ADAPTIVE TRAFFIC CONTROL SYSTEM: DESIGN AND SIMULATION

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Abstract

Adaptive Traffic Control System: Design and Simulation

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Traditional traffic control infrastructures have not changed much in the last several decades, while the volume of traffic has increased disproportionably to infrastructure improvement. A solution to mobility cannot be addressed by simply improving the technology of a single vehicle any further. A solution is to enable people to reach their destinations safely and in optimal time, given the topology of road networks. This thesis offers such a solution based on an adaptive traffic control algorithm which takes the road network topology and dynamically varying traffic streams as input, and guarantees dependable and optimal mobility for vehicles. The algorithm calculates dependable passages for vehicles to cross road intersections, and enables point-to-point travel by minimizing travel time and maximizing fuel consumption. The adaptive algorithm is embedded in the Arbiter, managed by an Intersection Manager at every road intersection. A distributed traffic management architecture, consisting of a hierarchy of road managers, is proposed in the thesis. Extensions to the adaptive algorithm and the architecture are given. The extended algorithm will efficiently function under exceptional situations, such as bad weather, road repairs, and emergency vehicle mobility. The extended architecture is expected to have autonomic computing properties, such as self-healing, self-recovery, and self-protection, and Cyber-physical system properties, such as tightly-coupled feed-back loops with all entities in its environment. A simulator has been implemented, and simulated results reveal that the adaptive algorithm is far superior in performance to fixed-time control systems.

Acknowledgments

I would like to express my kindest gratitude to my supervisor Professor Vangalur Alagar for his support, his guidance, and especially his trust and respect to me. During the last two years, he has been working extremely hard with me to solve all problems that we encountered. It is a privilege to know him, to work with him, and to be his student. In him, I learned not only from his profound knowledge but also from his great personality.

This work is also dedicated to my parents, my sisters, my brothers, and especially to my wife who always encouraged me throughout the work.

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Chapter 1

Introduction

For more than a century, automobile and other motorized vehicles have been used to efficiently transport people and products across a network of roads in the world. The demands for mobility have been increasing ever since urbanization happened after the industrial revolution. In modern times, the technology used to develop vehicles, which was mainly based on the laws of mechanics and chemistry, has become more sophisticated because of the embedding of electronic components and automated control systems. However, the topology of road networks and their infrastructure for regulating the traffic of modern day vehicles has not improved in most of the large urban areas in the world. Thus, the original traditional traffic control infrastructures are becoming awfully inadequate to handle the modern-day vehicular traffic which can be characterized by density of vehicles, speed of individual vehicles, timeliness constraints of human drivers, and the traffic regulation policies laid down by urban administrators. In reality, these aspects are not well coordinated. Consequently, traffic congestion occurs frequently in large metropolitan cities, even in developed countries such as United States, Canada and in many countries in Europe. INRIX [29] reports that in 2013 traffic congestion has cost Americans $124 billion in direct and indirect losses, and this amount is estimated to rise 50% percent by 2030. The cumulative loss over the 17-year period from 2014 to 2030 will be $2.8 trillion, which roughly equals the taxes paid in USA in 2013. Traffic congestion not only damages the lifeline of the economy, but also increases environmental pollution. It is estimated [10] that in 2004, transportation congestion would contribute approximately 33% of carbon dioxide emissions in the United States, which will

create serious health and safety problems. Thus, congestion avoidance is an absolute necessity for improving urban traffic system. It is needed now more than ever. It is in this context this thesis makes a significant contribution.

City planners and researchers have proposed two kinds of solutions to reduce traffic congestion. One solution is expanding road infrastructure and another solution is optimizing Traffic Control System(TCS). The first solution is either inapplicable in many cities, due to physical constraints, or unaffordable in many places, due to its huge cost overhead. Moreover, a simple extension of existing physical network of roads and their infrastructures will not yield optimal results unless sophisticated control algorithms are embedded in TCS. So, the second solution has been preferred by urban planners and actively researched recently. However, most of the current TCSs have many drawbacks. These include the following:

1. They are not *reactive* to traffic flow, and *adaptive* to dynamic changes in the traffic. Consequently there is no fairness in traffic distribution, especially across road intersections.

2. In general, current TCS design favors vehicular traffic, with little consideration for pedestrian mobility. Consequently, pedestrians might get frustrated and indulge in unsafe behavior [36].

3. Control mechanisms in current TCSs neither use *context information* nor driven by *traffic control policies*.

4. *Feedback* loop that is necessary to factor the dynamic changes in traffic flow is absent in most of current traffic control systems.

This thesis is a contribution to the development of a new resilient traffic control system in which (1) traffic control policies, governing pedestrian mobility and vehicular traffic will be enforced equitably in order to optimize the overall flow of vehicular and human traffic, (2) dynamic feedback loop will be realized at every road intersection, and (3) context-dependent policies will be used to regulate traffic flow. The TCS thus realized in this thesis is called *Adaptive Traffic Control System* (ATCS). The ATCS design and algorithmic features have been chosen in a judicious manner with the grand vision that the ATCS can be easily

extended and deployed in any future development of a dependable *Transportation Cyber Physical System*, which will enable vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V) cyber communications, and advanced assistance to driverless vehicles.

In order to identify a set of requirements and craft a design for ATCS, it is necessary to understand the basic concepts related to Transportation Domain (TDM), and these are given next.

1.1 Basic Concepts of TDM

Basic concepts of traffic system and traffic control system are explained in this section. These concepts, taken from TDM, were defined and used by many traffic experts and researchers for decades.

1.1.1 Control Variables

Some of the common control variables [1] that are used to estimate and evaluate the characteristics of traffic conditions are explained below. These are essentially the input parameters that ATCS will need for making traffic control decisions, both on a road as well as at any intersection.

Vehicle Presence

Vehicle Presence is a boolean variable that indicates the presence or absence of a vehicle at a certain point in a roadway. The presence of vehicle is detected through sensors, such as induction loop or camera.

