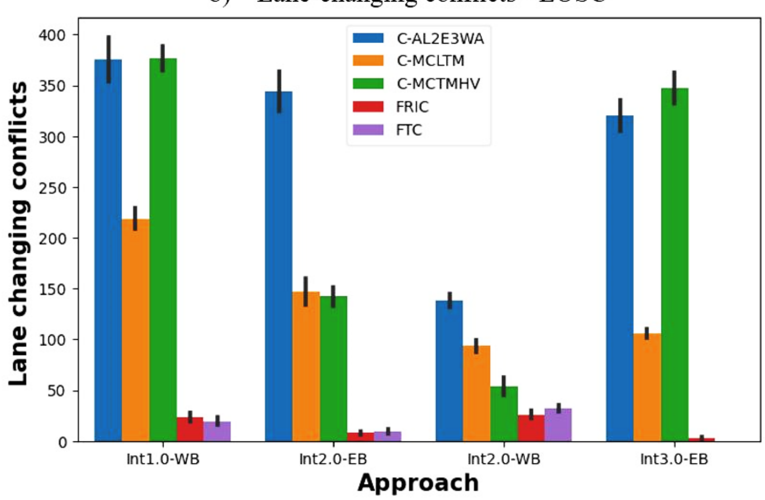
Figure 22 Intersection conflicts under three LOSs



a) Lane-changing conflicts - LOSB



b) Lane-changing conflicts - LOSC



c) Lane-changing conflicts - LOSD

Figure 23 Lane-changing conflicts under three LOSs

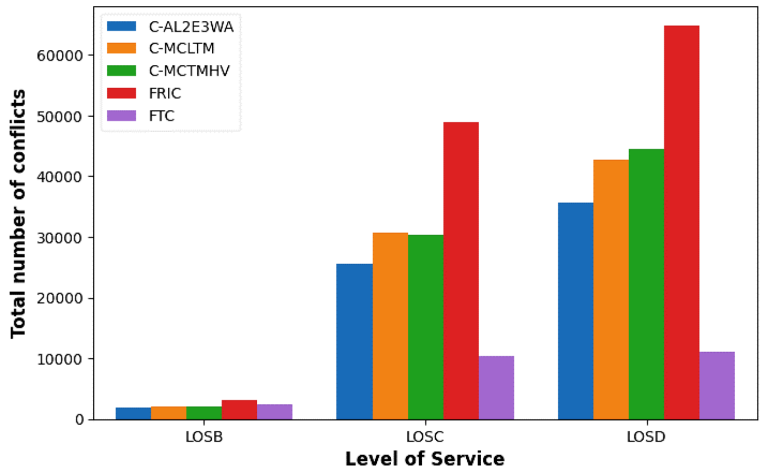
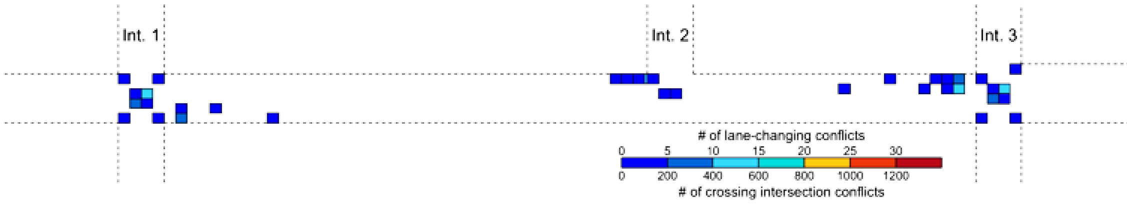
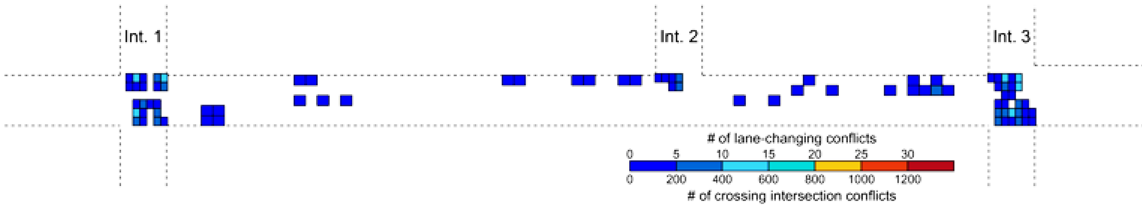


Figure 24 Total number of conflicts for various LOSs

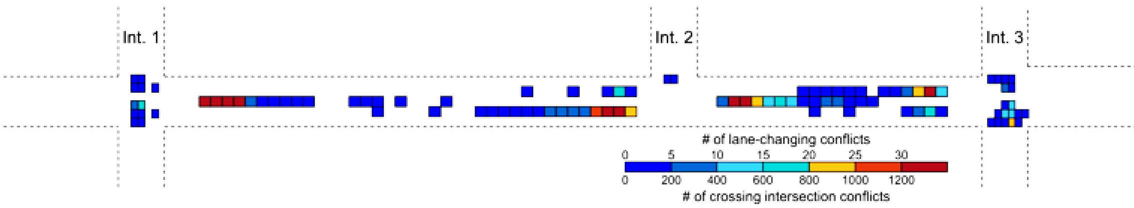
These findings are further detailed in Figure 25, which shows spatial distributions of conflicts in each scenario under the traffic demand conditions as observed in the field (LOS C). One can observe from Figure 25 several interesting findings. For example, FTC has very few intersection conflicts for left-turn and right-turn movements because some of these movements are given only permissive (not fully protected) green times. While the number of intersection conflicts is the highest for FRIC, unlike CADLARIC in previous studies (Mitrovic et al., 2020), the three CFLARIC scenarios also exhibit a certain number of intersection conflicts. This time such conflicts include some left-turning and right-turning conflicts, which is the consequence of the fact that left- and right-turners do not have fully dedicated lanes as in CADLARIC. Finally, one can observe quite distinctive patterns of lane-changing conflicts for CFLARIC scenarios, which testify that those three scenarios have very different between-intersection dynamics, caused by various lane configurations.



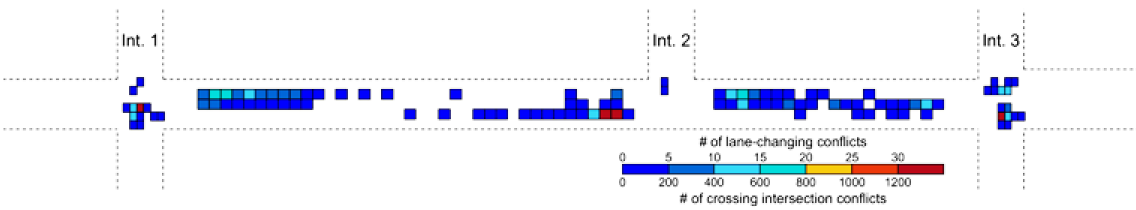
a) Fixed Time Control (FTC)



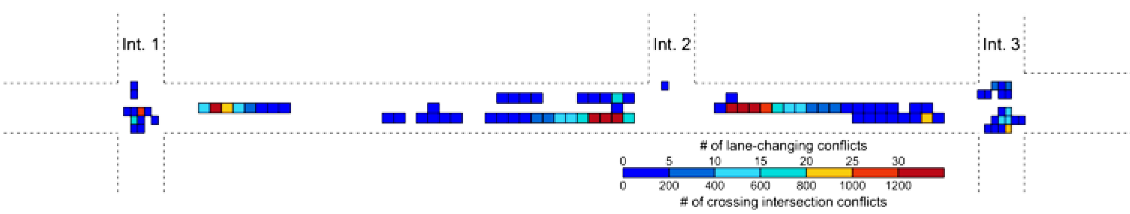
b) Full Reservation-based Intersection Control (FRIC)



c) Alternating Lanes (AL:2E3WA)



d) Minimum Conflicts for Left-Turn Movements (MCLTM)



e) Minimum Conflicts for Turning Movements with Higher Volumes (MCTMHV)

Figure 25 Spatial distribution of conflicts under LOS “C” for various traffic control scenarios

4.5 Conclusions

Motivated by the need to address the everlasting increase in travel demand, support sustainability, preserve existing transport land use, and modify traffic control mechanisms to better utilize opportunities offered by emerging Connected and Autonomous Vehicles (CAVs), a novel control concept for networks with CAVs and autonomous control called Combined Flexible Lane Assignment and Reservation-based Intersection Control (CFLARIC) has been introduced in in this study. The flexibility of CFLARIC increases its potential to be implemented in various geometric conditions.

This chapter presents the result for the deployment of CFLARIC on a three-intersection segment of 3500 S arterial in West Valley City. Three scenarios are proposed for this flexible control framework, (1) AL:2E3WA scenario allocates the lanes in an alternating fashion between two opposing directions, (2) MCLTM scenario is developed to reduce conflicts between the left-turn traffic and the other movements, and (3) MCTMHV reduces conflicts between high-volume turning movements (any) and all other movements. FAUSIM, a microsimulation platform for flexible utilization of roadways, is used to simulate the proposed CFLARIC scenarios. The scenarios are evaluated through a comparison with two well-known control regimes: (1) Fixed-Time Control (FTC), and Full Reservation-based Intersection Control (FRIC) for three LOSs (B to D).

The comparison of performance measures in all scenarios under the field conditions (LOSC) shows that two of the proposed CFLARIC models (AL:2E3WA and MCTMHV) outperform the FTC and FRIC control regimes in terms of delay and number of stops. Although MCLTM does not show promising results in this study, it may prove beneficial under a different traffic distribution (e.g., when traffic demand is higher for the left-turns than for through and right-turn movements). Also, the number of crossing conflicts at intersections is lower for any of the CFLARIC control regimes than for the FRIC. Although the lane-changing conflicts are remarkably higher than in the case of FRIC, the total number of conflicts is still half of the total number of conflicts in FRIC, which is the true (surrogate safety) benefit of CFLARIC. AL:2E&3WA scenario performs the best when compared to the other scenarios and it is always followed by the MCTMHV. The former one decreases delay and number of stops, when compared to FRIC – the best non-CFLARIC control regime, by an average of 30% and 50%, respectively. In general, the findings of this chapter prove that CFLARIC (similarly as CADLARIC did for a hypothetical network (Stevanovic and Mitrovic, 2018)) , can bring significant benefits in terms of efficiency and reduction of vehicular conflicts.

5.0 Chapter 5 - Impact of Shared Lanes on Performance of the CFLARIC

The presented objective in this chapter has been published in the Transportation Research Record as:

Azadi, F., Mitrovic, N., & Stevanovic, A. (2021). Impact of Shared Lanes on Performance of the Combined Flexible Lane Assignment and Reservation-based Intersection Control. Transportation Research Record, 03611981211064274.

5.1 Overview

Benefiting from opportunities offered by Connected and Autonomous Vehicles (CAVs), a concept called Combined Alternate-Direction Lane Assignment and Reservation-based Intersection Control (CADLARIC) was proposed recently for management of directionally unrestricted traffic flows in urban environments. In CADLARIC, resolution of vehicular conflicts is distributed between links and intersections to prevent intersections from turning into traffic bottlenecks. Although CADLARIC has shown promising results, it was observed once a volume on a certain lane reaches 'physical capacity', adding more traffic on that lane degrades performance of the entire system, as each lane is exclusively dedicated to a particular movement. To overcome this problem, the Combined Flexible Lane Assignment and Reservation-based Intersection Control (CFLARIC) system is proposed which offers more flexible lane-assignment possibilities. While the CFLARIC allows left- and right-turning lanes to be shared with through traffic, it is unclear how much of through traffic should be assigned to turning lanes. Thus, this chapter investigates which strategy is the most beneficial when reassigning extra through traffic to the turning lanes. This goal is decomposed into two objectives: 1. Identify which lanes should be shared, and 2. Find a close-to-optimal amount of through traffic that should be assigned to the identified shared lane. The proposed CFLARIC strategies are compared with Fixed-Time Control (FTC), Full Reservation-based Intersection Control (FRIC), and CADLARIC for multiple demand scenarios. The results show that the best performing CFLARIC strategies outperform FTC, FRIC, and CADLARIC in terms of delay and number of stops and reduce number of conflicting situations compared to FRIC and CADLARIC.

5.2 Introduction

In the current transportation networks, intersections are often considered physical bottlenecks where half of traffic fatalities and injuries occur (FHWA,2020). Therefore, it is imperative to advance intersection control mechanisms to better manage traffic flows. The latest advancements in Information Technology (IT) sector and the automotive industry have motivated researchers to develop innovative approaches to the traffic control problem (Hamilton et al., 2013). Autonomous Intersection Management (AIM) systems are innovative traffic control mechanisms which are responsible to coordinate movements of individual vehicles for collision-free passage through intersections. However, even in an advanced control system as Reservation-based Intersection Control the core remains the need to resolve traffic conflicts (only) at urban intersections. To this end, Stevanovic and Mitrovic (2018) proposed a novel framework called Combined Alternate-Direction Lane Assignment and Reservation-based Intersection Control (CADLARIC) which models directionally unrestricted traffic flows in a fully connected and automated vehicle environment. As explained in section 3.2, in CADLARIC each approach lane is dedicated only to a particular movement (through, left, or right). Such an approach negatively impacts CADLARIC's performance in (over) saturated traffic conditions (i.e., Level of Service (LOS) E and F), when the physical capacities of its single-lane movements are reached (Stevanovic and Mitrovic, 2018). To address this limitation of CADLARIC, the proposed control framework in this study, Combined Flexible Lane Assignment and Reservation-based Intersection Control (CFLARIC), which could be considered as an extension of CADLARIC, releases some of the constraints on lane-assignment schema and thus has the potential to enhance the overall performance in congested traffic environments.

This chapter evaluates the performance of CFLARIC, in terms of delay, number of stops, and potential-conflict indicators, in near- to over-saturated traffic conditions, when certain traffic movements are so congested that sharing lanes with other movements is the only solution to maintain capacity of the intersection. Thus, the objective is to explore various scenarios under such saturated regimes of CFLARIC operations, in order to find out which lanes should be shared, and what is the close-to-optimal amount of traffic that needs to be assigned to the shared lanes. For this purpose, three CFLARIC models are proposed, in which the excess through traffic is being shared either with right, left, or both turning movements, in various proportions. Then, the best performing CFLARIC scenarios are compared with base-case scenarios of Fixed-Time Control (FTC), Full Reservation-based Intersection Control (FRIC), and Combined Alternate-Direction Lane Assignment and Reservation-based Intersection Control (CADLARIC). The road network analyzed in this chapter is a generic three-intersection segment in which traffic moves in an alternate fashion.

The chapter is structured as follows. First the underlying methodology of the proposed lane assignment approach is briefly described. The following section discusses the experimental setup, including the study area, the proposed scenarios, and the traffic demand scenarios. The results section presents a comparison of the proposed scenarios under two various traffic demands (Level of Services). Finally, the concluding remarks are discussed. It should be mentioned that the relevant studies are reviewed earlier in Chapter 2 and the underlying methodology of CFLARIC scenarios is explained in detail in Chapter 3.

5.3 Proposed Lane Assignment Approach

Fixed-Time Control (FTC) system with a conventional lane assignment, the least flexible control system, handles all vehicular conflicts using traffic signals within the intersection box while there are no intersection-based conflicts among the vehicles traveling in the same direction (Urbanik et al., 2015). The reservation-based system (Dresner and Stone, 2004) brings more flexibility by adding an “intersection manager”, that handles the conflicts through a reservation process for traditional lane assignment schemas. Further flexibility might be obtained by introducing various lane assignment schemas into RIC. The Combined Alternate-Direction Lane Assignment and Reservation-based Intersection Control concept (CADLARIC) proposed by (Stevanovic and Mitrovic, 2018) tends to reduce the number of intersection conflict points at the cost of introducing the need for solving conflicts at the link. CADLARIC is limited to one lane assignment schema that excludes the option of having shared lanes (Details are explained in section 3.2). In the following, various lane assignment schemas in a fully connected and automated system are explored where every single user/agent must possess relevant information about neighboring agents (and their intentions) and communicate with infrastructure. In such an environment, a vehicle may use any part of the road, as long as it is not endangering other users.

Figure 26 presents two of many possible traffic control scenarios for such a futuristic traffic control environment. At the left intersection, a CADLARIC system (previously introduced by Stevanovic and Mitrovic (2018) is shown, where vehicles can use lanes that are traditionally reserved for the opposite direction of travel. In this approach, movements are assigned to dedicated lanes in an alternate fashion. All vehicles need to align themselves in appropriate lanes before reaching the downstream intersection. Therefore, by the time vehicles reach downstream intersection, they can make a smooth turn (left or right) without facing any conflicts with vehicles from the other movements. However, as mentioned before, it was observed that such a system (of fully dedicated movement lanes) cannot perform well under high traffic demands (e.g., LOSs E and F) when physical capacity of its single-lane movements (e.g., through movement) is reached.

Now, consider that in a fully connected and automated traffic environment the traffic control rules could be flexible enough to allow a certain traffic movement (in this case (Figure 26) the EB through movement) to take any of the lanes carrying traffic in the same direction, some of which also carry turning movement (left or right) traffic. The right intersection in Figure 26 shows such conditions where EB through vehicles can: 1) continue to move in the exclusive through lane (blue car), 2) join a lane on right that carries right-turn traffic (red car), or 3) join a lane on left that carries left-turning traffic (green car). Obviously, depending on the path that a vehicle takes, it would face conflicts (both for lane-changing and within-intersection maneuvers) with other vehicles which would differ in number, type, and location of conflicts, as indicated in a table shown within Figure 26.

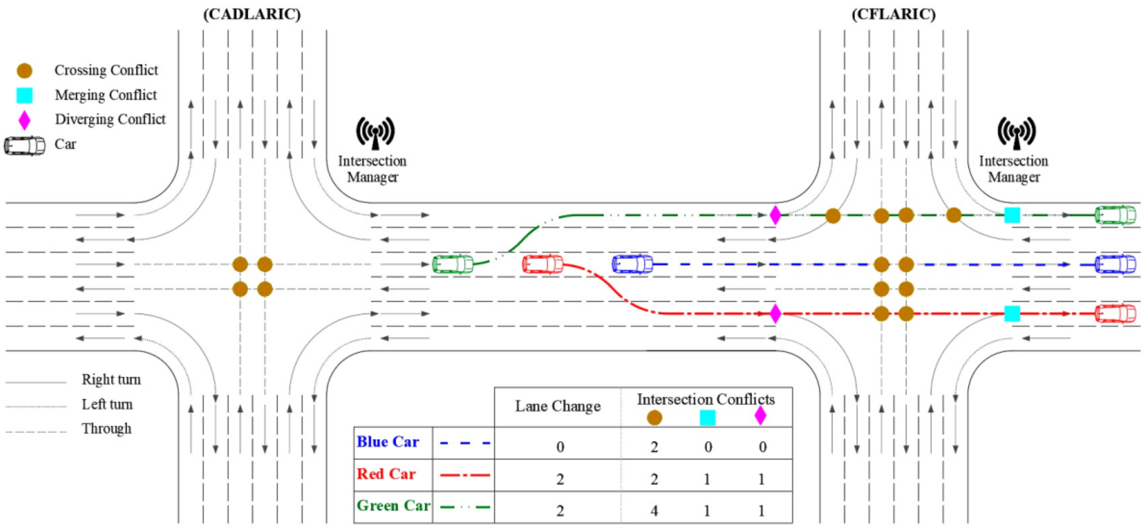


Figure 26 Potential lane assignments with CAVs

5.4 Experimental Setup

5.4.1 Test Network

This chapter evaluates sharing capabilities of the CFLARIC to show that such concepts can bring significant benefits in congested traffic conditions (e.g., LOS E and F). All experiments are performed on a generic 3-intersection network (similar to the network used previously by Stevanovic and Mitrovic (2018)). As observable from Figure 27, the arterial has six lanes in each approach, which can be arranged as three lanes in each direction, if a conventional traffic management method is utilized. The length of the corridor is 560 meters where the distance between each pair of intersections is 200 meters. Origins and destinations of this arterial network are represented by encircled numbers next to each network entrance/exit in Figure 27; which also shows all of the turning proportions of the main (East-West) and side (North-South) streets.