Flow rate

Flow rate Q is number of vehicles N passing through a specific point on a roadway during a time period T. It is defined as

$$Q = N/T, \tag{1}$$

Occupancy

Occupancy is defined as the percentage of time that a specific point on the road is occupied by a vehicle.

Traffic Flow Speed

In traffic management, *speed of traffic flow* is defined as average speeds of the sampling of vehicles either over a period of time or over space.

- **Time mean speed** is an average of speeds of vehicles passing a specific point on roadway over a period of time.

$$V_t = \frac{1}{N}\sum_{i=1}^{N} v_n \tag{2}$$

  where N is a total number of vehicles passing, v_n is the speed of vehicle n when passing.

- **Space mean speed** is a harmonic mean of speeds of vehicles passing a roadway segment.

$$V_s = \frac{N}{\sum_{i=1}^{N}(1/v_n)} \tag{3}$$

  where N is a total number of vehicles passing segment of road, v_n is the speed of vehicle n when passing.

Headway

Figure 1 depicts a *headway*, which is measured at any instant as the distance between the fronts of two consecutive vehicles in the same lane on a roadway.

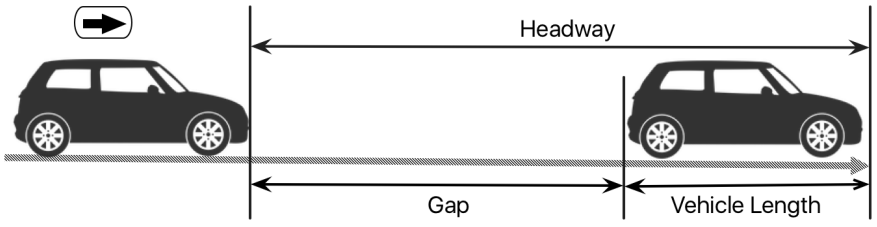


Figure 1: Headway, Gap and Vehicle Length

Queue Length

Queue Length is the number of vehicles that are waiting to cross an intersection on a specific lane on a roadway.

Flow Rate & Capacity

Flow Rate (throughput) is defined as the number of vehicles able to cross a specific point on a roadway during a given time period. *Capacity* is essentially synonymous to the maximum *throughput*.

Density

Density K is defined as the number of vehicles per unit distance.

$$Q = K \times V_s \tag{4}$$

where K is the density, Q is the volume of traffic flow (measured as number of vehicles / hour), and V_s is space-mean speed (measured in km / hour). In practice, *density* K can be computed by the following equation.

$$K = \left(\frac{1}{T}\right) \sum_{i=1}^{N} \left(\frac{1}{v_i}\right) \tag{5}$$

where N is the number of vehicles detected during time T, v_i is the speed of i^{th} vehicle crossing a detector in a lane, and K is the density of detected lane.

Fundamental diagram of traffic flow

Figure 2 is the fundamental diagram of traffic flow which illustrates the relation between flow rate and traffic density. The relation is changed over four different ranges of value of density. These ranges are outlined as below.

1. $0 \leq k < k_c$

   When density is less than the critical density(k_c), flow rate increases monotonically over

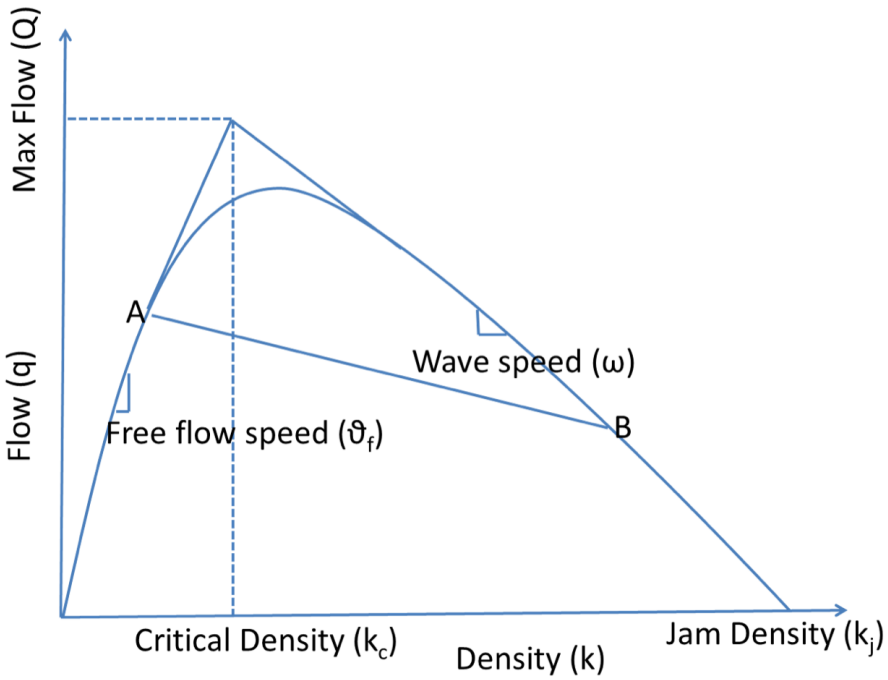


Figure 2: Relation between Flow Rate and Density [1]

density. In this range, vehicles can travel with the free-flow speed v_f (without braking) which principally equals to the desired speed.

2. $k = k_c$

   When density reaches the critical density(k_c), flow rate also reaches the peak or the maximum value of flow rate. Vehicles are still able to travel with the free-flow speed v_f.

3. $k_c < k_c < k_j$

   When density is greater than the critical density, both flow rate and the speed of flow decrease. Vehicles in the network are no longer to drive with the free-flow speed v_f but with a wave speed v_w which is lower than v_f.

4. $k_c = k_j$

   When density reaches to the jam density (k_j), both flow rate and speed of the flow reach to zero. In other words, traffic jam happens when density reaches to the jam density value.

1.1.2 Signal Parameters for Traffic at an Intersection

Phase

Phase is a set of combination of movements or scenarios at an intersection in which vehicles and pedestrians can cross without conflict. Some traffic control systems allow partial-conflict movements. Figure 3 shows an intersection with two partial-conflict phases.

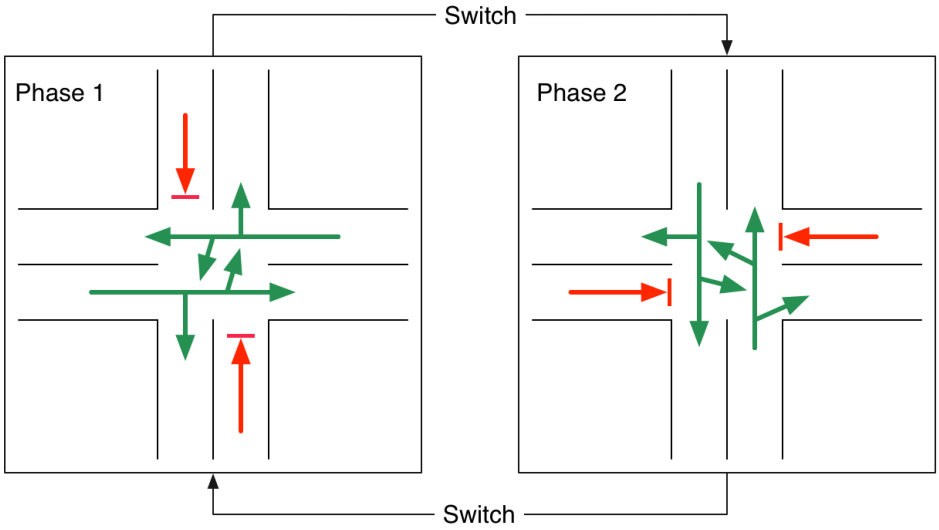


Figure 3: Partial-conflict phases

Cycle Length

Cycle Length is total length of time taken by a traffic light to repeat a complete sequence of phases at an intersection. In many modern traffic control systems, some phases are either skipped or repeated. That is, cycles are never formed. An adaptive traffic control system may not exhibit cyclic behavior.

Split

Split is the amount of 'green time' that a traffic control system allocates to a specific phase during one cycle in order that vehicles and pedestrians may cross an intersection.

Offset

Offset is green phase difference between consecutive intersections.

Platoon Dispersion

A group of vehicles that travel together (as a group) is called a 'Platoon of Vehicles'. *Platoon Dispersion Model* is employed in some traffic control systems to estimate the traffic flow profile at a downstream, based on the traffic flow that detected at its upstream. The behavior and pattern of a platoon of vehicles are identified according to the following parameters:

- Total number of vehicles in a platoon.
- The average headway of all vehicles in the same platoon.
- The average speed of vehicles in the same platoon.
- Inter-headway, which is defined as headway between the last vehicle and the first vehicle of two consecutive platoons.

Platoon Dispersion phenomenon happens when vehicles are moving together as a group from upstream to downstream, and then 'disperse' or spread out because of parking need, difference in speeds or lane changing. The primary purpose of studying of platoons is to estimate the arrival time of a platoon at an intersection in advance, which can potentially increase the ability to optimize the traffic flow along arterial roads.

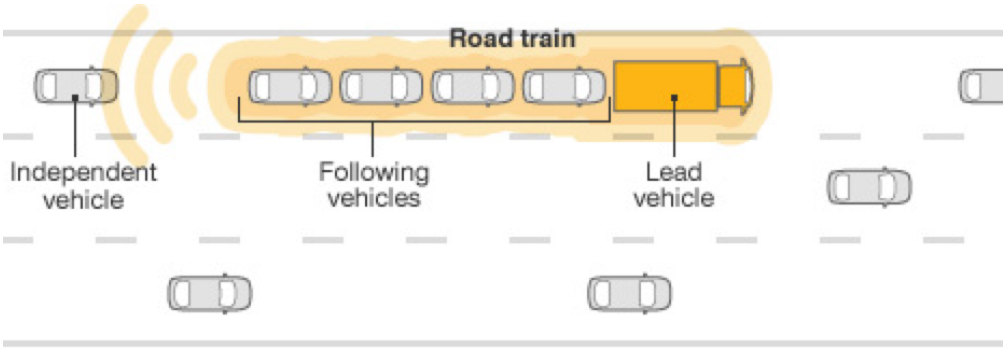


Figure 4: Platoon of Vehicles

Lost Time

Lost Time is the duration of non-utilization or unused time within the total time allocated by the traffic control system for vehicles or pedestrians to cross an intersection. There are three scenarios.

- *Scenario 1:* Two kinds of lost time occurs when phases are being switched from red to green or from green to red.
  - *Switch from Green to Red:* Lost time occurs when remaining time is too short for vehicles or pedestrians to fully cross the intersection. When a vehicle or a pedestrian starts to cross or in the middle of crossing an intersection, it may be that the remaining time for the light to turn red is too short. Hence, for safety reason the vehicle or pedestrian will decide not to cross the intersection.
  - *Switch from Red to Green:* Lost time occurs when vehicles are waiting at a red phase. When the traffic light switches to green, vehicles have to start up or increase its speed. During the first few moments no vehicles is crossing.
- *Scenario 2:* Lost time occurs when the traffic control system allocates green time to a lane but no vehicle is on that lane.
- *Scenario 3:* Lost time occurs when the traffic control system allocates green time to a combination of movements but the system allows partial conflict movement such as allowing left turn. Therefore vehicles from two lanes are attempting to cross each other at the same time using the same intersection space at the intersection. In this scenario, the drivers of the two vehicles have to agree on a protocol to solve the conflict. This delay is considered as lost time which reduces the intersection capacity. Figure 3 illustrates an intersection with two partial-conflict phases which can lead to Scenario 3.

In summary, lost time is the primary reason for the capacity at an intersection to be reduced and the total delay time at an intersection to be increased.