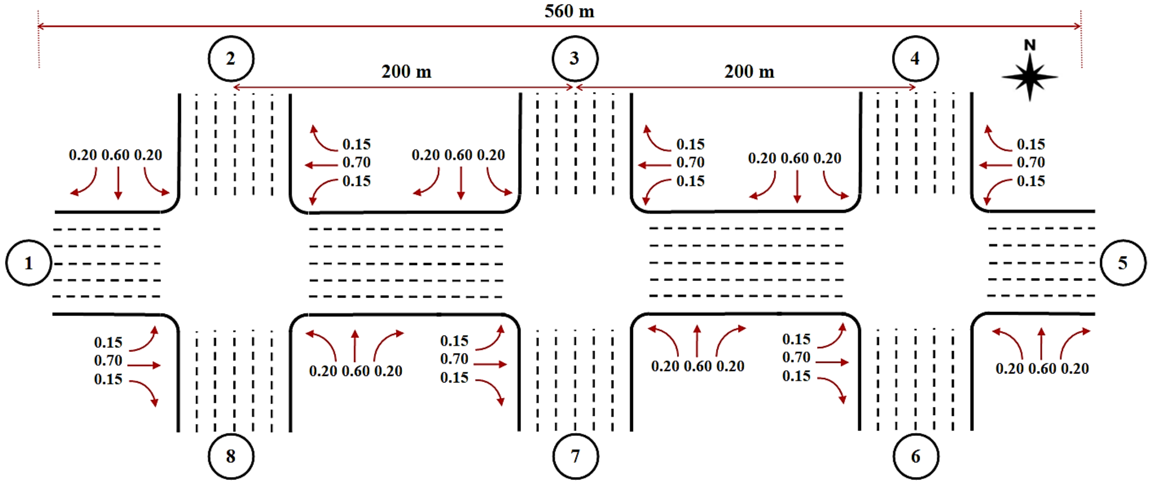
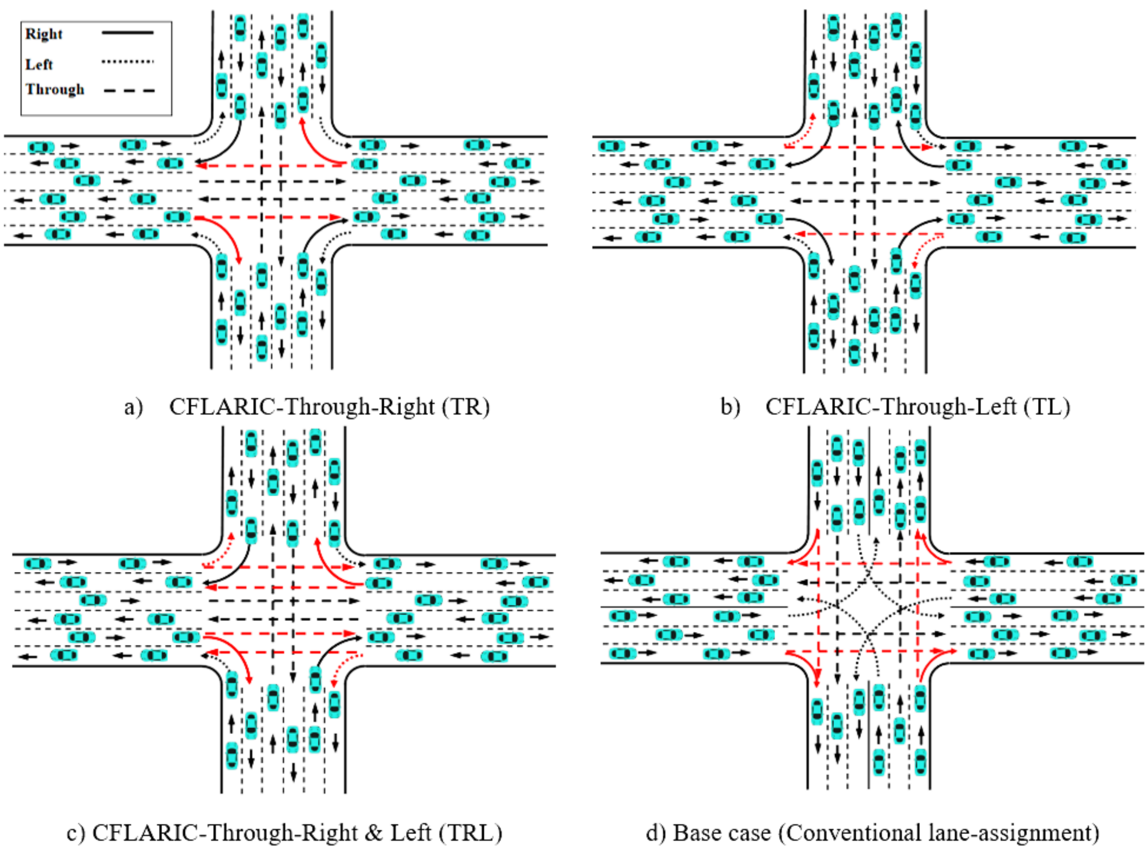


Figure 27 Geometric and traffic distribution of the test network

5.4.2 Proposed CFLARIC Scenarios

CFLARIC can assign lanes, between any two intersections, very flexibly between various turning movements, where the number of such movement assignment scenarios is a function of the road geometry (number of lanes and distance between intersections). Thus, although many CFLARIC scenarios could be developed for testing in this study, here only three such CFLARIC scenarios are investigated. This approach is well aligned with the objective to optimally share excess through traffic between right and left lanes (where 'excess' traffic means volume that exceeds capacity of the through lane).

Figure 28, parts a) to c) present the lane assignments in the three investigated CFLARIC scenarios. The proposed scenarios somewhat preserve the main rules of the CADLARIC, by alternating directions of the adjacent lanes, where the leftmost lane is used for all lefts turns, and the rightmost lane is assigned to all right turns. However, as Figure 28 indicates, the EB and WB through traffic is either shared with one of the turning movements (the right turn in Figure 28a, and the left turn in Figure 28b) or being split between both sharing lanes (Figure 28c). One can notice that the through traffic moving in the shared lanes faces various numbers of conflicts, depending on the movement with which it shares the lane. For example, while the vehicles in the shared right-through-lane face one diverging, two crossing, and one merging conflicts, the through traffic in left-through-lane faces one diverging, four crossing, and one merging conflicts. Obviously, this makes, as it will be shown later, right-through shared lanes much more favorable choices for assigning excess through traffic from the middle (dedicated) through lanes. It should be noted that the lane assignments presented in Figure 28 is applied to each intersection in the network.



a) CFLARIC-Through-Right (TR)

b) CFLARIC-Through-Left (TL)

c) CFLARIC-Through-Right & Left (TRL)

d) Base case (Conventional lane-assignment)

Figure 28 Proposed CFLARIC models for exploring the best sharing scenario

5.4.3 Base-Case Scenarios

Performances of the three proposed CFLARIC scenarios are evaluated in comparison with the three base-case scenarios: FTC, FRIC, and CADLARIC. The lanes in FTC and FRIC are assigned conventionally, with three lanes in each direction (Figure 28d) from which the most-right lane (in each direction) is shared between through and right turning movements. However, CADLARIC, as shown in the left intersection of Figure 26, assigns various turning flows to different lanes in an alternate fashion, in a way that left and right traffic movements go through an intersection without any conflicts and potential conflicts are reduced only to those between through vehicles. The signal timings of the FTC scenarios were optimized, for the given traffic demands/LOSs, by VISTRO (Vistro, 2014). It is important to mention that in the FTC system, not all the conflicts that are shown in Figure 28d can occur at the same time (unlike CFLARIC scenarios) as in this control system conflicts are controlled by using alternating phases of the traffic signals.

5.4.4 Traffic Demand Scenarios

To find the most efficient sharing proportions, as well as the best lane-sharing assignment, various percentages of the through traffic were shared with one or both turning-movement lanes of the main street. For this purpose, in each of the three proposed CFLARIC models (are called TR (through-right), TL (through-left), and TRL (through- left & right)) the excess through traffic (see Table 1) has been assigned in the following six proportions (15%, 25%, 30%, 40%, 50%, and 60%) leading to a total of 18 different CFLARIC scenarios. Each of these scenarios was tested under two traffic demands representing levels of services (LOS) E and F (under which CADLARIC cannot perform well due to physical capacity of a single lane (Mitrovic et al., 2020).

Table 2 shows the traffic volumes for each turning movement of the main and side streets for each LOS. It should be mentioned that the traffic volumes in Table 2 represent the congestion levels described by LOSs E and F for corresponding optimal fixed-time signal timings.

Table 2 Traffic volumes for turning movements for LOSs E and F

Street	Traffic volume (veh/hr)		Traffic distribution	
	LOS E	LOS F	Movement	Percentage
Main	1300	1450	Right	15%
			Through	70%
			Left	15%
Side	900	1050	Right	20%
			Through	60%
			Left	20%

The proportions of the main street excess through traffic volume that is shared with one or both turning lanes is presented in Table 3 for each scenario.

Table 3 Proposed CFLARIC scenarios

Scenario	% of through traffic shared with the left turn	% of through traffic shared with the right turn	Total shared percentage	Shared through traffic volume (veh/hr)	
				LOSE	LOSF
15%T-L	15	0			
15%T-R	0	15	15	136	152
15%T-R&L	7.5	7.5			
25%T-L	25	0			
25%T-R	0	25	25	228	254
25%T-R&L	12.5	12.5			
30%T-L	30	0			
30%T-R	0	30	30	273	304
30% T-R&L	15	15			
40%T-L	40	0			
40%T-R	0	40	40	364	406
40% T-R&L	20	20			
50%T-L	50	0			
50%T-R	0	50	50	455	507
50% T-R&L	25	25			
60%T-L	60	0			
60%T-R	0	60	60	546	630
60% T-R&L	30	30			

5.5 Simulation Results

The CFLARIC scenarios are evaluated in two steps. First, they are compared with each other, and then the best performing scenario (for each LOSs) is compared with FTC, FRIC, and CADLARIC traffic control regimes. As explained before (subchapter 3.5), the qualities of the proposed CFLARIC scenarios are comparatively assessed in terms of four performance measures:

delays and number of stops –representing measures of efficiency, and number of intersection and lane-changing conflicts – representing potential conflicting situations. Simulations for each of the scenarios were performed for a duration of 60 minutes, with 5 extra minutes of a warm-up time. To include the stochasticity within the microsimulation model, five simulation runs were performed with different random seeds. For every single vehicle in the network, a heterogeneous set of information contains (but is not limited to) vehicle position and speed, vehicle intention to change the lane, vehicle desire to accelerate, IDs of the leader and conflicting vehicles have been recorded with a 0.2-second sampling interval period during the simulation.

5.5.1 Network Efficiency

A comparison of the delays from all proposed CFLARIC scenarios is presented in Figure 29, from which one can observe that:

- The best delay performances are achieved, under LOS E and LOS F respectively, when 30% and 40% of excess through traffic is shared with the right turn lane (represented by blue full and dashed line, respectively).
- For each of the three proposed CFLARIC scenarios (TR, TL, and TRL), the best (close-to-optimal) (in terms of delay) shared percentage of through traffic is somewhere between 25% and 30% for LOS E, whereas this percentage falls somewhere between 30% and 40% for LOS F.
- Sharing through traffic with the right turning lane is the best choice when the shared proportion of the through traffic is 50% or less.

- When the shared proportions of through traffic are higher than 50%, it is not best to share the through traffic only with the right-turn approach, but the traffic should be shared with both left- and right- turning lanes.
- Under both LOSs, when shared proportions of through traffic are higher than the best performing option, sharing the through traffic with the left-turn lane is always the worst scenario (in terms of delay). In such conditions, the other two sharing models (TR and TRL) always perform better.

Figure 30 shows trends similar to those from Figure 29, but in this case, the number of stops were considered. The lowest observed stops, under LOSs E and F, are those associated with the scenarios in which 30% and 40% of the through traffic is shared with the right-turn lane, respectively.

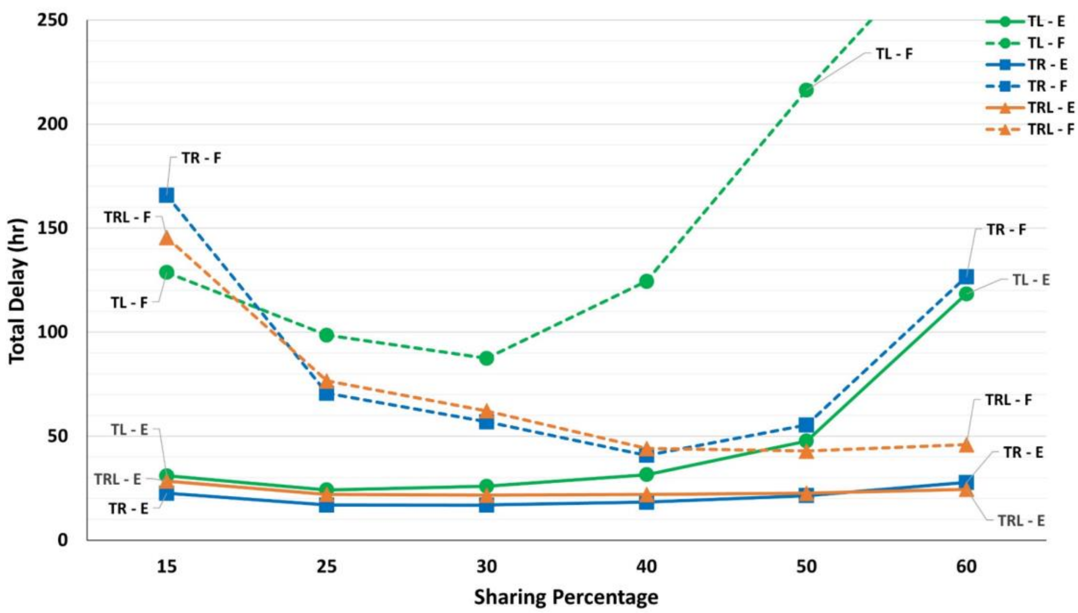


Figure 29 Total delay comparison-CFLARIC scenarios

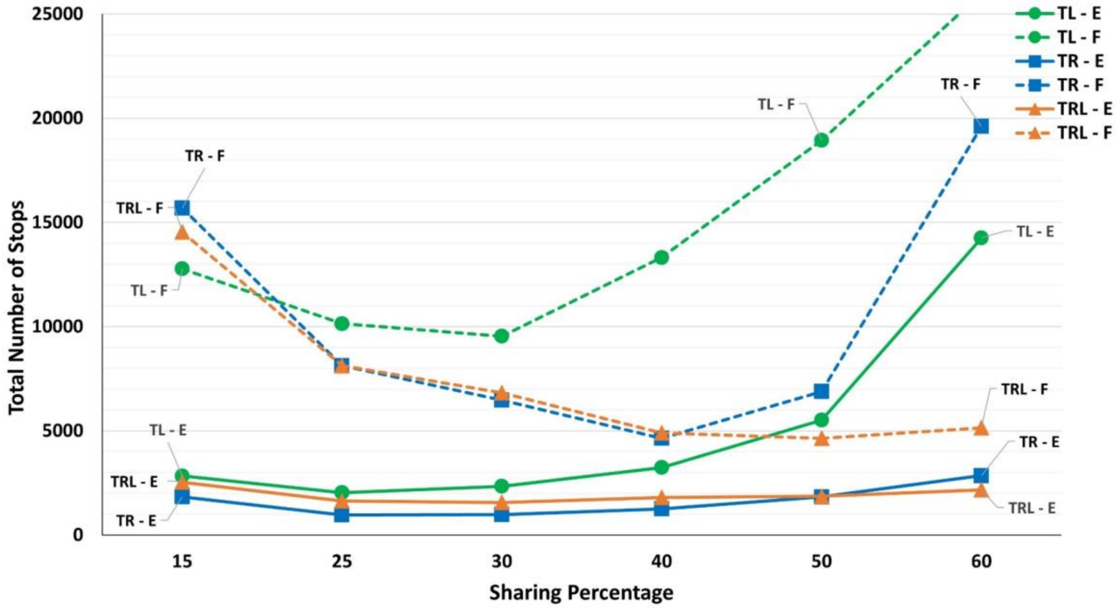


Figure 30 Total number of stops- CFLARIC scenarios

5.5.2 Conflict Resolutions

Figure 31 shows the results for the total number of crossing conflicts within intersection, for all of the proposed scenarios under LOSs E and F. The lowest numbers of intersection crossing conflicts, under LOSs E and F, are associated with the scenarios in which 30% and 40% of the through traffic is shared with the right-turn lane, respectively. Although the number of lane-changing conflicts (Figure 32) is lower in some other scenarios (e.g., 50% for TL scenario and 50% for TRL scenario), the total number of conflicts, which accounts for both intersection and lane-changing conflicts, is still the lowest for the 30% TR-E and 40% TR-F scenarios (Figure 33).