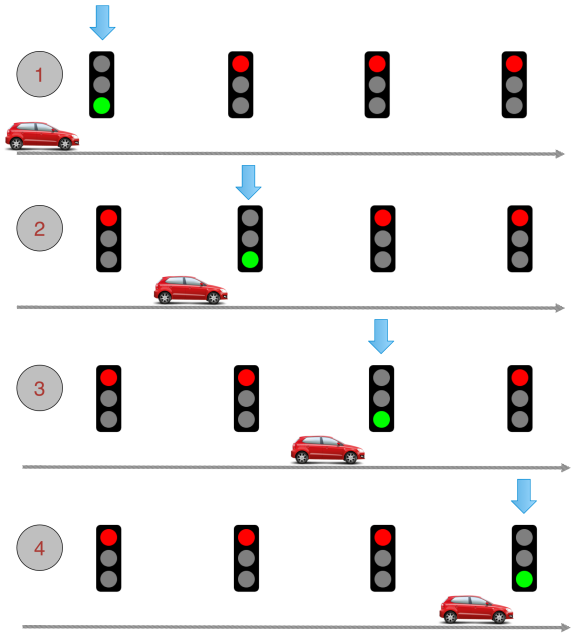


Figure 5: Green wave occurs when vehicle crossing intersections

Green Wave

Green wave is a coordination mechanism that traffic control systems at multiple intersections use to synchronize 'green times' to allow a platoon of vehicles traveling continuously and smoothly without stopping which can reduce lost time in *'Scenario 1'*. The sequence of movements in Figure5 illustrates how green wave occurs when the vehicle is moving from the intersection 1 to intersection 4. Figure 6 depicts the time, distance and phase coordination of this sequence of moves.

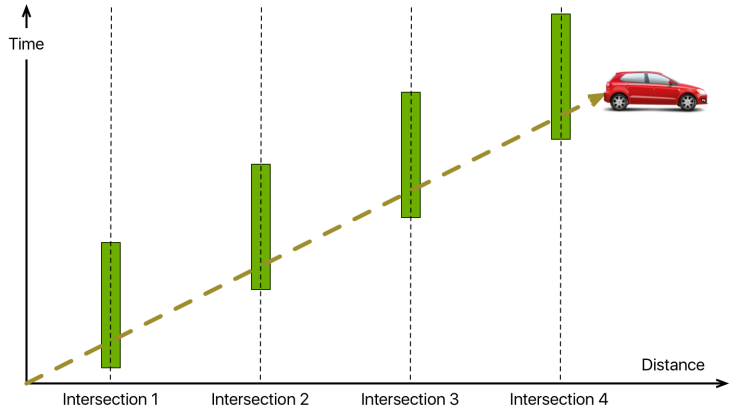


Figure 6: Time, distance and green phase coordination in Green wave

1.2 Contributions and Outline of Thesis

The thesis introduces a hierarchical architecture of traffic managers for regulating traffic flow along roads and intersections of roads. At each intersection, a feed-back control system enforces the safe passage of vehicles across the intersection. The control system at an intersection is managed by the Intersection Manager at the intersection. The behavior of the feed-back controller at an intersection is supported by formal mathematical models and the context-dependent traffic policies enforced by the Intersection Manager at that intersection. Collectively, the controllers and Intersection Managers at the intersections in an urban area fulfill the *dependability* and *optimization* properties stated in Chapter 3. The thesis includes an implementation of the ATCS and its simulation. The rest of the thesis, in seven chapters, describes the details regarding these results and a comparison with related works. The contributions are organized as follows.

The flowchart in Figure 7 depicts the organization of thesis contributions and how they are related to each other. Chapter 2 reviews the traditional traffic control strategies and the current operational systems based on them. The discussion on related work is restricted to only those works that deal with urban traffic management. A conceptual architectural design of ATCS is given in Chapter 3. The set of dependability and optimization properties to be realized through the detailed design based on this architecture are stated. The roles of the architectural elements are described to suggest how the satisfaction of the stated objectives in the architecture is met by their collective behaviors. Chapter 4 gives a detailed discussion on the design of *Arbiter*, which is the central piece of ATCS for an intersection. The rationale for choosing its parameters are stated and supported by formal mathematical models studied by transportation domain experts. The new features in the *Arbiter* design are (1) the concept of *cliques*, and *collision-free* traffic flow discharge algorithm based on it, (2) the definition of *vehicle scores* and *aging* function, which are crucial design decisions that facilitate *fairness* and *liveness*, and (3) the *Rolling Horizon Streams* (RHS) algorithm which adapts dynamically to changes in the traffic streams. An analysis of the algorithm is given to assert its satisfaction of the dependability and optimization objectives, and establish its polynomial-time complexity. Chapter 5 describes a presentation model for road networks

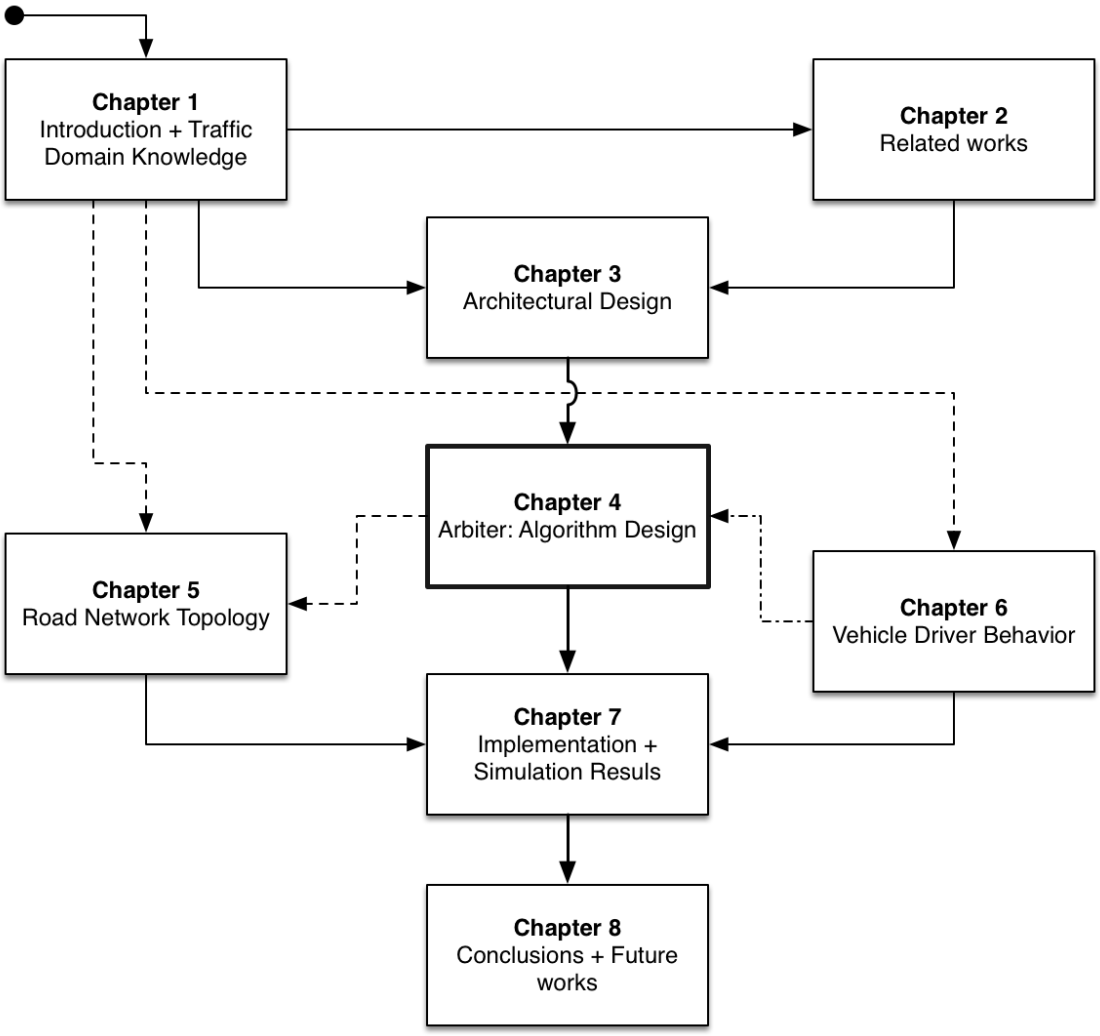


Figure 7: Outline of Thesis

and the preprocessing of network topology descriptions. Transformation tools necessary for the preprocessing tasks have been implemented. Chapter 6 discusses a *Vehicle Behavior Model*, which is necessary to simulate the *Arbiter* algorithm. Without such a model the traffic scenario necessary for *Arbiter* control cannot be realistic. Chapter 7 describes the simulator functionalities, and shows the simulation results on many data sets. Each dataset is created by combining different demand rates and road network topologies. The simulated results are compared on four criteria, chosen as measures to reflect the optimization properties. Chapter 8 concludes the thesis with a summary of contributions, their significance, and future work related to the contributions.

Chapter 2

Related Works

The current research trend pertaining to the development of Intelligent Transportation Systems(ITS) can be roughly classified into "driverless vehicles", "vehicles with human drivers", and "a hybrid of both". Research in the first kind focuses in creating autonomous vehicles (AVs, also called automated or self-driving vehicles) that can drive themselves on existing roads and can navigate many types of roadways and environmental contexts with almost no direct human input. Research in the third kind exploits wireless access for vehicular environments (WAVE) in order to enable vehicles exchange information with other vehicles on the road (called V2V) or exchange information with infrastructure mediums (called V2I) such as RSUs (Road Side Units). AV, V2V and V2I rely on continuous broadcast of self-information by all vehicles (or RSUs), which allows each vehicle to track all its neighboring cars in real time. The degree of precision, synchrony, and control vary across these three systems. The most pressing challenge in such systems is to maintain acceptable tracking accuracy in real-time while overcoming communication congestion (and failures). The acceptance of these technologies by policy makers, the inherent complexity in proving the safety and predictability, and the cost of integrating WAVE in vehicles are some of the major impediments in realizing the dream of either driverless or hybrid systems on the road. In this thesis, the focus is on maximizing the infrastructure facilities to minimize traffic congestion for "vehicles with human drivers". The TCS that is engineered in this thesis is expected to increase throughput, optimize human safety, enhance environmental sustainability, and improve human pleasure in driving. So, the discussion in this chapter is restricted to the current strategies and systems

that are in use with respect to vehicles with drivers.

2.1 Traffic Control Strategies

Current traffic control systems that regulate traffic can be classified into the three categories *Fixed-time*, *Traffic-responsive*, and *Traffic-adaptive* [41].

- **Fixed-time**

  Fixed-time strategy defines a set of traffic control parameters for each intersection for each period during a day such as morning peak, noon or midnight. These control parameters usually are determined after a statistical analysis of traffic flow patterns. The primary drawback of this strategy is its assumption that the traffic demand will be constant during a period of time, such as an hour or 30 minutes.

- **Traffic-responsive**

  Like *Fixed-time* strategy, *Traffic-responsive* strategy explicitly defines values of control parameters such as *Cycle*, *Split* and *Offset*. However, instead of using historical traffic data, this strategy uses real-time traffic data obtained from sensors. Thus, the control parameters remain valid over a short period in horizon.

- **Traffic-adaptive**

  Unlike *Fixed-time* and *Traffic-responsive*, *Traffic-adaptive* strategy does not use *Cycle*, *Split* and *Offset*. Instead, this strategy selects *phase* and its *green time* according to the real-time traffic data received from the sensors. The task of selecting traffic *phase* and its *green time* is called *decision* which can be implemented by an Optimization Approach, such as Dynamic Programming or Stochastic Programming.