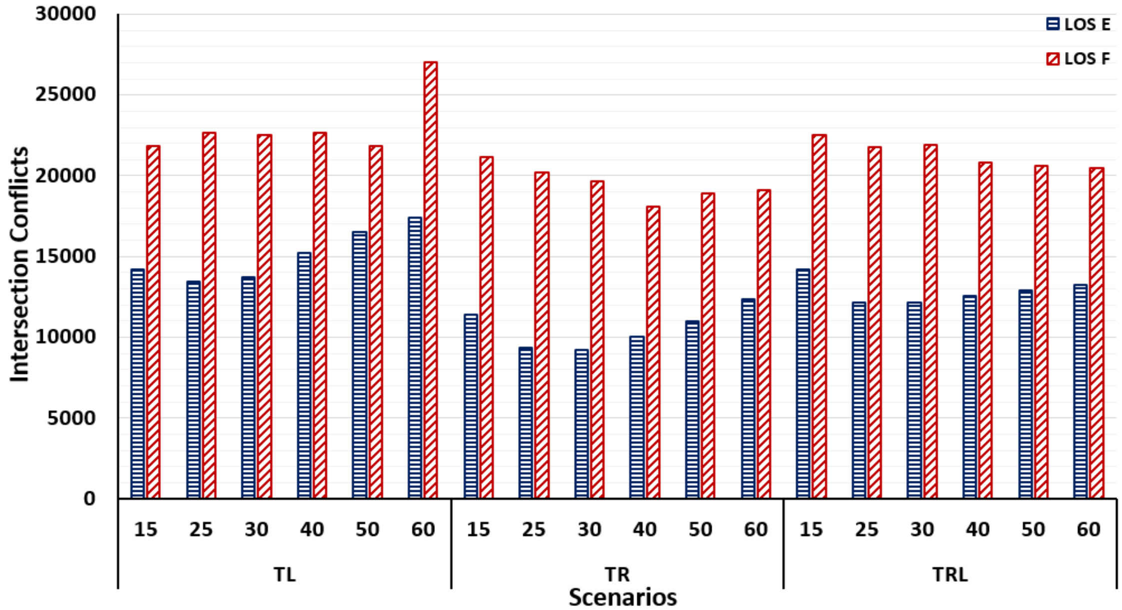


Figure 31 Intersection crossing conflicts

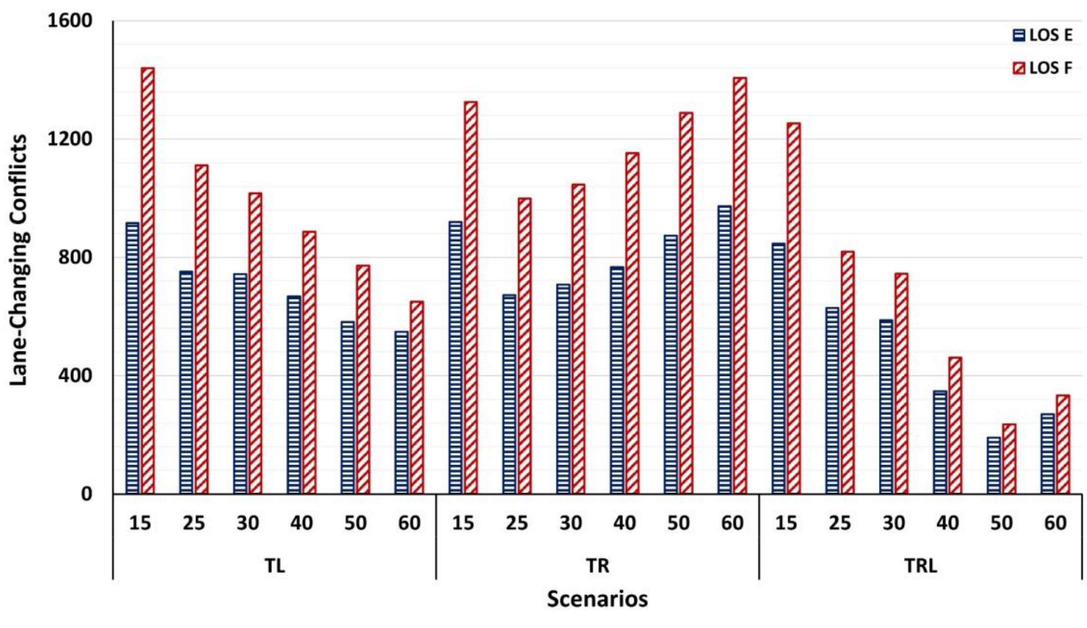


Figure 32 Lane-changing conflicts

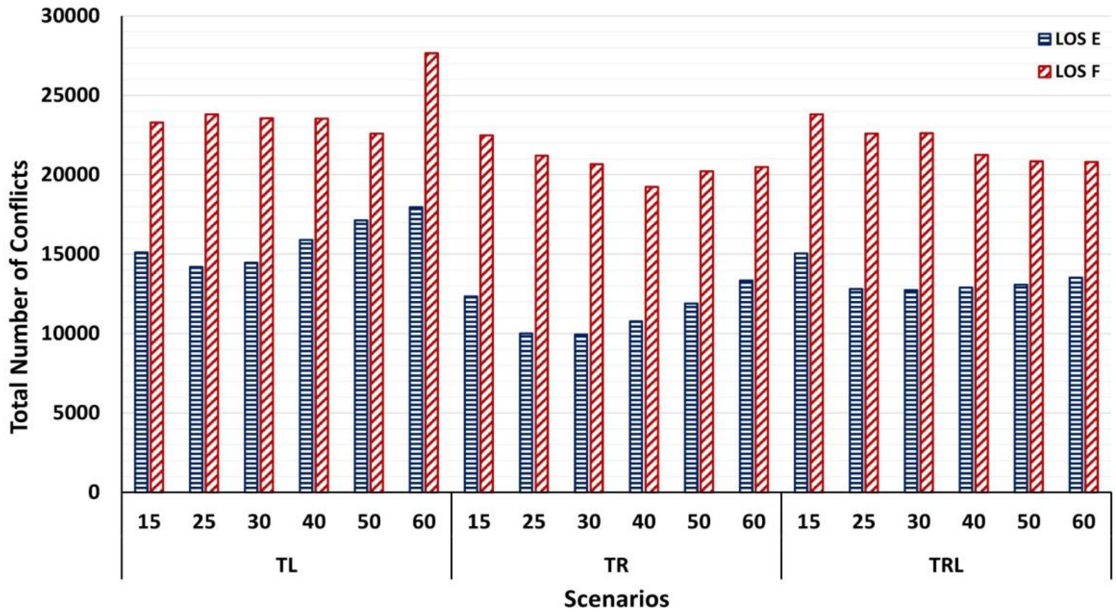


Figure 33 Total number of conflicts

5.5.3 Comparison of Performance of CFLARIC Models with Base-case Scenarios

In the next evaluation step, the performances of the best performing CFLARIC scenarios, for each of the three proposed CFLARIC models (TR, TL, and TRL), are compared with the three base-case scenarios: FTC, FRIC, and CADLARIC. As shown in Figure 34 and Figure 35, the three best-performing CFLARIC scenarios significantly outperform the FTC and FRIC scenarios (for both LOSs E and F), both in terms of delays and number of stops. The 30% TR CFLARIC scenario reduces the total delay by an average of 80%,50%, and 400% when compared to the FTC, FRIC, and CADLARIC, respectively. Also, in terms of number of stops, CFLARIC scenarios lead to significant reductions when compared to the FTC and FRIC for both LOSs. One can notice that the performance of CADLARIC has only been reported for LOS E. This is because CADLARIC does not provide enough capacity for the demand scenario with LOS F. However, the performances of the two best-performing CFLARIC scenarios (30% TR and 30% TRL) under LOS F are remarkably better than CADLARIC under LOS E.

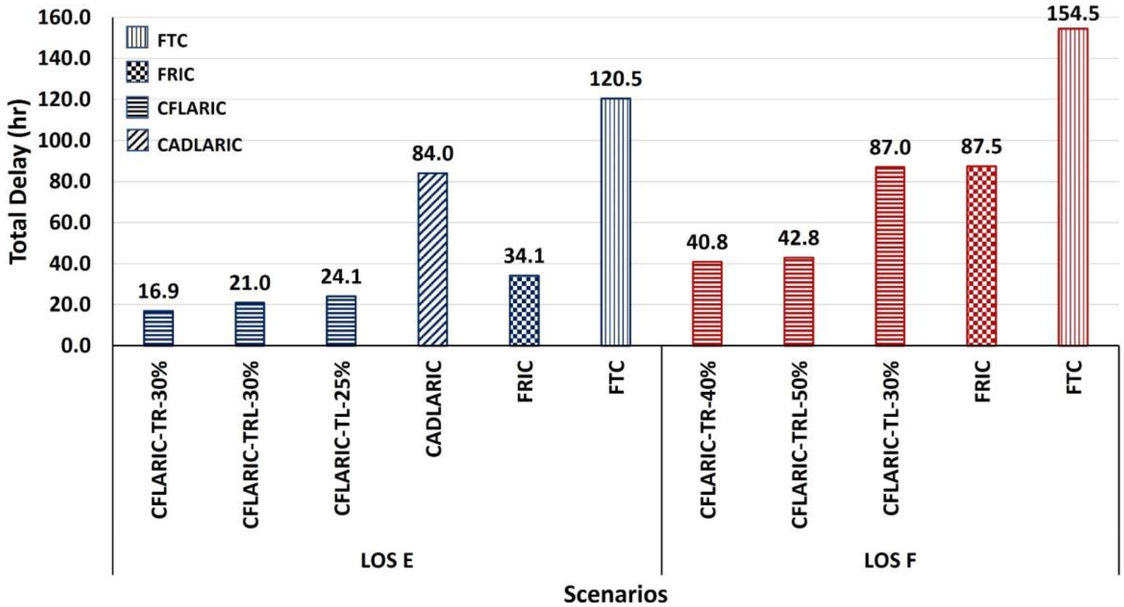


Figure 34 Total delay- comparison of CFLARIC and base-case scenarios

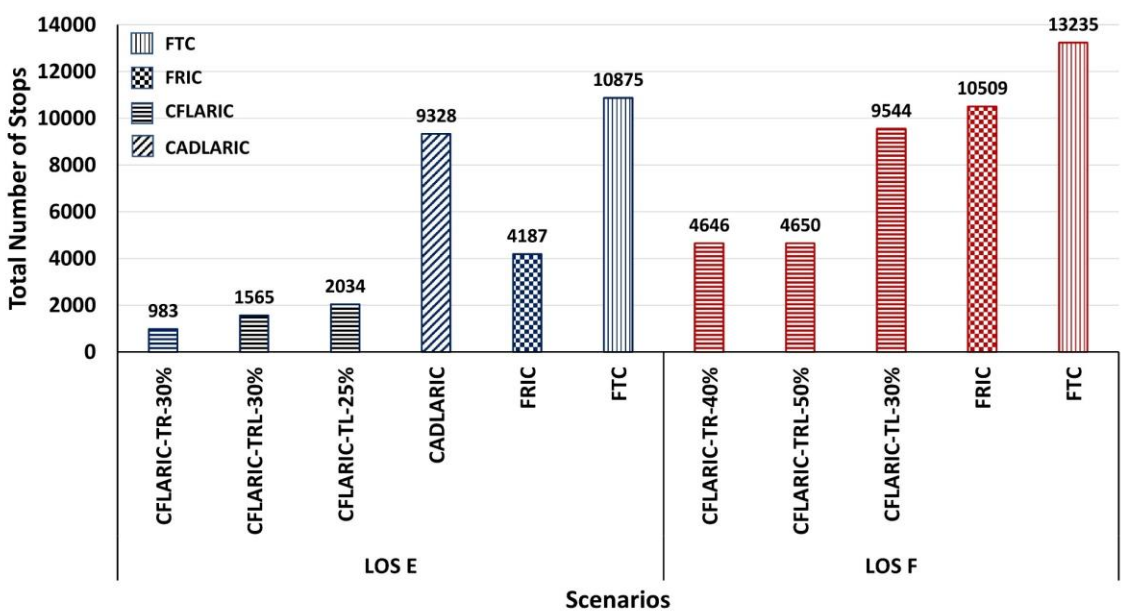


Figure 35 Total number of stops- comparison of CFLARIC and base-case scenarios

Figure 36 shows the total number of conflicts for the three investigated traffic management approaches. As shown in Figure 36, the best CFLARIC scenarios outperform FRIC and CADLARIC in terms of total number of conflicts where the CFALRIC-TR-30% reduces the number of conflicts by an average of 50%, when compared to the FRIC. Similarly, as shown in the two previous figures, the CADLARIC lacks sufficient capacity for the demand scenario with LOS F, and thus it is presented only under the LOS E. Of course, FTC produces the fewest conflicts of the three approaches, as this traffic control regime accounts only for lane-changing conflicts considering that all of the traffic movements within signalized intersections are fully protected.

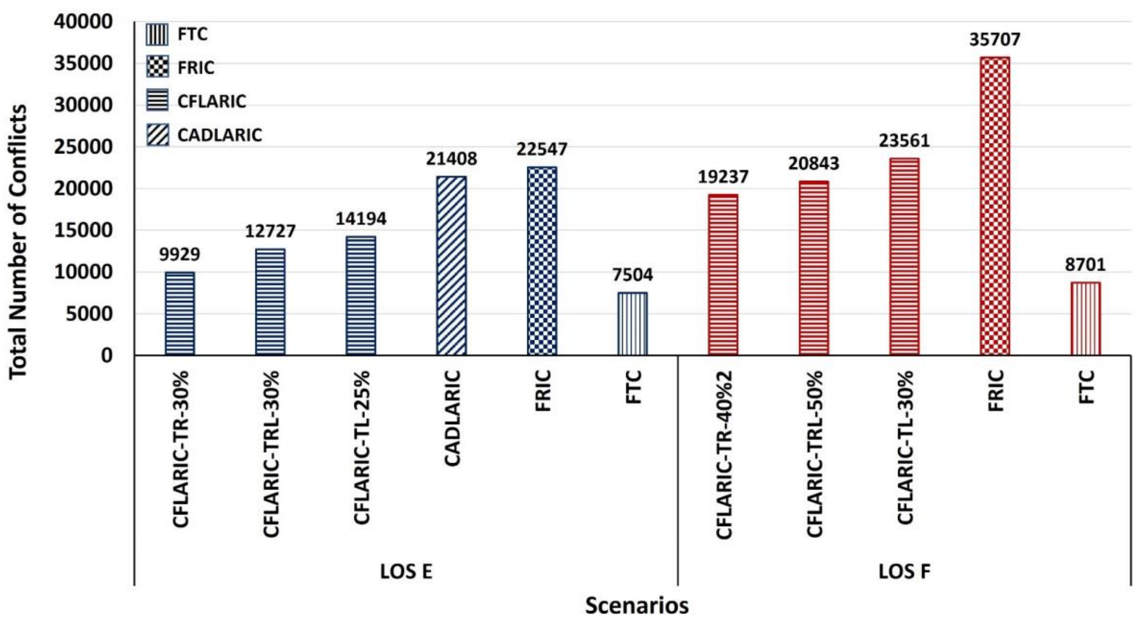


Figure 36 Total number of conflicts- comparison of CFLARIC and base-case scenarios

5.6 Conclusions

An increase in the level of connectivity between vehicles, and between vehicles and infrastructure, allows transportation designers to change the traditional restrictions and design novel traffic control systems. In response to the ever-increasing travel demand to further utilize the potential offered by emerging Connected and Autonomous Vehicles (CAVs), this chapter presents and evaluates a novel concept for autonomous intersection control called Combined Flexible Lane Assignment and Reservation-based Intersection Control (CFLARIC).

CFLARIC, similar to CADLARIC (Stevanovic and Mitrovic, 2018) eliminates number of vehicular conflicts at the intersections and moves the conflict resolution from intersection to mid-block areas to enhance the performance of the control system in a fully connected and automated driving environment. However, while in CADLARIC each approach lane is dedicated only to a single particular movement (through, left, or right), which impacts CADLARIC's performance in congested traffic conditions, this approach advocates sharing of excess through traffic with other turning-movement lanes (of the same directions) to improve efficiency and safety of the urban traffic operations. Thus, in this chapter, the CFLARIC is deployed on a hypothetical three-intersection segment where three traffic lane-sharing scenarios (TR, TL, and TRL) are investigated under various proportions of through traffic (varies from 15% to 60%).

To evaluate performance reliability of the proposed CFLARIC scenarios, they are tested under two LOSs (E and F). Also, the best performing CFLARIC scenarios (for each LOS, and each proposed sharing model) are evaluated through a comparison with two well-known control regimes: (1) Fixed-Time Control (FTC), and (2) Full Reservation-based Intersection Control (FRIC), as well as with an innovative control framework CADLARIC. FAUSIM, a microsimulation platform for flexible utilization of roadways (Stevanovic and Mitrovic, 2019), is used to simulate all scenarios in an agent-based modeling environment. The comparison of performance measures for all scenarios, under LOSs E and F, leads to the following conclusions:

- For LOS E, while the shared percentage is lower than 50%, the best sharing strategy (which results in the minimum delay, number of stops, and number of conflicts) is to share 30% of the through traffic with the right-turn lane.
- For LOS F, while the shared percentage is lower than 50%, sharing the excess through traffic with the right-turn lane is the best strategy. However, the optimal sharing percentage increases to 40%.
- For the shared proportions higher than 50%, the best CFLARIC scenarios are those in which the through traffic is shared with both turning movement lanes.
- The optimal CFLARIC scenarios (30% TR, and 40% TR) outperform FTC, FRIC, and CADLARIC control regimes (for the same traffic demands) in terms of delay, number of stops, and total number of conflicts.
- For the LOS E, when compared to the relevant FRIC scenario, the 30% TR CFLARIC scenario decreases delay and number of stops, by more than 80%.
- For the LOS F, when compared to the relevant FRIC scenario, the 40% TR CFLARIC scenario decreases delay and number of stops by more than 50%.
- The performances of two of the best performing CFLARIC scenarios (30% TR and 30% TRL) under LOS E and LOS F, are remarkably better than CADLARIC under LOS E. Since CADLARIC does not provide enough capacity for the demand scenario in LOS F, the results prove the applicability and robustness of the CFLARIC framework.

According to the results, when faced with different numbers and types of conflicts, the same percentage of shared through traffic could lead to significantly different delay times. In general, the results of this study prove that CFLARIC (similarly to CADLARIC) has the potential to significantly improve traffic operations, in a CAV environment, even in congested traffic. Although various types of roads and intersections would see different levels of efficiency benefits from the CFLARIC model, but the core of the proposed conflict-resolution strategies will always bring some improvements. In general, the findings of this chapter prove that benefits achieved by adopting traffic control concepts with more flexible lane assignments could be a reliable solution to unleash the full potential of CAVs.

6.0 Chapter 6 – Delay and Conflicting Request Predictive Models

The presented objective in this chapter is under second-stage review for publication in the ASCE's Journal of Transportation Engineering, Part A: Systems.

Azadi, F., Mitrovic, N., & Stevanovic, A.; Estimation of Delay and Surrogate Conflicts in Automated Network Management Using Linear Regression and Multigene Genetic Programming.

6.1 Overview

The use of predictive models to investigate the performance of an Automated Network Management (ANM) under multiple control strategies and given traffic demands will help assess control options in a connected and automated vehicular environment without testing them in a simulation environment. The current prediction models used to evaluate the traditional networks are not applicable in an automated environment. The goal of this chapter is to develop delay and surrogate conflict predictive models to examine the performance of a Reservation-based Intersection Control strategy in a flexible automated network. Efforts have been made to identify the correlation between the delay and the total number of conflicting requests with types and characteristics of the conflict points and conflicting flows. To generate an extensive origin-destination level dataset, three Combined Flexible Lane Assignment and Reservation-based Intersection Control (CFALRIC) models were used in which the through traffic is shared in six various proportions with one or both turning lanes; and tested under two different traffic demands leading to a total of 36 scenarios. The selection of appropriate input variables was a crucial step in this study. Linear regression and Multigene Genetic Programming (MGGP) approaches are utilized to derive new prediction models for delay and number of conflicting requests. Results reveal that the regression model is a reasonably appropriate fit for both models; however, the accuracy of the MGGP approach is higher for the delay prediction model. These models have great potential to be applied in planning purposes such as traffic assignment in an automated environment.

6.2 Introduction

The development of Connected and Autonomous Vehicles (CAVs), and the advances in Information Technology (IT) are destined to revolutionize transportation systems in terms of efficiency and safety. The multifaceted need to develop advanced control mechanisms to unleash the full potential of autonomous vehicles has inspired researchers to propose innovative approaches in traffic management (Olsson and Levin, 2020; Wang et al., 2021), such as autonomous intersection managers (AIMs) (Hausknecht et al., 2011). Automated Network Management (ANM) aims to enhance traffic flow management in a fully connected and automated urban system and ultimately to alleviate the ever-growing congestion problem. Thus, investigation of the performance of Automated Network Management (ANM) (for various traffic control strategies and different traffic demands) is needed both for planning and operations of the future facilities with significant CAV usage.

Reservation-based Intersection Control (RIC) (Dresner and Stone, 2004) is one of the most popular automated urban traffic control strategies in ANM. Although much attention has been paid to the development and optimization of this control strategy (Altche and De La Fortelle, 2016;

Baber et al., 2005; Levin and Rey, 2017; Yan et al., 2009) no studies have examined how to estimate efficiency of such system through capacity-planning-like approach for estimating traffic management performance on urban arterials. For example, the current delay models, which are often used for evaluating the signalized intersections, rely on signal timings to calculate delay (Caliendo, 2014). Therefore, one cannot use such methods for RIC strategies as those do not operate common sequence-based signal phases for groups of vehicles. On the other hand, the current procedures for estimating delay at stop-controlled intersections could be used as a guide, however, such control strategies are rather simplistic and are not equivalent to RIC (e.g., every vehicle is stopped at stopped-controlled intersections whereas RIC does not stop vehicles but only gives them certain priority). As a result, it is important to develop delay functions (or similar performance measures) to assess performance of networks with CAV operations and RIC (and similar) traffic control strategies. The development of such performance functions is also motivated by the needs to have such performance measures for planning purposes and estimation of future LOSs, when the field measurements are not available.

The current methods for assessing the performance of traffic control systems have another limitation. They do not simultaneously reflect safety and efficiency components of the actual traffic operations (Pan et al., 2008). Although some traffic control systems (such as conventionally signalized intersections) can be evaluated (to an acceptable level) only based on the delay (as safety is embedded in the movements protected by signal phases), in a CAV environment with RIC operations delays and conflicts are closely correlated. Findings from some previous studies, on Combined Alternate Lane Assignment and Reservation-based Intersection Control (CADLARIC), indicate that a higher number of conflicting requests (as a potential-conflict indicator) leads to a lower network efficiency (Stevanovic and Mitrovic, 2018). Therefore, it is important to investigate combined effect of such measures and discuss both concepts when evaluating such advanced control operations. To cover the above-mentioned gap in the existing body of knowledge, this chapter aims to investigate a CAV network with RIC strategy to assess combined efficiency and (surrogate) safety performances of such a network. Thus, the objectives of this chapter are to: 1. identify correlation between delay and conflicting requests with the type and characteristics of the conflict points, and 2. to develop predictive models for network-wide delays and conflicts. The developed models are expected to be significant aid for planning purposes (e.g., traffic assignment) in the future CAV network routing operations.

The current chapter is organized as follows. The introduction section is followed by a brief review on current delay functions. It should be noted that the recent studies on Reservation-based Intersection Control (RIC) have been reviewed earlier in the section 2.1. In the methodological section, the main ANM components are discussed with the focus on flexible alternate-lane assignment scenarios. In addition, the conflict, efficiency, and exposure parameters are discussed, as well as the statistical models utilized for developing delay and conflict estimates. Then, the test setup and the data collection process are described, which is followed by the result and discussion section. Lastly, concluding remarks are provided.