In general, a traffic control system can regulate a traffic flow at an intersection with or without *coordination* with its adjacent intersections. An *Isolated-Intersection* system solely uses its own traffic data gathered at its intersection to regulate traffic flow at its intersection. *Coordinated-Intersection* system at an intersection cooperates with the traffic regulators at its adjacent intersections and make traffic control decisions at its intersection. With the availability of traffic data from the traffic regulators at its adjacent intersections, the traffic

control system can support *Green wave* or *Oversaturated situations*. Our proposed system supports both green wave and oversaturated situation.

2.2 A Review of Existing Traffic Control Strategies

This section briefly reviews some notable traffic control systems which have received attention from town planners and researchers. These are listed in Table 1.

System	**Strategy**
SIGSET	Fixed-time
TRANSYT	Fixed-time
SCOOT	Traffic-Responsive
RHODES	Traffic-Adaptive

Table 1: Notable traffic control systems

2.2.1 SIGSET

SIGSET is a traffic analysis software which was proposed in 1971 by Allsop [6]. The primary purpose of the tool is to generate a set of control parameters for an intersection in a road network. The approach is a well-known example of isolated and *fixed-time* traffic control system. The input to the tool consists of an intersection E with m *phases*, a set of values d_i $(1 \leq i \leq n)$ denoting demand at each *phase*, and total lost time for each cycle λ_0. These input values are determined in advance through experiments. The output of the system consists of the length of the traffic light cycle L and a set of split values λ_i $(1 \leq i \leq n)$ for *phases* which minimize the total waiting time of vehicles at the intersection. Formally,

$$\lambda_0 + \lambda_1 + \cdots + \lambda_m = L, \tag{6}$$

$$s_j \sum_{i=1}^{m} \alpha_{\mathrm{ij}} \lambda_i \geq d_j \quad \forall j \tag{7}$$

Where λ_0 is the total lost time per cycle length, λ_i is split or amount of green time for *phase* i, L is the cycle length, j is a link at the intersection, $a_{ij} = 1$ if link j has right of way in *phase* i, otherwise $a_{ij} = 0$, and d_j is the demand at link j of the intersection.

2.2.2 TRANSYT

TRANSYT *(Traffic Network Study Tool)* is a traffic simulation and analysis software which was developed in 1968 by Robertson of the UK Transport and Road Research Laboratory (TRRL) [44]. Currently, two main versions of TRANSYT are being researched and developed in United Kingdom and United States. In United States, McTrans Center of University of Florida has released the latest of version TRANSYT-7F for Federal Highway Administration (FHWA). The primary purpose of TRANSYT is to help town planners or traffic experts to analysis traffic network and define a set of optimal control parameters for intersections inside a road network. Theoretically, the TRANSYT control mechanism is based on 'Platoon Dispersion Model' which also was originally developed by Robertson [20]. Formally,

$$q\prime_{t+T} = F \times q_t + [(1 - F) \times q\prime_{(t+T-1)}] \tag{8}$$

where $q\prime_{t+T}$ is the "Predicted flow rate" in time interval $(t + T)$ of the predicted platoon, q_t is the "Flow rate" of the interval platoon during interval t, T is 0.8× "the cruise travel time on the link", and F is "smoothing factor" defined below. In the equation below α is "Platoon Dispersion Factor (PDF)", selected by traffic experts.

$$F = \frac{1}{1 + \alpha T} \tag{9}$$

The TRANSYT control mechanism works in an iterative manner [41]. First, the 'initial policy' will be loaded into the system and that policy will be used for the next traffic light cycle. For each interval t, the system will estimate the traffic flow profile at stop line by Platoon Dispersion Model, then will calculate a Performance Index (PI) in monetary terms (based primarily on delays and stops). An optimization algorithms such as 'Hill Climb' [44] or 'Simulated Annealing' [44] will be selected to find optimal control parameters which minimizes

Performance Index but respects to defined constraints. The new optimal control parameters will be applied into the next cycle. Over time, the optimal traffic control parameters will be generated and these values can be used in real traffic control system. Over-saturation is not included in the first versions but added in the recent versions.

Both SIGSET & TRANSYT work on historical data instead of real-time data and assume that demand on each link is a constant during a period of time. However, this assumption is not accurate in real traffic systems. Because the policies selected by both strategies may not be appropriate for certain periods of time, traffic congestion might result in the road network or traffic capacity may be reduced.

2.2.3 SCOOT

SCOOT *(Split Cycle Offset Optimization Technique)* [41] is considered to be a *traffic-responsive* version of TRANSYT. SCOOT was also developed by Robertson of the UK Transport and Road Research Laboratory (TRRL). Currently, more than 200 SCOOT systems are being used in more than 150 cities [47] all over the world, including London, Southampton, Toronto, Beijing, and Sao Paulo. The mechanism of SCOOT is very similar to TRANSYT as both are based on 'Platoon Dispersion Model' to estimate the 'Cycle flow profiles' in advance. The main difference is that SCOOT obtains real-time traffic data through detectors to build 'Cycle flow profiles', whereas in TRANSYT historical data is used.

Figure 8 illustrates the SCOOT mechanism. When vehicles pass through a detector, SCOOT system continuously synthesizes this information to current state of system and builds platoon of vehicles. Based on this, it predicts the state of signal as the platoon arrives at the next traffic light. With this prediction, the system will try to optimize the signal control parameters to minimize the lost time at intersections, and reduce number of stops and delays by synchronizing sets of signals between adjacent intersections. Three key optimizers will be executed in SCOOT system. These are explained below.