6.3 Background

6.3.1 Delay Functions

The delay estimation models for signalized intersections can be categorized into three groups based on volume-capacity ratio (V/C): steady-state, oversaturation delay, and combined models (Roess and Mcshane, 2019). Webster (Webster, 1958) and Hurdle (Hurdle, 1984) are the most famous models for estimating the delay in steady and oversaturated conditions and the Highway Capacity Manual (HCM) delay model is representative of the combined models which originally developed to determine the intersection LOS. Since all three models rely on signal timings to calculate delay (Caliendo, 2014), they do not apply to signals-free intersections.

The delay estimation models have been also widely used for planning purposes in assessing the performance of a network and for various traffic assignment models (Kucharski and Drabicki, 2017; Leong, 2017). The correlation between delay/travel time and traffic volume has been addressed frequently in transportation modeling (Kucharski and Drabicki, 2017; Saric et al., 2018). In traffic assignment, the last step of the conventional four-step transportation modeling, traffic demand is assigned to the links of a network based on travel time and other impedances between origin and destination of a trip (Meyer, 2016). Volume-Delay Function (VDF), which correlates link travel time/delay and traffic flow, is one of the main functions in estimating such impedances (Leong, 2017). The correct determination of the VDF has been a key role in the traffic assignment process due to its strong effect on the reliability of the traffic model (Saric et al., 2018). With the most transportation models, the impedance function for each link is determined by the traffic volume on that link, and the signal delay function for each intersection approach (Mazloumi et al., 2010). Some models simplify link travel time as the sum of free-flow travel time and congestion delay and exclude intersection delays (Nielsen, 1998).

Although several delay models are available for various purposes (some have been discussed before), none of them can be applied to fully automated urban networks in which an advanced signal-free algorithm-controlled system controls traffic flow over the entire roadway surface. Another limitation of the current methodologies for assessing the performance of a network is that the procedures for evaluation of intersections' performance (e.g., LOS) do not take safety into account therefore they do not reflect the actual operation of an intersection (Pan et al., 2008). Although some attempts have been made to incorporate conflicts as a well-known surrogate safety measure (Arun et al., 2021; Zheng et al., 2014) in the developed procedures, the proposed models still cannot be applied to a network with a reservation-based intersection control due to significant differences in the control logics.

Thus, the present chapter contributes to the state of the art by developing predictive models for network-wide delays and conflicts considering types and characteristics of the conflict points and conflicting flows to assess combined efficiency and (surrogate) safety performances when evaluating such a network. In addition to the above mentioned limitations, this research is also motivated by the findings from the previous studies (are presented in Chapters 4 and 5) that indicate a higher number of conflicting requests (as a surrogate conflict measure) in an ANM system with reservation-based intersection control leads to a lower network efficiency (Stevanovic and Mitrovic, 2018). The proposed models in this chapter also can be used in the future for traffic assignment purposes in a network with reservation-based intersection control.

6.4 Methodology

The methodology utilized to develop predictive models for estimating the performance of a control framework in an automated (vehicular/network) environment is described in this section. The analyzed control strategy refers to a combination of a flexible lane assignment on the segment and associated Reservations-based Intersection Control (RIC) that has been adjusted for the evaluated lane assignment schema (Dresner and Stone, 2004; Stevanovic and Mitrovic, 2018).

The investigated performance parameters include key efficiency and surrogate conflict metrics such as delay and conflicting requests that a vehicle experiences while traveling from its origin to destination.

The Combined Flexible Lane Assignment and Reservation-based Intersection Control (CFLARIC) used as the flexible automated network management in this study can be considered as an extension of traditional Automated Network Management (ANM) (Fajardo et al., 2011). The main components/modules of the CFLARIC has been described in subsection 3.3. As mentioned in the previous chapters, CFLARIC can assign lanes, between any two intersections, very flexibly between various turning movements. Although many CFLARIC scenarios could be developed, this chapter considers an alternate lane assignment (Stevanovic and Mitrovic, 2018) for the mid-block links. This novel approach allows left- and right-turning vehicles to align themselves in an appropriate lane before reaching the downstream intersection and turn smoothly by the time they reach the downstream intersection. CFLARIC, however, offers higher levels of flexibility, since shared lanes within the intersection box allow vehicles traveling in a certain direction to use lanes available in that direction. Figure 37 shows such a condition for the EB through movement, where EB through vehicles has three options:

- Stay in the exclusive through lane (blue car),
- Join the right-turn lane (red car),
- Join the left-turn lane (green car).

Depending on the path that a vehicle takes, it would face conflicts (both for lane-changing and within-intersection maneuvers) with other vehicles which would differ in number, type, and location of conflicts, as presented in a table shown in Figure 37. Therefore, for different lane assignment schemas, the delay might significantly vary depending on the set of conflicts encountered (based on the results presented in Chapter 5 (Azadi et al., 2021)). Also, it is important to mention that due to flexible lane assignment in CFLARIC vehicles might experience a higher number of lanes changing conflicts, but lower number of intersection conflicts when compared to traditional RIC (Azadi et al., 2021; Stevanovic and Mitrovic, 2018).

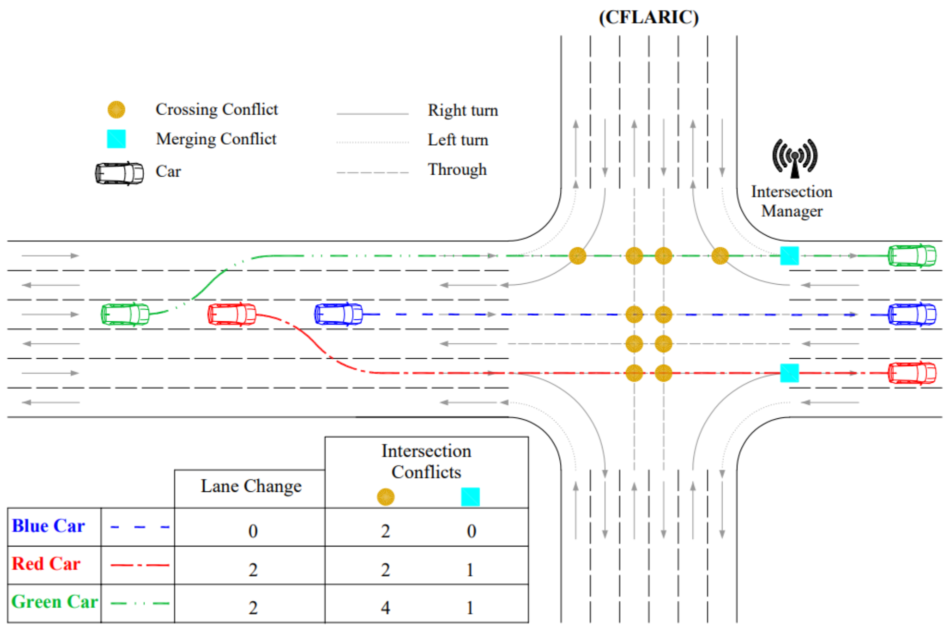


Figure 37 Potential lane-assignment in CFLARIC

In what follows, the key input components that are used to develop the predictive models and are calculated from the outputs obtained from simulation are described. These includes calculation of delay (efficiency measure), number of conflicting requests (surrogate conflict measure) and conflicting flow (exposure measure) in flexible ANM. These (and similar) performances can be revealed from the simulation output records. However, simulation can cover only a handy number of experiments/scenarios and in this chapter, attempts have been done to reveal the certain relationships between predictive factors (derived from the given demand and evaluated control strategy) and the performance of flexible ANM. The potential "predictors" and the development of models are discussed in the subsequent section.

It should be mentioned that the details of mathematical formulation for delay and number of conflicting requests (efficiency and safety performance measures that are used for the evaluation purposes) are described earlier in section 3.4.

6.4.1 Efficiency, Safety, and Exposure Parameters

6.4.1.1 Delay (Efficiency Metric)

The total and average delays in the network were computed for all the vehicles at the OD level, where the delay of a subject vehicle is calculated by deducing the free-flow travel time between its origin and destination points ($ftt_k^{o,d}$) from the correspondent travel time. The calculation of delay is explained in details in subchapter 3.5 (Equations (3-23) to (3-28)).

6.4.1.2 Conflicting Requests (Potential-Conflict Metric)

In current transportation networks, conflict points are places where two vehicles' trajectories/paths collide or are too close to each other, increasing the risk of a crash. In such a network, conflicts are controlled using traffic signals or stop signs. However, in the CFLARIC system, in which the traditional signal has been replaced with an intersection manager (IM), conflicts are handled through the reservation process. In such a system a "conflict" refers to a conflicting request for the same time-space lot which could be considered as "potential-conflict indicator". The total number of conflicting requests for all vehicles on a given OD route in such a system is a summation of the lane-changing conflicts and intersection conflicts for those vehicles traveling from origin node o to destination node d.

A lane-changing conflict is an event when a vehicle is not allowed to change the lane due to the presence of a conflicting vehicle in one of the lanes that it needs to cross or merge. Similarly, an intersection conflict event is when a vehicle wants to reserve a time-space block at an intersection that has already been reserved for another vehicle. The details of mathematical calculation of lane-changing, intersection, and total number of conflicting requests are explained in subchapter 3.5 (Equations (3-35) to (3-39)).

6.4.1.3 Conflicting Flow (Exposure Metric)

Conflicting flow, derived from given traffic flow, is one of the potential input candidates for predictive models. HCM provides two different methods for estimating conflicting traffic flow for Two-way Stop-Controlled (TWSC) and All-Way Stop-controlled intersections. For a TWSC intersection, first, the movements are ranked by priority and then the conflict flow is calculated for the movements not given absolute priority. For an AWSC, HCM defines different levels, or degrees of conflict, faced by a subject approach. The probability of occurrence is computed based on the degree of utilization of the opposing and conflicting movements (Highway Capacity Manual, 2010). HCM methods, however, do not differentiate between conflict types (e.g., crossing or merging). In addition, none of the above mentioned HCM procedures works For a RIC system with a FCFS priority since such a system does not prioritize any movements. Therefore, this study calculates the conflicting flow using a procedure that is more compatible with the FCFS-RIC system. From this perspective, this study adds originality by considering not only the number but also the characteristics of conflict points when calculating the conflicting flows. Thus, intersection conflict points are categorized based on type (merging or crossing) and considering whether they are located on a shared lane or an exclusive lane.

Let us classify conflicts using parameter α_E , where α represents the type of conflict (crossing or merging) and E indicates if the conflict point is located on the exclusive lane or shared lane. Also, let us consider $V_{M.\alpha_E}^{o.d}$ as the OD traffic volume having conflict with movement M_c at conflict point $C\alpha_E$, and $V_{M_c.\alpha_E}$ as the traffic volume of the corresponding conflicting movement. Since an OD traffic traveling in lane l, can face several numbers of intersection conflicts, the conflicting flow for an OD movement M in lane l is computed as shown in Equation (6-1).

$$V_{Conf(M(l_i))} = \sum V_{M_c.\alpha_E} \quad , \forall \text{ conflict points on lane } l \tag{6-1}$$

The total amount of conflicting flow associated with a particular OD traffic in a particular lane (shared or exclusive) is equals the sum of all the corresponding intersection conflicts.

$$TV_{Conf(M(l_i))} = \sum V_{Conf(M(l_i))} \quad , \forall \text{ intersections} \tag{6-2}$$

Figure 38 indicates a sample lane assignment schema at an intersection in which two lanes are assigned to the East bound through traffic from which one (lane 4) is an exclusive lane and the other (lane 2) is a shared lane. As shown in the figure the through traffic faces two crossing conflict points on lane 4 and two crossing conflict points plus one merging points on lane 2. The corresponding conflicting flow for the evaluated East-bound through movement (EBT) on each of those lanes is calculated as:

$$V_{Conf(EBT(l_2))} = \alpha_{Sh}(V_{NBT} + V_{SBT}) + \beta_{Sh}(V_{NBR}) \tag{6-3}$$

$$V_{Conf(EBT(l_4))} = \alpha_E(V_{NBT} + V_{SBT}) \tag{6-4}$$

Where α_E and α_{Sh} are coefficients for the crossing conflict points on the exclusive and shared lane, respectively and β_{Sh} is a coefficient for the merging conflict point on the shared lane.

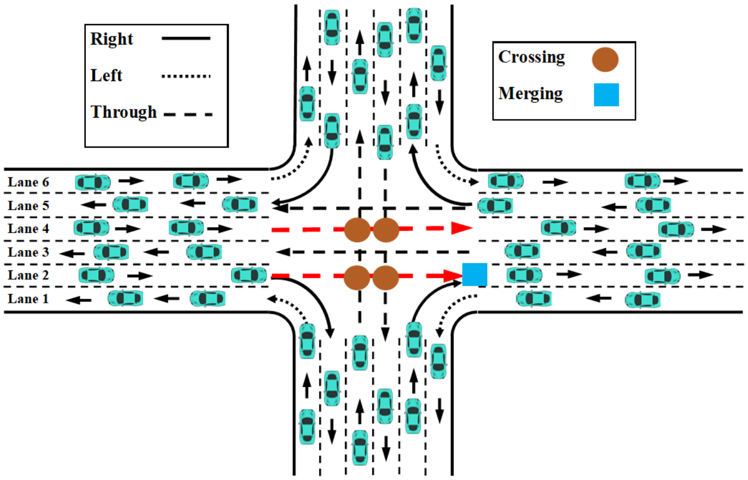


Figure 38 East-bound through movement (EBT) conflict points

6.4.2 Input Parameters for Model Development

The type, location, and number of conflict points that each OD movement encounters are extracted. Also, three corresponding volumes at each conflict point included OD volume, the total traffic volume traveling in the same lane as the subject OD traffic, and conflicting volume are extracted from the simulation. Table 4 presents the 13 independent variables that are considered as the input to generate predictive models for the delay and the total number of conflicts (dependent variables). In summary, the geometry class (input variable X_1) is a categorical variable representing the lane assignment schema that the observation belongs to. Input variables X_3 to X_5 represent the number of each type of conflict points (crossing or merging) on either a shared lane or an exclusive lane. Therefore, conflict points are classified by their type (crossing/merging) and location (on an exclusive lane or shared lane). Input variables X_7 to X_{13} represent the corresponding volumes in each conflict point for a subject OD movement including OD, lane, and conflicting traffic volumes. Zero values for any of the X_3 to X_5 variables in the dataset indicate that the subject

OD movement does not encounter a particular point of conflict. For example, as shown in Figure 38, the EBT movement traveling in the exclusive lane (lane 4) does not face any crossing point on the shared lane, therefore for the subject movement X_4=0, and consequently, the corresponding volumes, in this case, X_{10}, X_{11}, and X_{12}, are all equal to zero.

Table 4 Input variables

No	Description	Notation	Min	Mean	Max
X_1	Geometry Class	G	-	-	-
X_2	Distance Traveled	D	538	692	837
X_3	Number of crossing points on an exclusive lane	CrEx	0	2.5	6
X_4	Number of crossing points on a shared lane	Crush	0	3.4	18
X_5	Number of merging points on a shared lane	MeSh	0	1.1	6
X_6	Lane-changing ratio	Lch	0	0.3	1
X_7	OD volume at crossing points on an exclusive lane	CrEx_Vod	0	130	465
X_8	Total conflicting traffic volume at crossing points on an exclusive lane	CrEx_Vcon	0	1337	3551
X_9	Total lane traffic volume at crossing points on an exclusive lane	CrEx_TVL	0	342	772
X_{10}	OD volume at crossing points on a shared lane	CrSh_Vod	0	74	287
X_{11}	Total conflicting traffic volume at crossing points on a shared lane	CrSh_TVcon	0	1406	8261
X_{12}	Total lane traffic volume at crossing points on a shared lane	CrSh_TVL	0	292	703
X_{13}	Total conflicting traffic volume at merging points on a shared lane	MeSh_TVcon	0	200	1142

It should be mentioned that the total traffic volume at a conflict point (X_9 and X_{12}) is equal to or higher than OD volume at the same conflict point (X_7 and X_{10}, respectively), as the corresponding lane can be assigned to more than one OD movement. The lane-changing ratio variable, X_6 , is a value between 0 and 1 and is defined as the proportion of the OD traffic volume which need to change their lanes to be aligned in the proper lane before reaching their destination. In case the traffic for the evaluated OD is split between two lanes and only traffic in one of those lanes needs to change lane before reaching its destination, the ratio will be less than one.

6.4.3 Predictive Models

6.4.3.1 Regression Model

Regression models, widely used for prediction and forecasting, estimate mathematically the relationship between a dependent variable (response variable) and one or more independent variables (predictors). The ordinary least square method is a common form of regression analysis that minimizes the squared differences between the actual data and a proposed line that closely fits the data (James et al., 2013). In its general form, a regression model for a system with N independent variables can be described as Equation (6-5).

$$y = \sum_{i=1}^{N} \beta_i \, x_i + \varepsilon \tag{6-5}$$

Where y is the dependent variable, β_i are the coefficients obtained by regression analysis $(1 \leq i \leq N)$, and ε is the random error term.

The least-square method minimizes the residual, which is the difference between the predicted ($\hat{y}_i$) value and the actual value (y_i) for all data points (n).

$$SSR = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 \tag{6-6}$$

The major assumptions of regression analysis are as follows:

- The relationship between the dependent variable (y) and independent variables (x_i) is almost linear.
- The error term ε has zero mean and constant variance of σ^2.
- The errors are normally distributed and uncorrelated.

The validity of the above mentioned assumptions should be studied to examine the adequacy of the regression models (Montgomery et al., 2006) as a gross violation of the assumptions may lead to an unstable model. Such a model may produce opposite conclusions when applied to different samples.

6.4.3.2 Multigene Genetic Programming (MGGP)

Genetic programming (GP), is a branch of evolutionary computation (EC) methods and has been successfully used in various optimization problems (Moridpour et al., 2015; Park et al., 1999; Zhang et al., 2020). A classical GP model has a tree-shaped structure and utilizes a randomly selected population as a starting point to generate a predictive model. A tree-based GP consists of functions and terminals arranged hierarchically. Basic operations $(+, -, \times, etc.)$ and Boolean logical functions (AND, OR, etc.) can serve as functions. Functional arguments, called terminals, consist of variables, numbers, or logical contents. The diversity of the evolved solution is added by using genetic operations such as crossover, mutation, and reproduction. MGGP, which is a weighted linear combination of individual GP programs, is a robust variant of the classic GP (Zhang et al., 2020). The maximum tree depth and the maximum number of genes are the two parameters that need to be controlled in the application of MGGP in practice. The choice of these parameters always involves a trade-off between compactness and accuracy. For reasons listed below, this study considers MGGP as the second model for formulating delay and number of conflicts:

- MGGP effectively combines the model structure selection ability of the standard GP with the parametric estimation power of classical regression.
- MGGP derives explicit relationships between variables without requiring any prior assumptions.

- GP-based prediction equations are transparent compared to other machine learning models (Zhang et al., 2020).

It should be noted that stepwise regression analysis, in which the variable with the highest t-value among the remaining independent variables is added to the model in each step, could also be used to select significant variables. However, it considers only one variable at a time. Therefore, its search domain is smaller than MGGP's. Thus MGGP has a good chance of identifying the optimal solution if stepwise regression provides it (Lingras et al., 2002).

To develop the delay and conflicting request models, the following steps were followed:

- Model the proposed lane-assignment schemas.
- Run the simulation and extract the required OD level information.
- Select/define the potential input parameters.
- Generate the database derived from simulation outputs.
- Perform exploratory analysis to exclude the outliers.
- Divide the data into the training and testing datasets.
- Run regression and MGGP models on the training data and select the significant variables and the best performing model.
- Evaluate the selected models based on their performance on the test dataset.

6.4.4 Test Network

Experiments are conducted on a generic three-intersection network (six lanes on each approach) with identical lane assignments at all three intersections. Figure 39 displays the origins and destinations of this arterial network as well as the turning proportions for the main (East-West) and side (North-South) streets.

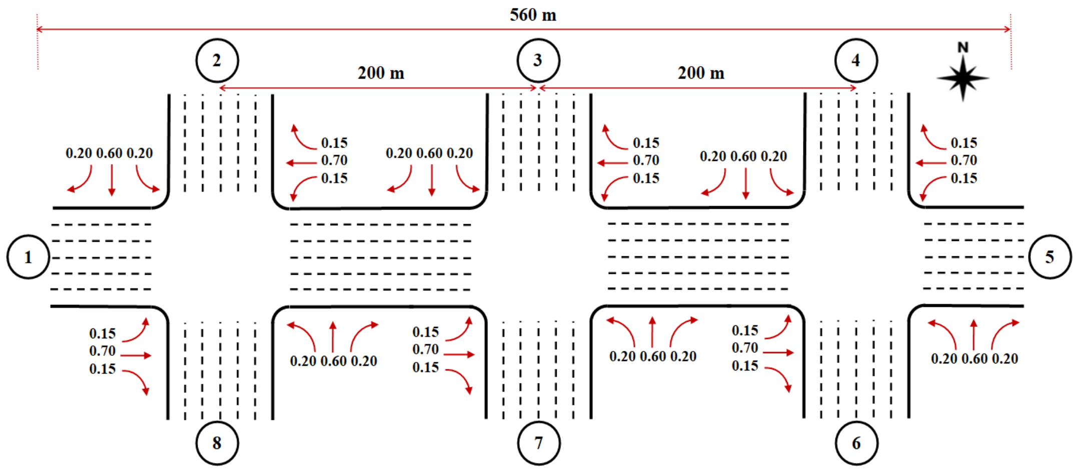


Figure 39 Geometric and traffic distribution of the test network

6.4.5 Lane Assignment Schemas

Three CFLARIC schemas (Figure 40) in which the through traffic is shared with one or both turning-movement lanes of the main street are considered. Figure 40 shows the number and types of conflict points exist in the excluded and shared lanes for the eastbound through movement in each one of the scenarios.

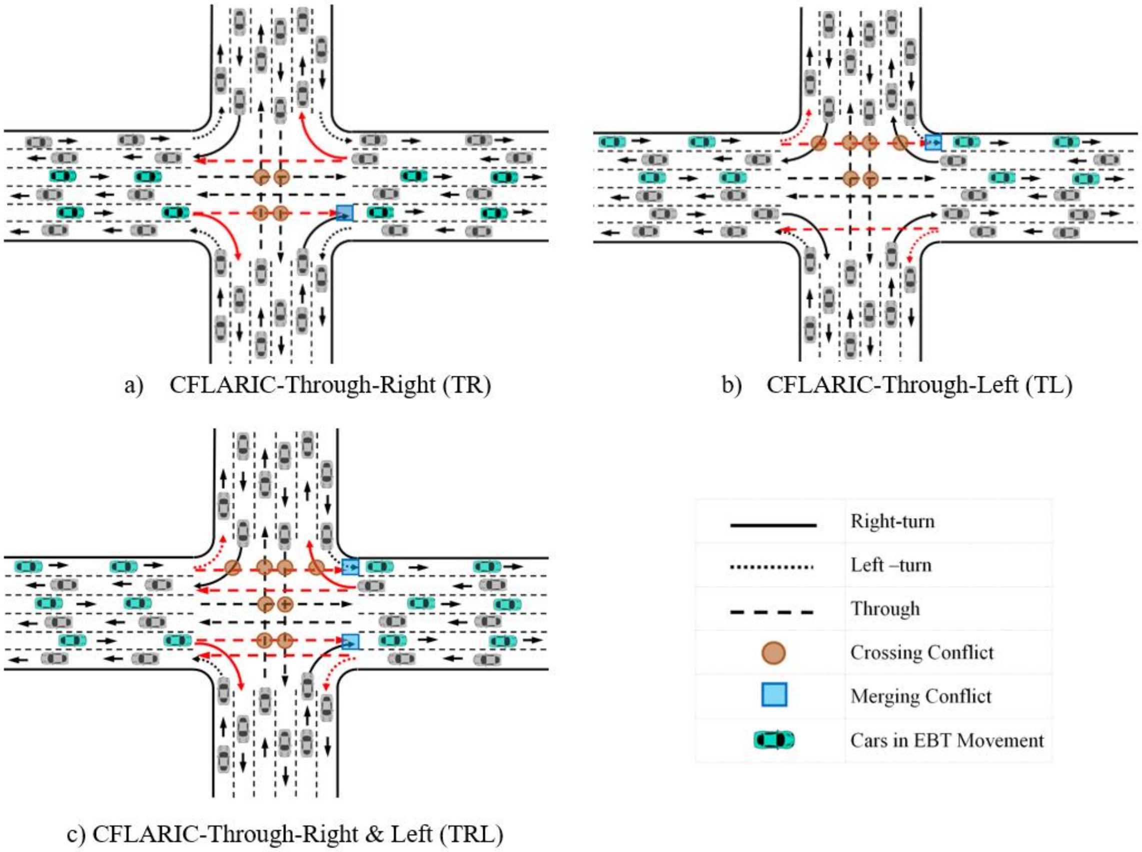


Figure 40 Evaluated lane-assignment schemas

6.4.6 Traffic Demand Scenarios

To generate an extensive dataset from simulation, in each of the three proposed models (which are called TR (through-right), TL (through-left), and TRL (through-right & left)) the through traffic has been shared in the following six proportions (15%, 25%, 30%, 40%, 50%, and 60%). Scenarios were tested under two different traffic demands leading to a total of 36 different scenarios. Table 5 shows the traffic volumes for each street (main and side), the turning proportions (right, through, left), and the proportions of the main street excess through traffic volume that is shared.

Table 5 Traffic volumes and distributions

Street	Traffic volume (veh/hr)		Traffic distribution		Shared Through Traffic	
	Level 1	Level 2	Movement	Percentage	Percentage	Volume (veh/hr)
Main	1300	1450	R-T-L	15-70-15	15	136
					25	228
					30	273
					40	364
					50	455
					60	546
Side	900	1050	R-T-L	20-60-20	15	152
					25	254
					30	304
					40	406
					50	507
					60	630

6.5 Data Acquisition and Input Parameters

The required data for this study is measured within the NetLogo through a series of custom-made codes written in Scala. Vehicle reports its status, contains multiple attributes, at each time step (i.e., 0.2s). Those attributes are static (such as origin and destination) as well as dynamic (such as speed and position). The traditional attributes such as (but not limited to) vehicle lateral and longitudinal position, speed, and acceleration are used to assess the efficiency-based performance metrics (e.g., delay). In addition, non-traditional attributes such as vehicle desire to change the lane along the links and/or reserve the path within the intersection are also recorded on a high temporal resolution and used to evaluate conflict-based indicators.

A dataset consists of OD level observations for the eight origins and eight destinations (56 ODs), three lane-assignment schemas (TR, TL, TRL), six sharing proportions (15% to 60%), and two traffic demand levels (presented in Table 5) is generated. To deal with the overfitting, a subset of 70 % of the OD data records from the entire database was selected randomly for the training phase. The remaining 30% of the data was used for the testing purposes. Several preliminary analyses were performed to exclude the outliers and to find the input parameters with significant impact on the two dependent variables: delay and total number of conflicting requests.

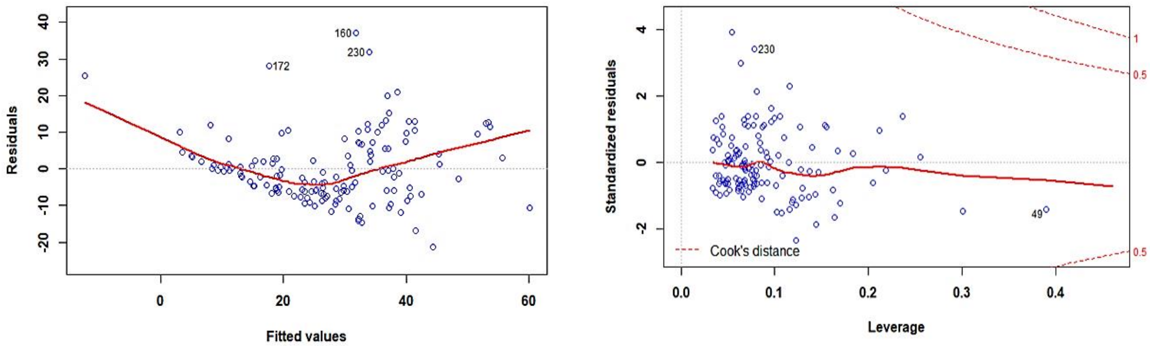
6.6 Results and Discussion

This section presents and compares the regression and Multigene Genetic Programming (MGGP) models which are developed for delay and conflict prediction.

6.6.1 Regression Predictive Models

6.6.1.1 Model Adequacy Checking

The validity of the regression analysis assumptions should always be examined before developing a regression model. A gross violation of the assumptions (explained earlier in section 6.4.3.1) may lead to an unstable model. Such a model may produce opposite conclusions when applied to different samples. In this section an analysis of model residuals has been conducted to study the violations of the basic regression assumptions. Results are shown in Figure 41.



a) Residuals vs Fitted values b) Residuals vs Leverage

Figure 41 Plots of Residuals Analysis

The outward-opening funnel pattern in Figure 41a) implies that the variance is an increasing function of the dependent variable. The usual approach for dealing with inequality of variance of the errors is to apply appropriate transformation to either dependent or independent variable or to use the weighted least square method (Montgomery et al., 2006). In addition, the curvy shape of pattern in the same figure indicates some levels of nonlinearity. The Residual vs Leverage plot presented in Figure 41b) shows no outlier or influential observations.

6.6.1.2 Regression-Conflict Model

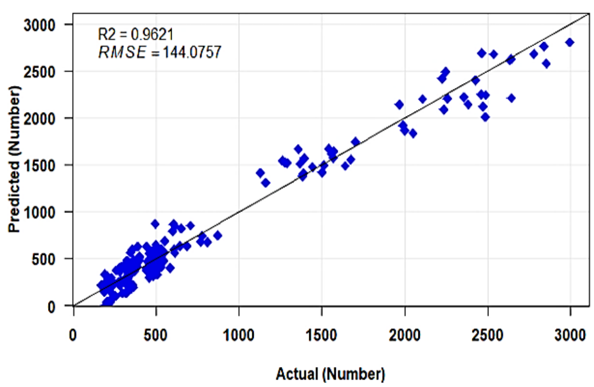
Several runs were performed to find the input parameters with higher impact on the dependent variables. The preliminary regression models for both delay and the total number of conflicting requests includes only the simple form of the independent variables as presented previously in Table 4.

From 13 variables only 9 variables are significant for predicting the number of conflicting requests. The regression model for number of conflicting requests is presented in Equation (6-7).

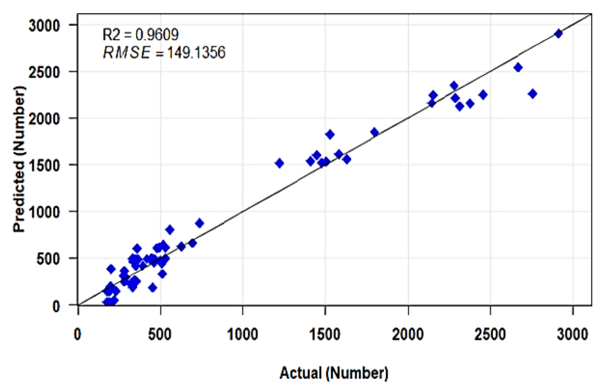
Total Number of Conflicting requests

$$= 0.821(\mathrm{D}) - 455.28(\mathrm{CrEx}) - 346.8(\mathrm{MeSh}) - 204.21(\mathrm{Lch}) + 2.90(\mathrm{CrEx}_{\mathrm{Vod}}) + 1.05(\mathrm{CrEx}_{\mathrm{Vcon}}) - 0.20(\mathrm{CrEx}_{\mathrm{TVL}}) + 5.10(\mathrm{CrSh}_{\mathrm{VodX10}}) - 0.38(\mathrm{CrSh\_TVL}) - 625.14 \quad \textbf{(6-7)}$$

Figure 42 shows the prediction made by the regression models for the total number of conflicting requests. The values for R^2 and RMSE are presented on the top left side of the graphs. As shown in Figure 42, the RMSE values for the test and train models are close indicating the proposed regression models can predict the dependent variables very well.



a) Conflict-Train Model

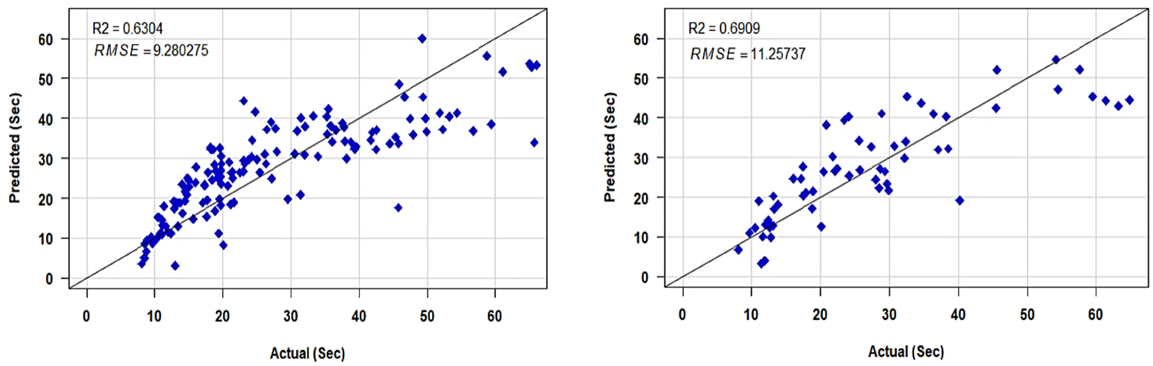


b) Conflict-Test Model

Figure 42 Actual versus predicted conflicts using regression model

6.6.1.3 Regression-Delay Model

The preliminary regression model for delay included the simple form of the variables. As shown in Figure 43 this model did not show very promising results (R2< 0.7).



a) Delay-Train Model b) Delay-Test Model

Figure 43 Actual versus predicted delay using regression model with simple form of variables

To improve the prediction accuracy of the delay model the following interactive terms (Table 6) have been defined based on logical interactions and through a trial-and-error process.

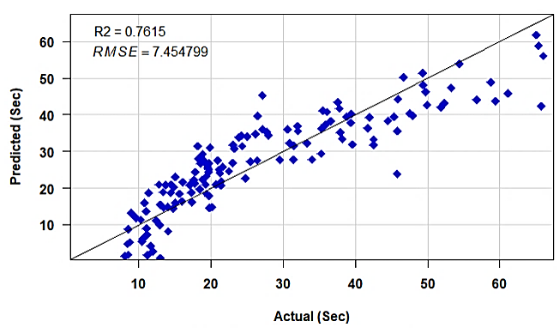
Table 6 Additional interactive input variables

No	Description	Notation
X_{14}	Distance Traveled × Total OD Volume	D_TVod
	$(X_2 \times (X_7+X_{10}))$	
X_{15}	Total Lane Volume × Total Conflicting Volume:	TVL_TVcon
	$(X_9+X_{12}) \times (X_8+X_{11}+X_{13})$	
X_{16}	Total number of conflict points × Total Lane Volume:	CP_TVL
	$\Sigma((X_3 \times X_8) + (X_4 \times X_{11}) + (X_5 \times X_{13}))$	

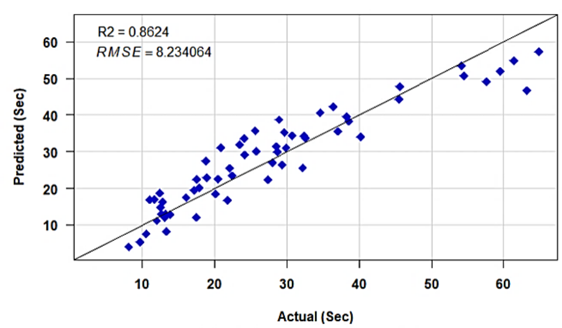
Thus, it has been found that the best performing regression prediction model for the delay is as shown in Equation (6-8). It is noted from Equation (6-7) and Equation (6-8) that the lane-changing ratio (Lch) is not a significant variable for predicting delay, however, it affects the total number of conflicts significantly.

$$\text{Average Delay (sec)} \\ = 2.52(\text{CrEx}) - 3.12(\text{CrSh}) - 47.34(\text{MeSh}) + 0.043(\text{CrEx}_{\text{Vcon}}) \\ + 0.026(\text{CrEx\_TVL}) + 0.019(\text{CrSh\_TVcon}) + 0.025(\text{CrSh}_{\text{TVL}}) \\ + 0.014(\text{TVL\_TVcon}) - (1.27 \times 10^{-5})(\text{CP\_TVL}) - 55.10 \tag{6-8}$$

Figure 44 shows the delay prediction made by the regression model. The values for R^2 and RMSE are presented on the top left side of the graphs. As shown in Figure 44, the RMSE values for the test and train models are close indicating the proposed regression models can predict the dependent variables very well.



a) Delay-Train Model



b) Delay-Test Model

Figure 44 Actual versus predicted delay using regression model

Comparing the Adjusted R^2 between two models (0.86 for the delay model and 0.96 for the conflicting request model) shows that regression model results in more accurate prediction for the total number of conflicting requests.

6.6.2 MGGP Predictive Models

In the next step, MGGP models were also developed by using the same training and testing datasets used for the regression models. The parameter settings are shown in Table 7.

Table 7 Training parameters setting for the MGGP models

Training parameters	Settings	
	Delay Model	Conflict Model
Function Set	$+, -, \times, /, sqrt, square$	
Population size	250	
Number of Generations	100	50
Maximum number of genes allowed in an individual	5-10	
Maximum tree depth	6	5
Number of runs	5	
Tournament size	50	
Tournament type	Pareto (probability = 1)	
Number of inputs	13	
Elite fraction	0.7	
Complexity measure	Node Count	
Fitness Function	Regressmulti_fitfun.m	

6.6.2.1 MGGP- Conflict Model

MGGP-Conflict model represents the total number of conflicting requests. The best-developed model consists of 7 individual genes which are presented in Table 8 by Equations (6-9) to (6-16).