1. **Split Optimizer**

   For each *phase* at every intersection, the *split optimizer* is executed several seconds

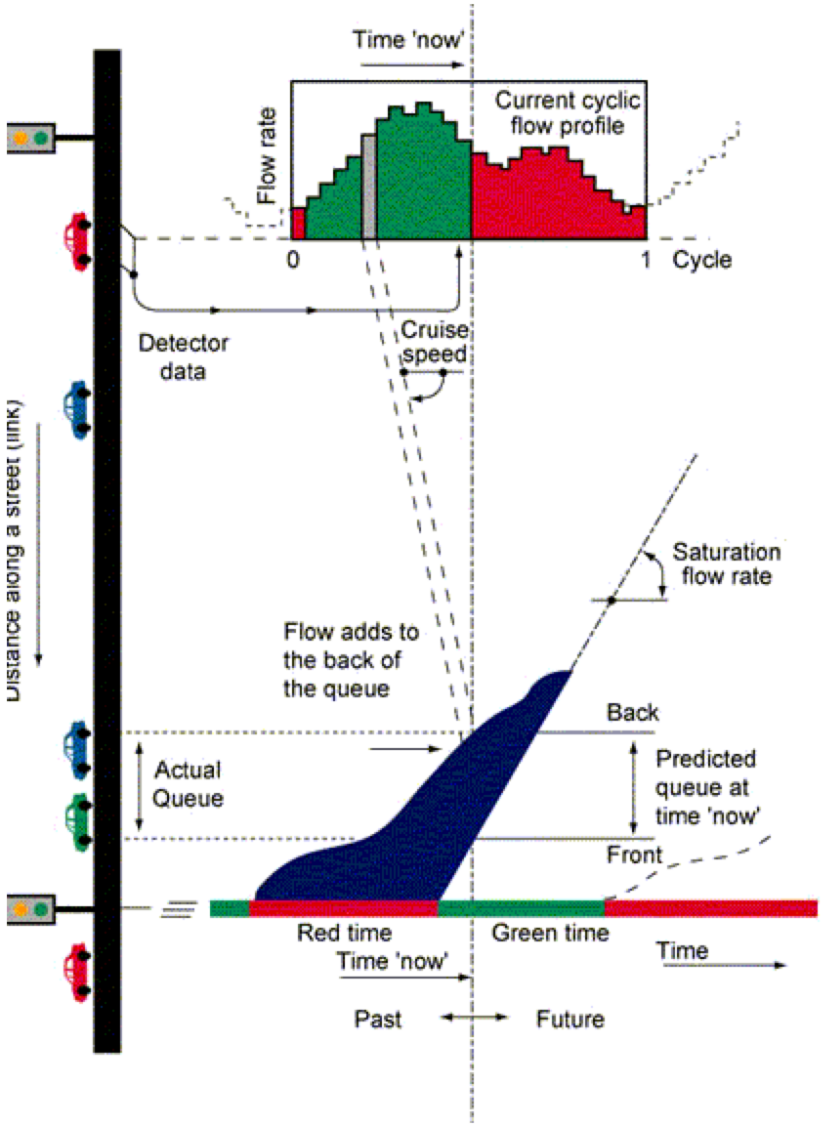


Figure 8: How SCOOT works [47]

before switching phase from green to red. The traffic controller will decide independently from other intersection controllers whether to switch *phase* earlier or later or as due. The purpose of this optimization is to *minimize the maximization degree of saturation* flow at all approaches of an intersection. In order to avoid large change, amount of changed time must be small. In practice, the value is in the range [-4,+4] seconds.

2. **Offset Optimizer**

   For each cycle at every intersection, the *offset optimizer* is executed several seconds before a cycle completes. The traffic controller will decide either to keep or alter the

scheduled *phases* at that intersection. The output of this decision will affect offset values between that intersection and its adjacent intersections. The purpose of this optimization is to *minimize the sum of Performance Index* on all adjacent roads with offset as scheduled or earlier or later. Like the *split optimizer*, the amount of change time must be small to avoid a sudden transition.

3. **Cycle optimizer**

   For 2 - 5 minutes, the SCOOT system will make a *cycle optimizer* at a region (global) level which consists of many intersections. First, the SCOOT identifies the *critical nodes* whose saturation levels are over the defined threshold (usually 80%), then adjusts the cycle time for those intersections. Like previous types of optimizer, the cycle time will be adjusted with small change.

Although the system is very successful and being used by many cities, SCOOT system has received many criticisms. According to the BBC News Report [36], data pertaining to pedestrian traffic do not have any real effect on SCOOT controller. Pedestrians in cities where SCOOT is being used, call the pedestrian signal button as 'Placebo buttons'. The problem can be that the SCOOT mechanism gives more importance to vehicular traffic than pedestrian traffic. Another issue of SCOOT is its centralized architecture. All optimizations will be processed at a central computer. Consequently, there is a single point of failure and no support for load balance.

2.2.4 RHODES

RHODES [35] *(Real-Time Hierarchical Optimized Distributed Effective System)* is a typical example of traffic-adaptive control which does not have explicit values of control parameters (see Section 1.1) such as *Cycle*, *Split*, and *Offset*. Only Phase is defined explicitly. In general, the RHODES system consists of two main processes. One process, called *Decision Process* (DP), builds a current and horizon traffic profile, based on traffic data from detectors and other sources. Another process, called *Estimation Process* (EP), produces a sequence of *phases* and their lengths continuously over the time according to the traffic profile of the previous process. Both DP and EP are situated at three aggregation levels of RHODES

hierarchy, as shown in Figure 9.