Table 8 MGGP- Conflict model genes

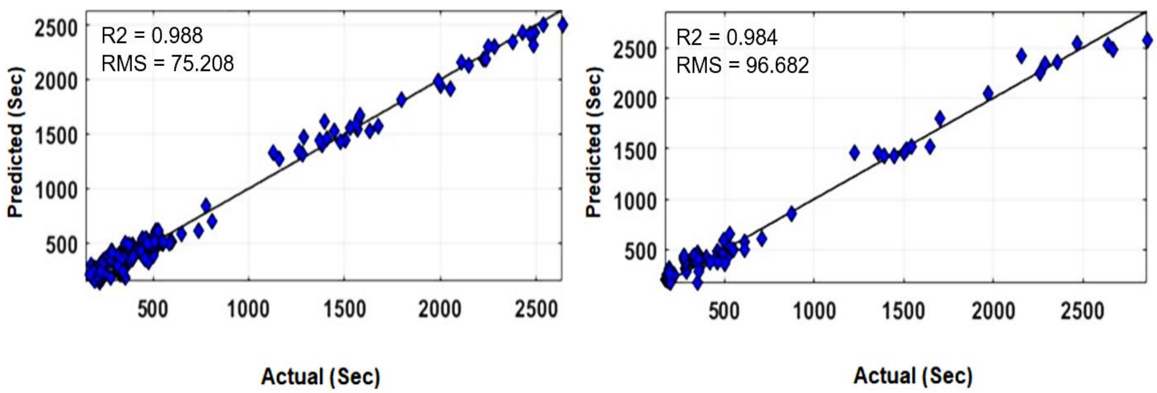
$\mathrm{Bias} = 3.577\times10^{-4}$	**(6-9)**
$\mathrm{Gene1} = -0.2391\,(\lvert \mathrm{CrEx\_Vcon} - \mathrm{CrSh\_TVL} / G \rvert)$	**(6-10)**
$\mathrm{Gene2} = 0.4519\,(\lvert \mathrm{MeSh} - \mathrm{CrEx\_Vcon} \rvert)^{1/2}\,(\lvert G + \mathrm{CrEx\_TVL} \rvert)^{1/2}$	**(6-11)**
$\mathrm{Gene3} = 1.363\times10^{-3}\,(\mathrm{CrEx\_Vod} \times \mathrm{CrEx\_Vcon} - \mathrm{MeSh} \times \mathrm{MeSh\_TVcon})\,(\mathrm{CrEx\_Vcon} - \mathrm{CrEx\_Vod} + \lvert \mathrm{MeSh\_TVcon} \rvert^{1/2})$	**(6-12)**
$\mathrm{Gene4} = 0.1929\,[(\mathrm{MeSh\_TVcon} + D \times \mathrm{Lch} - G \times \mathrm{CrSh\_TVcon}) + (\lvert \mathrm{MeSh} \rvert^{1/2})\,(\mathrm{CrSh\_TVL} + 0.9078)\,(-\mathrm{CrEx\_TVL}^{2} + \mathrm{CrEx\_TVL} + G)]$	**(6-13)**
$\mathrm{Gene5} = -1.363\times10^{-3}\,[(\mathrm{CrEx\_Vod} \times \mathrm{CrEx\_Vcon} - \mathrm{MeSh} \times \mathrm{MeSh\_TVcon})\,(\mathrm{CrEx\_Vcon} - \mathrm{CrEx\_Vod} + \lvert \mathrm{MeSh\_TVcon} \rvert^{1/2}) + (\lvert \mathrm{MeSh} \rvert^{1/2})\,(\mathrm{CrSh\_TVL} + 0.9078)\,(G + \mathrm{CrEx\_TVL} - \mathrm{MeSh}^{1/2})]$	**(6-14)**
$\mathrm{Gene6} = 0.1906\,[(G.\,\mathrm{CrSh\_TVcon} - \mathrm{CrSh\_Vod} - \mathrm{CrEx\_Vod} - (\lvert \mathrm{MeSh\_TVcon} \rvert^{1/2} / \lvert G \rvert^{1/2}) - (\lvert \mathrm{MeSh} \rvert^{1/2})\,(\mathrm{CrSh\_TVL} + 0.9078)\,(-\mathrm{CrEx\_TVL}^{2} + \mathrm{CrEx\_TVL} + G)]$	**(6-15)**
$\mathrm{Gene7} = 2.338\times10^{-3}\,(\mathrm{CrSh\_Vod} \times \mathrm{CrSh\_TVcon} - G - \lvert G \rvert^{1/2}\,(\mathrm{CrEx\_TVL} + \mathrm{CrSh\_TVL}) - (\lvert \mathrm{MeSh} \rvert^{1/2})\,(\mathrm{CrSh\_TVL} + 0.9078)\,(-\mathrm{CrEx\_TVL}^{2} + \mathrm{CrEx\_TVL} + G)]$	**(6-16)**

Simplified overall GP expression for MGGP-Conflict model is presented as Equation (6-17).

Total number of conflicting requests =

$$0.1929\,(\mathrm{MeSh\_TVcon} + D \times \mathrm{Lch}) - 0.1906\,(\mathrm{CrEx\_Vod} + \mathrm{CrSh\_Vod}) - 2.338\times10^{-3}\,(G - \mathrm{CrSh\_Vod} \times \mathrm{CrSh\_TVcon}) - 0.2391\,(\lvert \mathrm{CrEx\_Vcon} - \mathrm{CrSh\_TVL} / G \rvert) - 2.337\times10^{-3}\,G \times \mathrm{CrSh\_TVcon} + 0.4519\,(\lvert (\mathrm{MeSh} - \mathrm{CrEx\_Vcon})\,(G + \mathrm{CrEx\_TVL}) \rvert)^{1/2} + 5.304\times10^{-7}\,(\mathrm{CrEx\_Vod} \times \mathrm{CrEx\_Vcon} - \mathrm{MeSh} \times \mathrm{MeSh\_TVcon})\,(\mathrm{CrEx\_Vcon} - \mathrm{CrEx\_Vod} + \lvert \mathrm{MeSh\_TVcon} \rvert^{1/2}) - 0.1906\,(\lvert \mathrm{MeSh\_TVcon} \rvert^{1/2} / \lvert G \rvert^{1/2}) - 2.338\times10^{-3}\,\lvert G \rvert^{1/2}\,(\mathrm{CrEx\_TVL} + \mathrm{CrSh\_TVL}) - 1.363\times10^{-3}\,(\lvert \mathrm{MeSh} \rvert^{1/2})\,(\mathrm{CrSh\_TVL} + 0.9078)\,(G + \mathrm{CrEx\_TVL} - \mathrm{MeSh}^{1/2}) - 1.169\times10^{-6}\,(\lvert \mathrm{MeSh} \rvert^{1/2})\,(\mathrm{CrSh\_TVL} + 0.9078)\,(-\mathrm{CrEx\_TVL}^{2} + \mathrm{CrEx\_TVL} + G) + 3.577\times10^{-4} \tag{6-17}$$

Figure 45 shows the prediction made by the MGGP models for the total number of conflicts. The values for R^2 and RMS, presented at the top of the graphs, show that the MGGP model accurately predicts the number of conflicting requests.



a) Conflict-Train Model b) Conflict-Test Model

Figure 45 Actual versus predicted conflicts using MGGP model

6.6.2.2 MGGP- Delay Model

MGGP-Delay model represents the average delay in seconds. The 10-gene model proved to be the most effective. Individual gene expressions are listed in Table 9 by Equations (6-18) to (6-28).

Table 9 MGGP-Delay model genes

Bias = –75.4	**(6-18)**
Gene1 = 5.693×10^{-5} (CrSh_TVL ^{2} – CrEx_TVL) + 4.149×10^{-4} CrSh_TVL	**(6-19)**
Gene2 = 9.784 | D |$^{1/4}$ (CrEx + | CrEx_TVL |$^{1/4}$)	**(6-20)**
Gene3 = –22.93 | CrEx_TVL |$^{1/2}$	**(6-21)**
Gene4 = 1.859 (|CrSh_TVcon |$^{1/2}$ + | CrEx – G + MeSh + CrEx_Vod |$^{1/4}$)	**(6-22)**
Gene5 = (2.541×10^{-5} CrSh_Vod ^{2} | CrSh_TVcon |$^{1/2}$) / | G |$^{1/2}$	**(6-23)**
Gene6 = (13.22 / | Lch -3.764|$^{1/2}$) – 3.875 | D |$^{1/2}$	**(6-24)**
Gene7 = 5.724×10^{-4} (D – CrEx ^{2} + CrEx_Vod – CrSh_Vod ^{2})	**(6-25)**
Gene8 = 49.82 | G + CrEx_Vod + CrEx_Vcon + MeSh_TVcon |$^{1/4}$	**(6-26)**
Gene9 = 0.4386 CrEx_TVL	**(6-27)**
Gene10 = –78.77 (CrEx + | MeSh |$^{1/2}$)	**(6-28)**

Simplified overall GP expression for MGGP-Delay model is presented as Equation (6-29).

Average delay (sec) =

$$5.724\times10^{-4} (D - CrEx^{2} + CrEx\_Vod - CrSh\_Vod^{2}) - 78.77 (CrEx + | MeSh |^{1/2}) + 0.4385\ CrEx\_TV + 4.149\times10^{-4}\ CrSh\_TVL + 49.82 | G + CrEx\_Vod + CrEx\_Vcon + MeSh\_TVcon |^{1/4} + 9.784 | D |^{1/4} (CrEx + | CrEx\_TVL |^{1/4}) + (13.22 / | Lch - 3.764|^{1/2}) - 3.875 | D |^{1/2} - 22.93 | CrEx\_TVL |^{1/2} + 1.859 (|CrSh\_TVcon |^{1/2} + | CrEx - G + MeSh + CrEx\_Vod |^{1/4}) + 5.693\times10^{-5}\ CrSh\_TVL^{2} + (2.541\times10^{-5}\ CrSh\_Vod^{2} | CrSh\_TVcon |^{1/2}) / | G |^{1/2} - 75.4 \quad \textbf{(6-29)}$$

Figure 46 illustrates three randomly selected MGGP-delay model gene trees to compare the complexity and operations/logical functions applied.

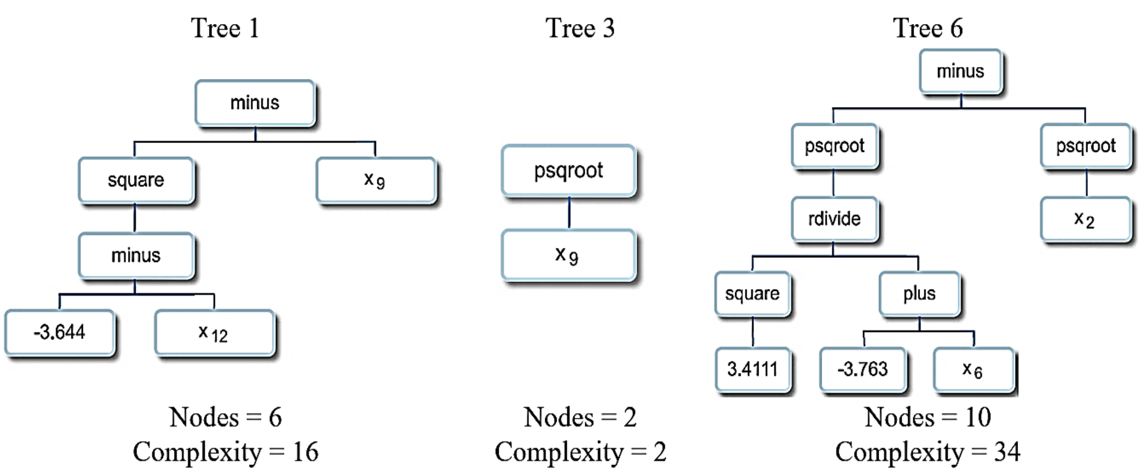
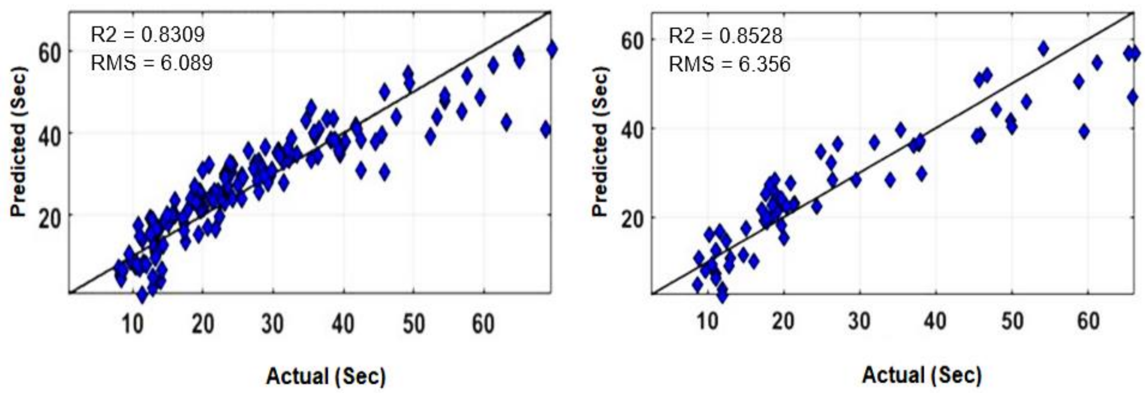


Figure 46 MGGP-Delay model-Sample individual gene trees

Figure 47 shows the prediction made by the MGGP models for the delay. It is noticeable that the delay regression model that includes the interaction terms (presented in section 6.6.1.2) has almost the same R2 values as the MGGP delay model. Accordingly, it suggests the interaction variable terms in the regression delay model, which improve its performance, are appropriately defined.



a) Delay-Train Model b) Delay-Test Model

Figure 47 Actual versus predicted delay using MGGP model

6.6.3 Parametric Analysis

To ensure the robustness of the developed models, a parametric analysis was performed to investigate the impact of the independent variables on the delay and number of conflicting requests. In this analysis, a single parameter is varied within a practical range, whereas other parameters are kept at their average values. Figure 48 shows the result for the OD traffic volume and conflicting traffic volume on both exclusive and shared lanes. As shown in the figure the OD traffic volume in a lane and the total conflicting volume have significant impacts on the delay time.

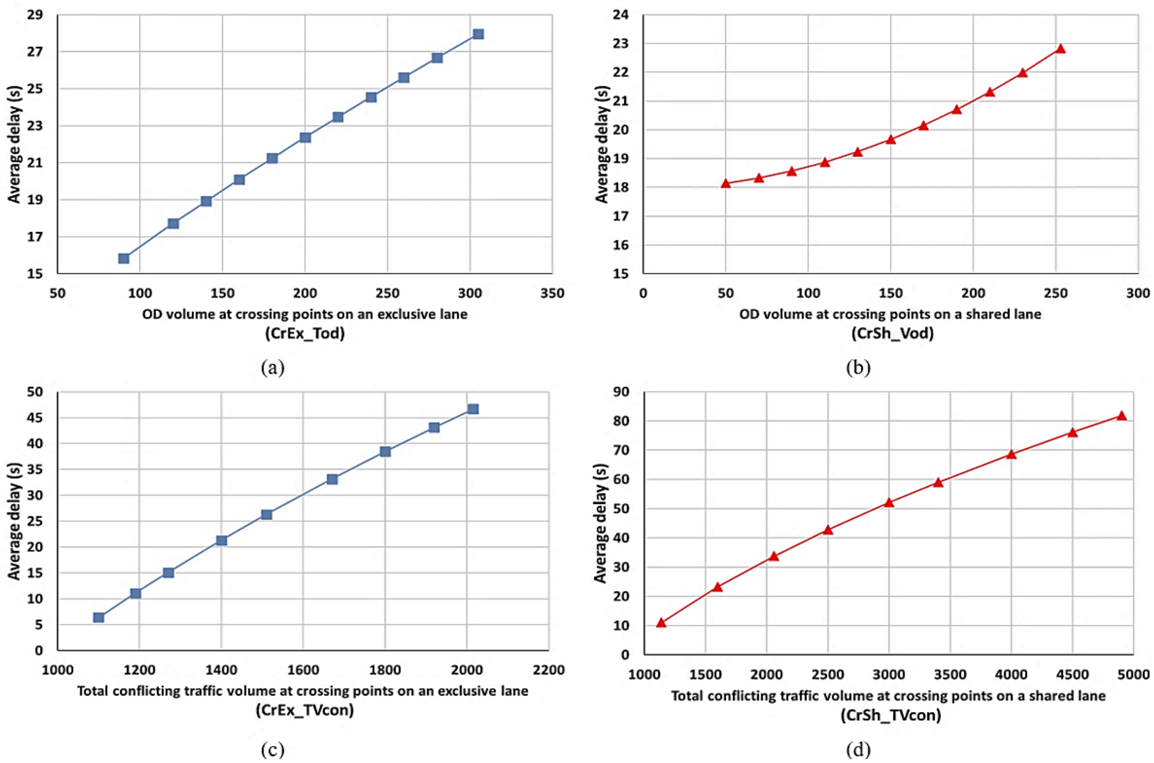


Figure 48 Parametric analysis of the developed models

6.7 Conclusions

This chapter presents novel formulations for predicting the delay and number of conflicting requests for a Combined Flexible Lane Assignment and Reservation-based Intersection Control system that benefits from directionally unrestricted traffic flow management to enable the resolution of vehicular conflicts align links and within the intersection boxes to prevent traffic bottlenecks at intersections. This research adds originality to the area by:

- Developing a compound efficiency- potential conflict functions for predicting delay and conflicting requests for the RIC system. The proposed functions both can be used in the traffic assignment process.

- Incorporating the number and characteristics of conflict points (e.g., conflict type and sharing status of the corresponding lane) in conflicting flow calculation.

A comprehensive OD level database was developed by testing 36 various reservation-based scenarios on a hypothetical three-intersection segment where the three lane-sharing scenarios (TR, TL, and TRL) are investigated under various proportions of shared through traffic (varies from 15% to 60%) and considering two traffic demand levels. Correlations were developed utilizing regression, and a powerful evolutionary computation (EC) method known as Multi-Gene Genetic Programming (MGGP). The performance of the developed models is evaluated using the test datasets. Both regression and MGGP conflicting request models have shown a very good prediction ability in the present context with a coefficient of determination (R^2) value of 0.96 and 0.98, respectively. However, because of the inherent nonlinearity in the delay data, the R^2 value for the delay model is lower when compared to the conflicting request models.

The regression model for delay which only considers the simple form of the variable does not show promising result ($R^2<0.7$). However, adding three interactive terms to the independent variables improve the performance of the regression model significantly ($R^2= 0.86$ for the train dataset). The MGGP delay model performed almost the same ($R^2 = 0.85$).

Considering the interpretable equation-based results of MGGP, these models are promising tools to be considered in the future to develop Reservation-based intersection delay-conflict-volume equations to determine the LOS of such a system in an automated environment. Although the performance of the proposed model has been evaluated by using the test dataset, further research is needed to validate the proposed models with various traffic volume scenarios, network geometries, and priority rules (other than FCFS).

7.0 Chapter 7 - Optimized Flexible Lane Assignment Using Metaheuristic algorithms

The presented objective in this chapter is currently in preparation for publication:

Azadi, F., Mitrovic, N., & Stevanovic, A.; Optimized Flexible Lane Assignment Using Metaheuristic algorithms.

7.1 Overview

In recent years, technological advances with connected and autonomous vehicles (CAVs) have opened opportunities to increase the efficiency of transportation networks. A novel control framework called Combined Flexible Lane Assignment and Reservation-Based Intersection Control (CFLARIC) system has been recently proposed for the management of directionally unrestricted CAVs traffic flows in an urban environment. The objective of this chapter is to address the flexible traffic lane assignment in such a system as a network optimization problem, in which an optimal lane assignment schema is achieved using metaheuristic optimization algorithms. To this end, simulation modeling is performed in NetLogo, and the BehaviorSearch tool of NetLogo is used for the optimization process. The output of the optimization process is the lane assignment that leads to a minimum total travel time for a given network and traffic volumes. Results indicate that the optimal scenario outperforms the conventional lane assignment.

7.2 Introduction

Recent advancements in the Information Technology (IT) sector and automotive industry have motivated researchers to develop innovative traffic control mechanisms such as Autonomous Intersection Managements (AIMs) (Dresner and Stone, 2004; Stevanovic and Mitrovic, 2018) that coordinate vehicle movements to ensure collision-free passage through intersections. Reservation-based Intersection Control (RIC), one of the novel urban traffic control concepts, has been addressed in different studies (A detail literature review is provided in Chapter 2). As the RIC does not guarantee optimality (Levin et al., 2016) several attempts have been done to utilize optimization-based methods to improve the efficiency of such systems some of which are described in Chapter 2. However, despite the great contributions of the studies cited in the literature, none of them explored potential challenges to fully utilizing road infrastructure and to minimize conflicts at the intersections by releasing the strong directional constraints.

As a solution to the above problem, two innovative control frameworks called Combined Alternate-Direction Lane Assignment and Reservation-based Intersection Control (CADLARIC) (Stevanovic and Mitrovic, 2018), and Flexible Lane Assignment and Reservation-Based Intersection Control (CFLARIC) system (Azadi et al., 2021) have been introduced in this study. CFLARIC can be considered a more flexible version of CADLARIC which further relaxes constraints of how various lanes can be utilized. The details of the main control concepts in CADLARIC/CFALRIC are explained in Chapter 3, sections 3.2 and 3.3. In such frameworks, vehicles can use lanes that are traditionally reserved for the opposite direction but they need to align themselves in desired lanes before reaching the downstream intersection. The RIC algorithm handles the conflicts at the intersections.

The preliminary results of testing CFLARIC in the field-like conditions (is presented in Chapter 4), and in a very congested hypothetical traffic network (is presented in Chapter 5) prove that the proposed flexible system brings significant operational benefits in terms of efficiency and safety. Although, CFLARIC has the potential to provide a whole spectrum of possible lane assignment scenarios, in the previous chapters, only some lane assignment scenarios have been designed using some preset rules and based on the research objectives. Therefore, although the proposed CFLARIC scenarios outperformed other control systems such as Fixed-Time Control (FTC) and Full Reservation-based Control (FRIC) systems in the given condition, the optimality of their performance has not been studied. Thus, the goal of this chapter is to consider all the possible (and feasible) lane assignments scenarios and find the optimal one(s) by using a metaheuristic optimization algorithm for a given network and traffic demand.

7.3 Methodology

7.3.1 Framework and Terminology

In a fully connected and automated environment, where vehicles communicate with each other (and with infrastructure), constraints of lane assignments do not have to be as restrictive as those in the traditional fixed-lane systems. In such a flexible network, with no physical medians between travel lanes, a vehicle can travel on any part of the road, as long as it does not endanger the other road users. Also, the number of directional lanes can change dynamically in response to the variations in traffic demand. In such a case there would be multiple combinations of paths for vehicles to travel from their origins to destinations. To present such a flexible lane assignment the following framework and terminology are introduced.

For a given urban network (Figure 49), let us index intersections and lanes by η and l , respectively, where $\eta = 1, \dots, N$ and $l_{i,j}^{\eta,d}$ is a lane with an ID = j at arm i of an intersection η carries traffic in direction d.

$i = 1, \dots, I_\eta$, where I_η is the number of approaches/arms at the investigated intersection, (In Figure 49 are shown in rectangles next to the arms)

$j = 1, \dots, J_{i_\eta}$, where J_{i_η} is the number of lanes on the approaching arm i of the intersection η.

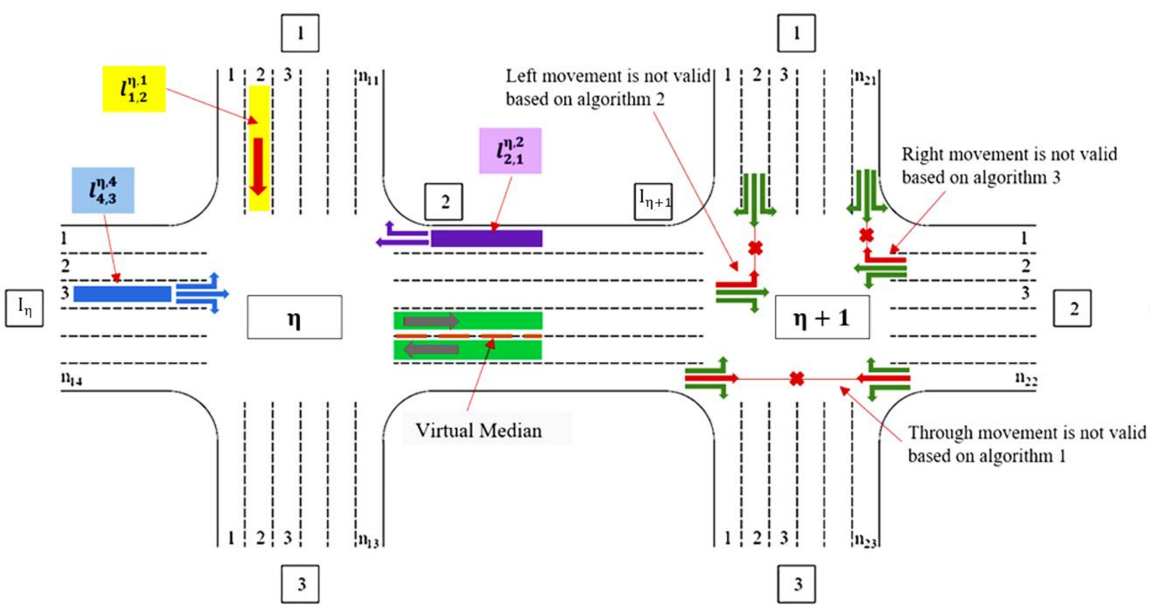


Figure 49 Illustration of different states of a lane assignment

The direction of a lane is defined clockwise as d= 1, …, 4, starting from the north side of the intersection where:

$$d_{i,j}^{\eta} = \begin{cases} 1, & \text{if } l_{i,j}^{\eta} \text{ carries traffic in the NS direction} \\ 2, & \text{if } l_{i,j}^{\eta} \text{ carries traffic in the EW direction} \\ 3, & \text{if } l_{i,j}^{\eta} \text{ carries traffic in the SN direction} \\ 4, & \text{if } l_{i,j}^{\eta} \text{ carries traffic in the WE direction} \end{cases} \tag{7-1}$$

Therefore, $l_{1,2}^{\eta,1}$, for example, represents lane # 2 in arm # 1 of the intersection η, which carries traffic in the NS direction (shown in Figure 49 by yellow color). The traffic lanes are numbered (with lane IDs) consecutively from the left to the right, in the SN and WE directions. Therefore, for a vehicle traveling from an upstream to a downstream intersection, the lane ID has a constant value until the vehicle changes its lane. A concept of a virtual median (VM) is defined earlier in Chapter 3 that is placed between any two adjacent lanes in different directions. The VM means that a vehicle from the opposite direction cannot permanently take that lane but it can cross it if it needs to reach another lane of its direction. Therefore, for any two adjacent lanes with a virtual median the condition in Equation (7-2) is satisfied.

$$|d_{i,j}^{\eta} - d_{i,j+1}^{\eta}| = 2 \tag{7-2}$$

For any arm i at intersection η the total number of lanes in one direction is defined with Equation (7-3) and is less than or equal to the total number of lanes in the subject arm (J_{i_η}). However, as this study assumes that vehicles traveling from all origins to all destinations, at least one lane in each approach needs to be considered for the exiting traffic.

$$nL_{i,d}^{\eta} = \text{Count}\left(l_{i,j}^{\eta,d}\right) \tag{7-3}$$

$$nL_{i,d}^{\eta} \leq J_{i_\eta} - 1 \tag{7-4}$$

In this chapter, unlike with the previous experiments presented in Chapter 4 and Chapter 5, there are no pre-defined lane assignments. Therefore, at the initialization step, each lane, of each arm, can be assigned to any of the three movements (through, right- and left-turns) at a downstream intersection. Thus, a list of binary variables ($\delta_{i,j}^{\eta,d}$), Equations (7-5) to (7-8), is introduced to indicate whether a movement is assigned to a lane or not.

$$\delta_{i,j}^{\eta,d} = (\mathrm{m}_1, \mathrm{m}_2, \mathrm{m}_3) \text{ where ;} \tag{7-5}$$

$$m_1 = \begin{cases} 1, & \text{if } l_{i,j}^{\eta,d} \text{ is assigned to a left} - \text{turn movement} \\ 0, & \text{otherwise} \end{cases} \tag{7-6}$$

$$m_2 = \begin{cases} 1, & \text{if } l_{i,j}^{\eta,d} \text{ is assigned to a through movement} \\ 0, & \text{otherwise} \end{cases} \tag{7-7}$$

$$m_3 = \begin{cases} 1, & \text{if } l_{i,j}^{\eta,d} \text{ is assigned to right} - \text{turn movement} \\ 0, & \text{otherwise} \end{cases} \tag{7-8}$$

As an example, for the movements assigned to the lane $l_{4,3}^{\eta,4}$, $\delta_{4,3}^{\eta,4}$ has a value of $(1,1,1)$ (highlighted in Figure 49 with a blue color). Although all three movements can be assigned to a lane, not all lanes can be shared by all of the movements. For example, as shown in Figure 49, if lane # 2 of arm # 1 at intersection $\eta + 1$ is assigned to the through movement in the exiting direction (SBT), no left turn from arm # 4 of that intersection (EBL) is allowed to enter that lane. More examples have been presented in Figure 49 (red arrows at intersection $\eta + 1$). To eliminate such unacceptable lane assignments, several constraints are considered from which the three algorithms are presented in the following.

Algorithm 1: Constraint for the through movements

for i in range (1, …,4)
set $\delta_{i,j}^{\eta,d} = (1,1,1)$
  if (j=j')
    if (i≤2)
      if $d_{i,j}^{\eta} \neq d_{i+2,j'}^{\eta}$, **then**
        set $\delta_{i,j}^{\eta,d} = (m_1, 0, m_3)$
        set $\delta_{i+2,j'}^{\eta,d} = (m_1, 0, m_3)$
    else
      if $d_{i,j}^{\eta} \neq d_{i-2,j'}^{\eta}$, **then**
        set $\delta_{i,j}^{\eta,d} = (m_1, 0, m_3)$
        set $\delta_{i-2,j'}^{\eta,d} = (m_1, 0, m_3)$

Algorithm 2: Constraint for the left-turn movements

for i in range (1, …,4)
set $\delta_{i,j}^{\eta,d} = (1, m_2, 1)$; m_2 is extracted from Algorithm 1
  if i≠4
    if $d_{i,j}^{\eta} - d_{i+1,j'}^{\eta} = -1$ **then**
      set $\delta_{i,j}^{\eta,d} = (0, m_2, m_3)$
  else
    if $d_{i,j}^{\eta} - d_{i-3,j'}^{\eta} = 3$ **then**
      set $\delta_{i,j}^{\eta,d} = (0, m_2, m_3)$

Algorithm 3: Constraint for the right-turn movements

for i in range (1, …,4)
set $\delta_{i,j}^{\eta,d} = (m_1, m_2, 1)$; m_1 and m_2 are extracted from Algorithms 2 and 1, respectively.
  if i≠4
    if $d_{i,j}^{\eta} - d_{i-1,j'}^{\eta} = 1$ **then**
      set $\delta_{i,j}^{\eta,d} = (m_1, m_2, 0)$
  else
    if $d_{i,j}^{\eta} - d_{i+3,j'}^{\eta} = -3$ **then**
      set $\delta_{i,j}^{\eta,d} = (m_1, m_2, 0)$

7.3.2 Simulation-Optimization Process

As mentioned in Chapter 3, the simulation environment for modeling the CFLARIC scenarios is modeled in NetLogo through a series of custom-made codes. The entire road network is discretized into cells to enable space reservation at the intersections (and for lane-changing processes), to resolve conflicts, and to evaluate performance of various traffic control scenarios.

The BehaviorSearch tool of NetLogo (BehaviorSearch.org) has been used for the optimization. This tool automates the exploration of agent-based modeling processes, by using various heuristic techniques (e.g., Genetic Algorithms, Random Search). The BehaviorSearch is interfaced with NetLogo' s code that executes CFLARIC scenarios, to search for combinations of model parameters that will result in near-optimal target behavior (Calabrò et al., 2020; Kponyo et al., 2017). Figure 50 indicates a flowchart for a high-level perspective of the combined simulation and optimization processes.

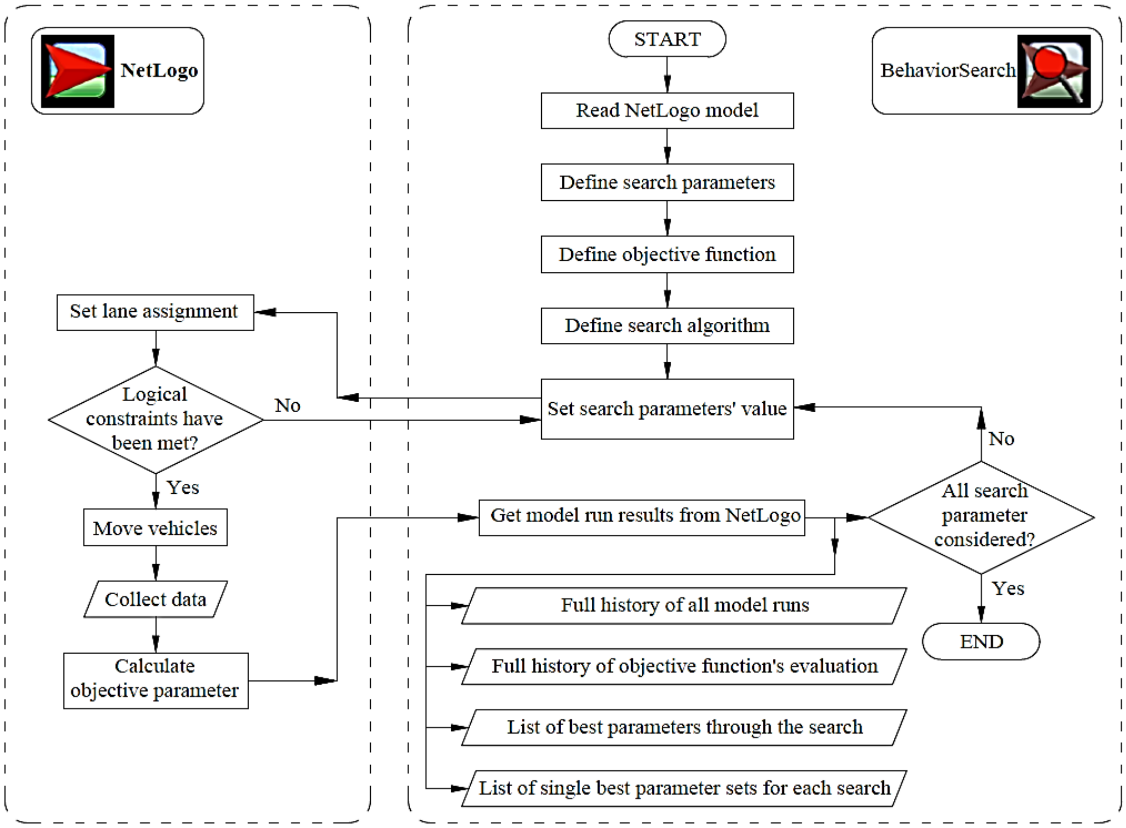


Figure 50 Combined simulation and optimization process

7.3.2.1 Test-case Network

The experiments are performed on a generic 3-intersection network with six lanes in each approach and 8 Origin-destination pairs. Figure 51 shows all of the turning proportions of the main (East-West) and side (North-South) streets.

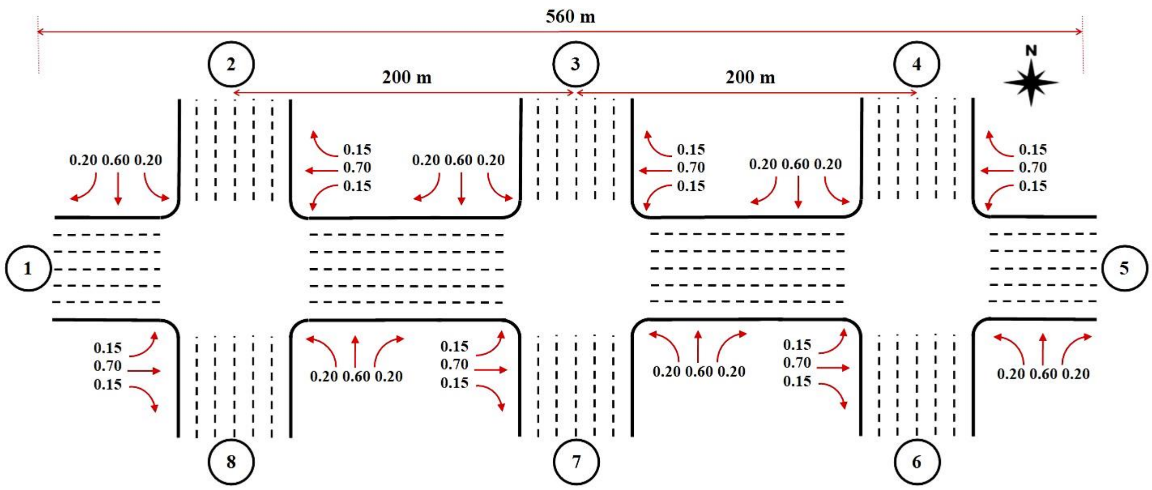


Figure 51 Geometric and traffic distribution of the test network

7.3.2.2 Optimization on the Major Street

In the first step, the flexible lane assignment has only been evaluated only on the major street (East-West), while the lane assignment on the minor streets (North-South) is fixed (three lanes in each direction). A total of 64 combinations exist for assigning two directions (east and west) to the six lanes in the main street, from which two combinations must be discarded as in those all of the lanes are assigned to one direction and they do not provide access to one of the destinations (1 or 5).

In Figure 52, each column represents a lane assignment combination on a major street. Zero represents lanes in the EB direction and one represents lanes in the WB direction. Each combination is known by a number (1 to 62) which is called “lane scenario parameter”. Although all three movements in one direction can use any of the available lanes in that direction, left- and right-turning vehicles need to align themselves in appropriate lanes before reaching the downstream intersection, to go through the intersection with minimum possible radius.

Lane Scenario Parameter	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
Binary code	000001	000010	000011	000100	000101	000110	000111	001000	001001	001010	001011	001100	001101	001110	001111	010000	010001	010010	010011	010100	010101
Lane 1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Lane 2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1
Lane 3	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0
Lane 4	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1
Lane 5	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0
Lane 6	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1

Lane Scenario Parameter	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42
Binary code	010110	010111	011000	011001	011010	011011	011100	011101	011110	011111	100000	100001	100010	100011	100100	100101	100110	100111	101000	101001	101010
Lane 1	0	0	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1
Lane 2	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0
Lane 3	0	0	1	1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1
Lane 4	1	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1	1	0	0	0
Lane 5	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1
Lane 6	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

Lane Scenario Parameter	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62
Binary code	101011	101100	101101	101110	101111	110000	110001	110010	110011	110100	110101	110110	110111	111000	111001	111010	111011	111100	111101	111110
Lane 1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Lane 2	0	0	0	0	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Lane 3	1	1	1	1	1	0	0	0	0	0	0	0	0	1	1	1	1	1	1	1
Lane 4	0	1	1	1	1	0	0	0	0	1	1	1	1	0	0	0	0	1	1	1
Lane 5	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1	1	0	0	1
Lane 6	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0	1	0

Lane direction		
	1	→
	0	←

Figure 52 Lane scenario parameters

By using Random Search algorithm, an optimization has been performed for 15 minutes of simulation time under two traffic volume scenarios:

- Lower traffic demand of 800 veh/hr on the major street and 540 veh/hr on the minor streets.
- Higher traffic demand of 1,200 veh/hr on the major street and 800 veh/hr on the minor streets.

7.3.2.3 Optimization on the Major and Minor Streets

In the next step, the flexible lane assignment has been evaluated on the major street and the minor streets. To reduce computation complexity, while the lane assignment could be different in the major and minor streets, it is considered the same in the three minor streets at each lane assignment combination. Therefore, considering 62 combinations for assigning two directions (east and west) to the six lanes in the main street and 62 combinations for assigning two directions (north and south) to the six lanes in the minor streets, a total of 3844 combinations are evaluated for the optimization purpose. Optimization has been performed for 15 minutes of simulation time under the same two traffic volume scenarios as the as the previous step.

7.4 Results and Discussion

7.4.1.1 Results on the Major Street

In what follows results of the search progress (only on the major street) are presented in Figure 53 and Figure 54, where the red labels show the values of the lane scenario parameter. Comparison of the results between the optimal scenarios and the conventional traffic lane assignment (lane scenario # 7) indicates that the flexible lane assignment improves the performance of the network.

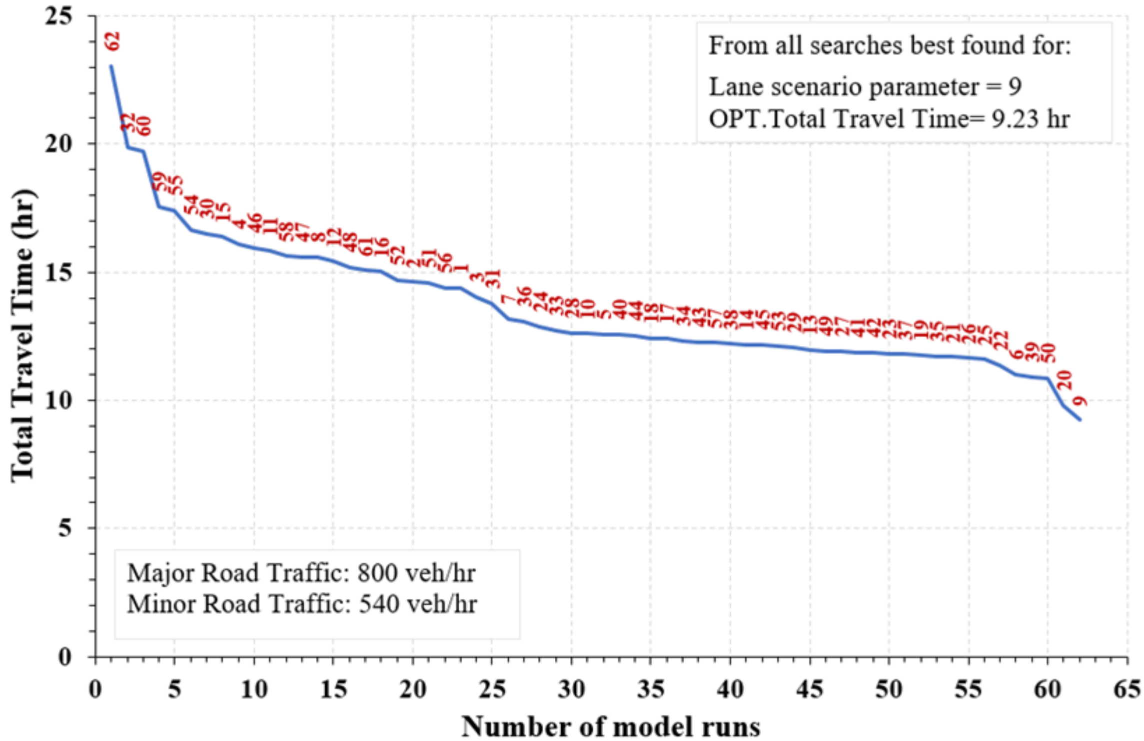


Figure 53 Search results on major street– Traffic volume scenario 1

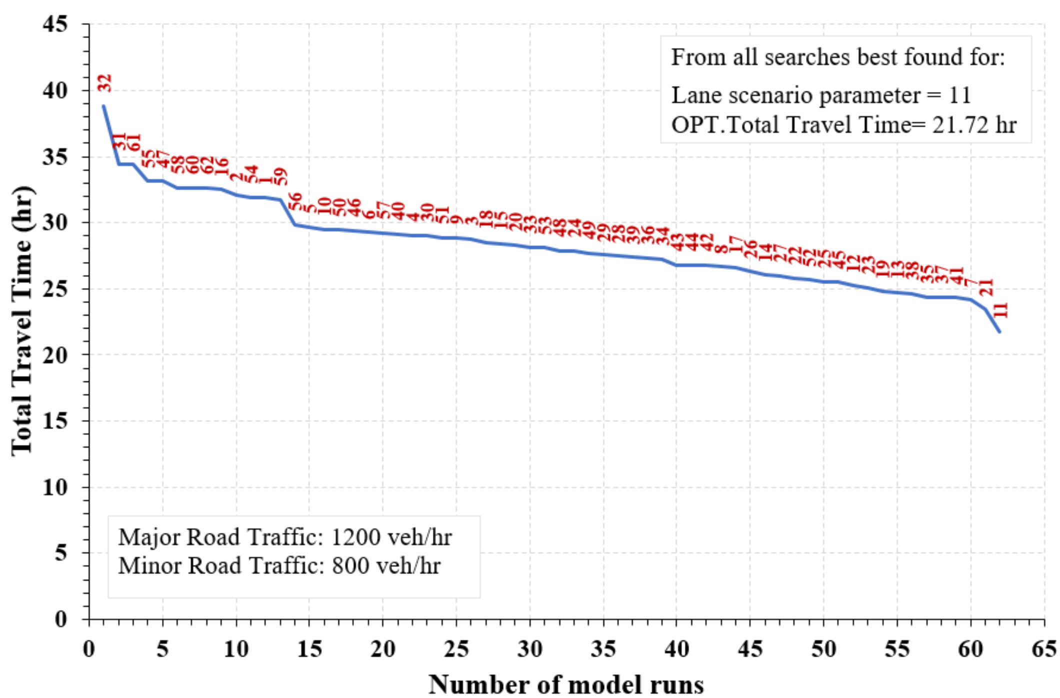


Figure 54 Search results on major street– Traffic volume scenario 2

Figure 55 and Figure 56 show the lane assignments of the two optimal scenarios, with red and blue colors representing lanes in the east-west and west-east directions, respectively.

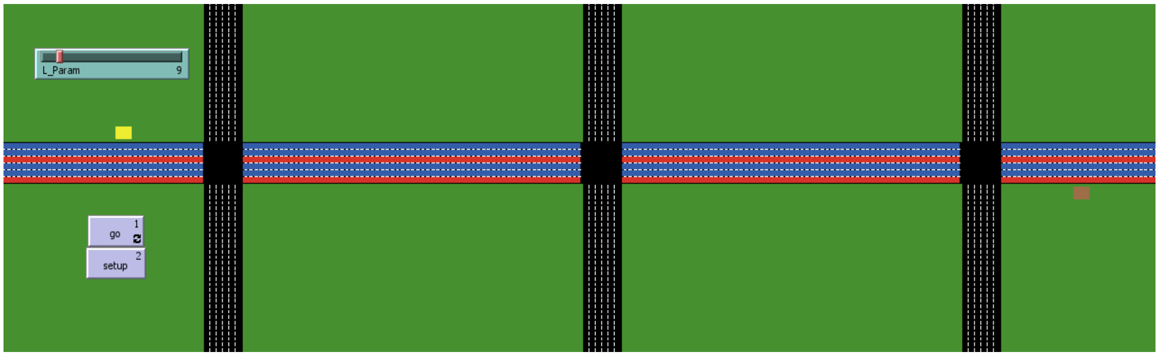


Figure 55 Optimal lane assignment – Lane scenario #9

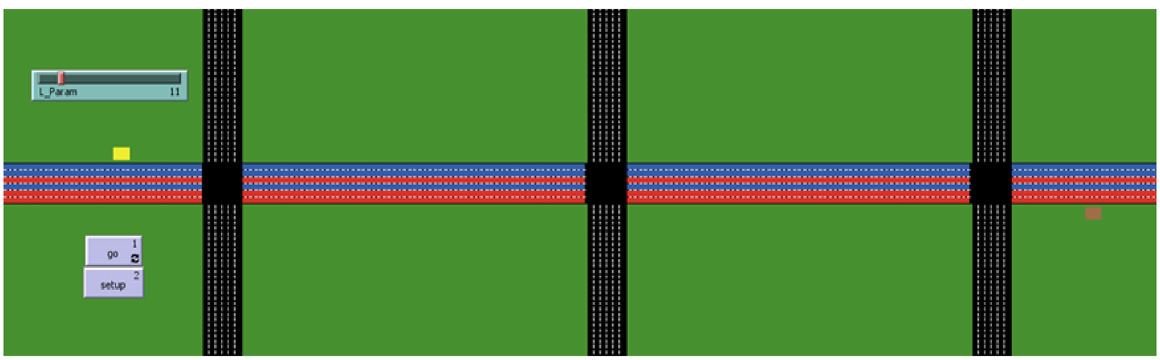


Figure 56 Optimal lane assignment – Lane scenario #11

7.4.1.2 Results on the Major and Minor Streets

A second stage optimization, which optimizes the lane assignments on major and minor streets, is currently being evaluated. A sample lane assignment scenario (from the 3844 possible combinations) is shown in Figure 57 with lane scenario #9 on the major street and lane scenario #38 on the minor streets. The red color represents lanes in the east to west and south to north directions and blue color represents lanes in the west to east and north to south directions.

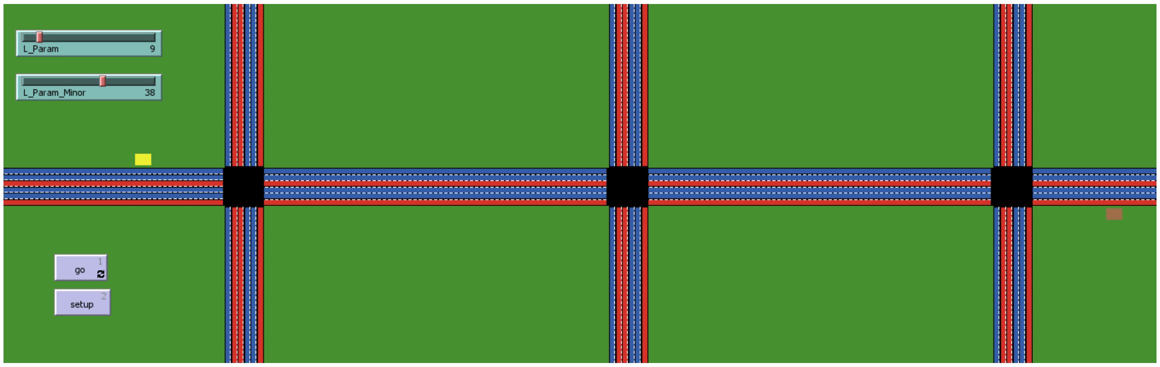


Figure 57 Sample lane assignment

7.5 Conclusions

This chapter presents the result of the flexible lane assignment optimization on Combined Flexible Lane Assignment and Reservation-based Intersection Control (CFLARIC). The simulation and optimization of lane assignment scenarios have been performed by using the NetLogo and Behavior Search. The optimum lane assignments have been found for two traffic volume scenarios. Currently, this work is optimizing flexible lane assignment on both major and minor roads considering various traffic volumes and distributions of traffic. The results will be added to this chapter.

8.0 Chapter 8 – Conclusions and Future Research

This chapter consists of two sections. In the first section, the conclusions of the research are presented. The second section provides the limitations of the research, as well as direction for future research.

8.1 Conclusions

Traffic congestion is a major issue in urban transportation systems, which not only results in loss of efficiency by causing substantial delay, but it also generates many critical safety events such as crashes and near-crashes and leads to significant negative environmental impact. Considering the environmental concerns and space limitations of urban areas, construction of new roads and broadening existing ones, to manage the growing traffic, are not accepted practices anymore. Therefore, there is a necessity to advance control mechanisms to better manage traffic flows in urban networks.

Connected and Autonomous Vehicles (CAVs) are promised to revolutionize urban transportation and bring significant efficiency and safety benefits to transportation users. This research is motivated by the need to address the everlasting increase in travel demand, support sustainability, preserve existing transport land use, and modify traffic control mechanisms to better utilize opportunities offered by emerging Connected and Autonomous Vehicles (CAVs).

The current methods for managing traffic flows in urban networks use a directional Right of Way (ROW) to organize traffic along urban roads and are focused on resolution of traffic conflicts at urban intersections. This approach turns such intersections into bottleneck points wherever traffic demand exceeds intersection capacities. However, in a fully automated driving environment, where vehicles communicate with each other and with infrastructure, and every single user has relevant information about adjacent users, current restrictions could be lifted.

This study contributes to the area of autonomous urban traffic control by presenting and evaluating a novel network control concept for fully connected and automated networks called Combined Flexible Lane Assignment and Reservation-based Intersection Control (CFLARIC). CFLARIC is a traffic control framework, more than a single traffic control strategy, which deploys directionally unrestricted traffic flows and the concept of Reservation-based intersection control where every traffic movement, when not endangering the other movements, can utilize any lane of the paved road surface. This premise helps to move the process of resolving vehicular conflicts from intersections boxes to mid-block zones, in which way it is able to eliminate a number of vehicular conflicts at the intersections. As the traditional simulation tools (e.g. Vissim / Aimsun) are not capable of modeling link-based models, a microsimulation tool called Flexible Arterial Utilization Simulation Modeling (FAUSIM) has been developed in NetLogo and used for simulation purposes in an agent-based modeling environment.

This study has four main objectives. In what follows the conclusions for each objective have been presented.

8.1.1 Application of CFLARIC in a Field-like Traffic Condition

CFLARIC is deployed on a field-like condition (tested on a three-intersection segment of 3500 S arterial in West Valley City, Utah). Three scenarios are proposed for this flexible control framework, (1) AL:2E3WA scenario allocates the lanes in an alternating fashion between two opposing directions, (2) MCLTM scenario is developed to reduce conflicts between the left-turn traffic and the other movements, and (3) MCTMHV reduces conflicts between high-volume turning movements (any) and all other movements. The scenarios are evaluated through a comparison with Fixed-Time Control (FTC), and Full Reservation-based Intersection Control (FRIC) for various Level-of-Services (LOSs B to D).

The comparison of performance measures in all scenarios under the field conditions (LOSC) shows that two of the proposed CFLARIC models (AL:2E3WA and MCTMHV) outperform the FTC and FRIC control regimes in terms of delay and number of stops. Although MCLTM does not show promising results in this study, it may prove beneficial under a different traffic distribution (e.g., when traffic demand is higher for the left-turns than for through and right-turn movements). Also, the number of crossing conflicts at intersections is lower for any of the CFLARIC control regimes than for the FRIC. Although the lane-changing conflicts are remarkably higher than in the case of FRIC, the total number of conflicts is still half of the total number of conflicts in FRIC, which is the true (surrogate safety) benefit of CFLARIC. AL:2E&3WA scenario performs the best when compared to the other scenarios and it is always followed by the MCTMHV. The former one decreases delay and number of stops, when compared to FRIC – the best non-CFLARIC control regime, by an average of 30% and 50%, respectively. The result of testing CFLARIC control regimes under three LOSs (B, C, and D) also shows consistency in their performances. In general, the findings of this study prove that CFLARIC (similarly as CADLARIC did for a hypothetical network (Stevanovic and Mitrovic, 2018), can bring significant benefits in terms of efficiency and reduction of vehicular conflicts. It can be concluded that CFLARIC, and similar flexible concepts have a great potential to improve the traffic control strategies in future of automated vehicle environments.

8.1.2 Application of CFLARIC in Congested Traffic Environments

This objective evaluates sharing capabilities of the CFLARIC to show that such concepts can bring significant benefits in congested traffic conditions. CFLARIC is deployed on a hypothetical three-intersection segment where three traffic lane-sharing scenarios (TR, TL, and TRL) are investigated under various proportions of through traffic (varies from 15% to 60%) being shared with one or both turning movements. To evaluate performance reliability of the proposed CFLARIC scenarios, they are tested under two LOSs (E and F). Also, the best performing CFLARIC scenarios (for each LOS, and each proposed sharing model) are evaluated through a comparison with two well-known control regimes: (1) Fixed-Time Control (FTC), and (2) Full Reservation-based Intersection Control (FRIC), as well as with an innovative control framework CADLARIC. The comparison of performance measures for all scenarios, under LOSs E and F, leads to the following conclusions:

- For LOS E, while the shared percentage is lower than 50%, the best sharing strategy (which results in the minimum delay, number of stops, and number of conflicts) is to share 30% of the through traffic with the right-turn lane.
- For LOS F, while the shared percentage is lower than 50%, sharing the excess through traffic with the right-turn lane is the best strategy. However, the optimal sharing percentage increases to 40%.
- For the shared proportions higher than 50%, the best CFLARIC scenarios are those in which the through traffic is shared with both turning movement lanes.
- The optimal CFLARIC scenarios (30% TR, and 40% TR) outperform FTC, FRIC, and CADLARIC control regimes (for the same traffic demands) in terms of delay, number of stops, and total number of conflicts.

- For the LOS E, when compared to the relevant FRIC scenario, the 30% TR CFLARIC scenario decreases delay and number of stops, by more than 80%.
- For the LOS F, when compared to the relevant FRIC scenario, the 40% TR CFLARIC scenario decreases delay and number of stops by more than 50%.
- The performances of two of the best performing CFLARIC scenarios (30% TR and 30% TRL) under LOS E and LOS F, are remarkably better than CADLARIC under LOS E. Since CADLARIC does not provide enough capacity for the demand scenario in LOS F, the results prove the applicability and robustness of the CFLARIC framework.

According to the results, when faced with different numbers and types of conflicts, the same percentage of shared through traffic could lead to significantly different delay times. In general, the findings of this objective prove that adopting traffic control concepts with more flexible lane assignments could has the potential to significantly improve traffic operations, in a CAV environment, even in congested traffic. Although various types of roads and intersections would see different levels of efficiency benefits from the CFLARIC model, but the core of the proposed conflict-resolution strategies will always bring some improvements.

8.1.3 Delay and Conflicting Request Predictive Models

A comprehensive OD level database was developed by testing 36 various reservation-based scenarios on a hypothetical three-intersection segment where the three lane-sharing scenarios (TR, TL, and TRL) are investigated under various proportions of shared through traffic (varies from 15% to 60%) and considering two traffic demand levels. Correlations were developed utilizing regression, and a powerful evolutionary computation (EC) method known as Multi-Gene Genetic

Programming (MGGP). The performance of the developed models is evaluated using the test datasets. Both regression and MGGP conflicting request models have shown a very good prediction ability in the present context with a coefficient of determination (R^2) value of 0.96 and 0.98, respectively. However, because of the inherent nonlinearity in the delay data, the R^2 value for the delay model is lower when compared to the conflicting request models. The regression model for delay which only considers the simple form of the variable does not show a promising result (R^2<0.6). However, adding three interactive terms to the independent variables improve the performance of the regression model significantly (R^2= 0.86 for the training dataset). The MGGP delay model performed almost the same (R^2 = 0.85).

This objective adds originality to the area by:

- Developing a compound efficiency- potential conflict functions for predicting delay and conflicting requests for a network with flexible lane assignment and Reservation-based Intersection Control. The proposed functions both can be used in the traffic assignment process.
- Incorporating the number and characteristics of conflict points (e.g., conflict type and sharing status of the corresponding lane) in conflicting flow calculation.

8.1.4 Optimized Flexible Lane Assignment Using Metaheuristic algorithms

The proposed control framework, CFLARIC, has the potential to provide a whole spectrum of possible lane assignment scenarios in a network. However, in Chapters 4,5, and 6, only some lane assignment scenarios have been designed using some preset rules and based on the research objectives of those chapters. Therefore, although the results have shown that the proposed CFLARIC scenarios outperformed other control systems such as Fixed-Time Control (FTC) and

Full Reservation-based Control (FRIC) systems in the given condition, the optimality of their performance has not been studied. Thus, the goal of this chapter is to consider all the possible (and feasible) lane assignments scenarios and find the optimal one(s) by using a metaheuristic optimization algorithm for a given network and traffic demand. To this end, simulation modeling is performed in NetLogo, and the BehaviorSearch tool of NetLogo is used for the optimization process. The output of the optimization process is the lane assignment that leads to a minimum total travel time for a given network and traffic volumes. The result of optimization on the major street indicate that the optimal CFLARIC scenario outperforms the conventional lane assignment. Simultaneous optimization of major and minor streets is being analyzed and will be added to this chapter.

8.2 Limitations and Future Research

The proposed futuristic traffic control system in this study opens up a wide range of possibilities for expanding the current research in a number of directions:

- So far, CADLARIC, and CFLARIC have been compared with two control systems; FTC and FRIC. Future research could compare CFLARIC with other common types of traffic control (e.g., actuated, adaptive).
- As is mentioned in the assumptions, this study does not consider pedestrian and other multimodal operations at this stage. Future research will evaluate the performance of CFLARIC in multimodal operations.
- At this stage, all of the tested lane assignments schemas are preset and remain fixed during the entire simulation time. Developing CFLARIC scenarios with

'adaptive/dynamic' lane assignment, where lane assignments (as in the concept of "reversible lanes") change based on the traffic is another direction for this research.

- In this study, CFLARIC follows the First Come First Served (FCFS) ordering policy within its reservation process. Future research will evaluate the performance of CFLARIC with various priority rules.
- Further research is suggested to investigate the impact of the reservation-based control parameters as well as the reliability of the conflict resolution logic, on the efficiency and surrogate safety of CFLARIC for various levels of traffic demand.
- Future studies will assess the effect of the "intersection spacing" on the performance of the control system (i.e. performance of the cooperative lane changing process) and evaluate the reliability of the conflict resolution logic. The number of vehicles (if any) that do not reach their destinations (because they could not change their lanes before reaching the downstream intersection) can be considered a performance metric for evaluating the lane changing process. In addition, criteria for the minimum required spacing for given volumes and origin/destination patterns will be provided.
- Future studies can assess the operation of mixed fleets of conventional and automated vehicles in so many ways. With knowing the exact context of the operations of conventional vehicles and CAVs, the applicability of CADLARIC and CFLARIC can be discussed, and their performances can be evaluated in such a network. It is expected that the mixed fleet will limit efficiency of the proposed control framework when compared to a fully connected and automated environment.

- The performance of the predictive delay and conflict models, presented in Chapter 6, has been evaluated by using the training dataset. Further research is needed to validate the proposed models for various traffic volumes, network geometries, and priority rules.

Appendix A Simulation of CFLARIC Models in FAUSIM

Several videos from simulation of the proposed CFLARIC scenarios in FAUSIM are accessible on the PITTS-LAB website.

https://www.engineering.pitt.edu/subsites/Labs/pitts-lab/arterial-traffic-control-for-cavs/

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