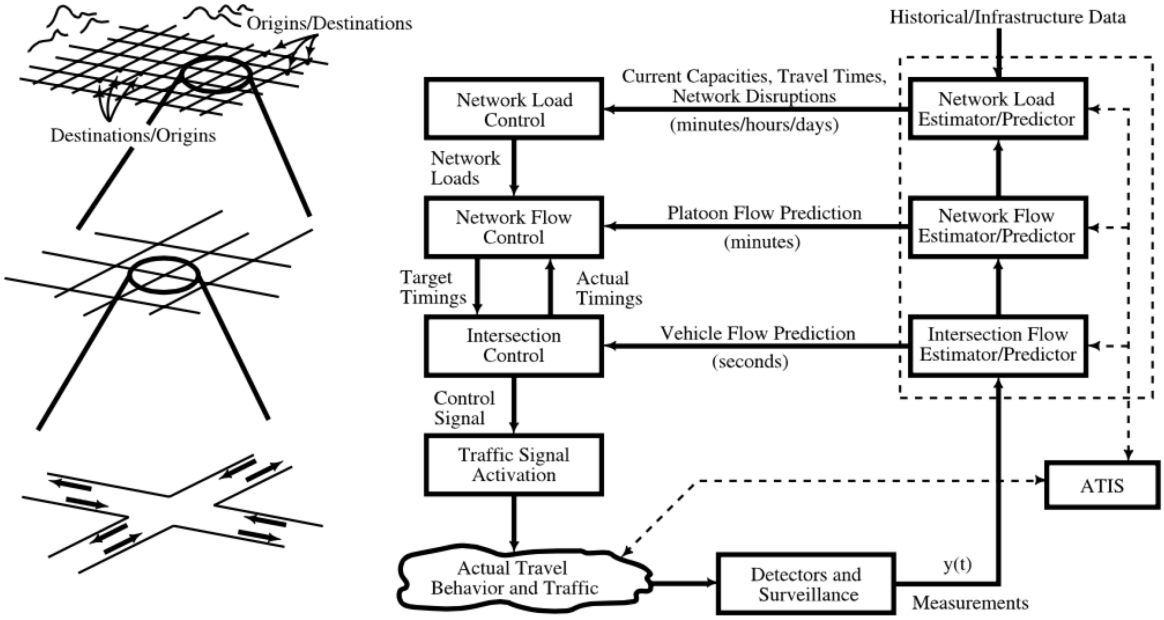


Figure 9: The RHODES hierarchical architecture [34]

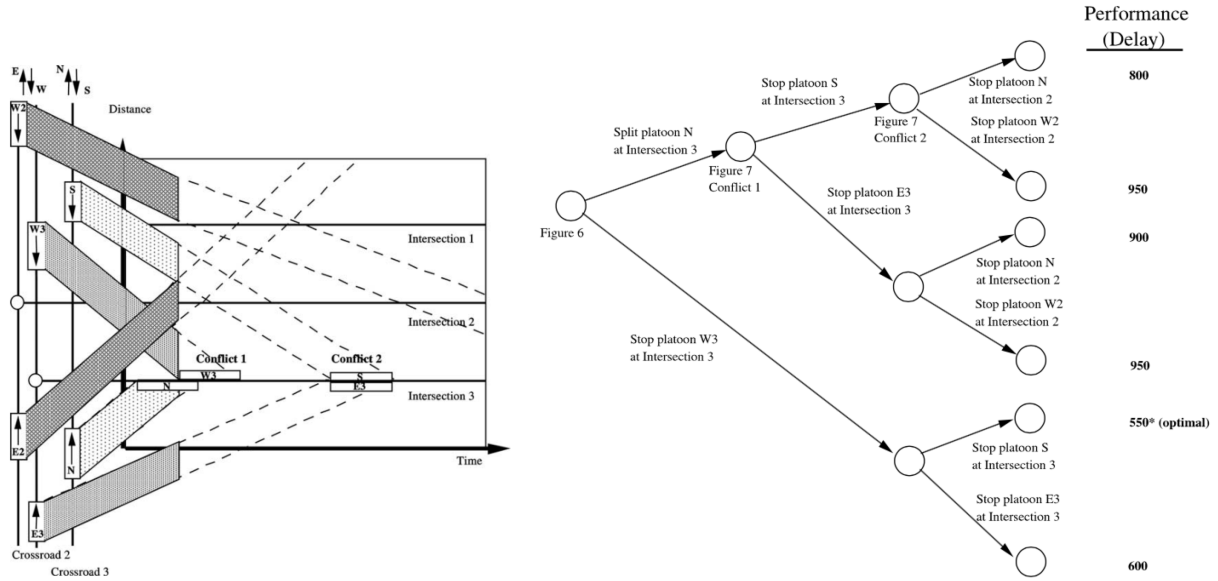
1. **Dynamic Network Loading**

   Dynamic Network Loading is the highest level in system hierarchy which continuously and slowly captures macroscopic information of the current traffic. Based on this information it estimates a load or demand on each particular road segment for each direction in terms of the number of vehicle per hour. With these estimates, RHODES system can allocate *green times* for *phases* in advance for each intersection in the network.

2. **Network Flow Control**

   Network Flow Control is the middle level in system hierarchy. It combines the estimated result received from the higher level with current traffic flow in terms of platoon or individual vehicle to optimize the movement of platoon or vehicle individually. Figure 10 illustrates how the mechanism of this layer works. In Figure 10a, it is predicted that 4 platoons may arrive at the same intersection and request to cross. These requests create some conflict movements. The RHODES will solve the conflicts by making a

tree-based decision on the predicted movement of platoons over horizon as in Figure 10b.



(a) Platoons request conflict movements (b) RHODES's decision tree

Figure 10: How RHODES works

3. **Intersection Control**

   Intersection Control is the lowest level in the system hierarchy. At this level, the system is dealing with each vehicle at microscopic level. Based on the presence of a vehicle in each lane and decisions communicated by Dynamic Network Loading and Network Flow Control, the Intersection Control uses a Dynamic Programming [34] algorithm to select phase and assign length of time for that phase.

Although *Dynamic Programming* helps RHODES system to optimize traffic flow by minimizing average delay and number of stops and maximizing network throughput, Dynamic Programming has its own limitations in optimizing real-time traffic flow problem. Powell explains the *"Three Curses of Dimensionality of Dynamic Programming"* [43], of which computation demand of Bellman's recursive equation [13] is exponential to the size of state space, information space and action space. So, when the volume of traffic is high and the traffic controller has to synchronize with physical entities (such as sensors and actuators), it is hard to guarantee a solution in an optimal time.

2.2.5 Summary and Comparison

This section provides a brief comparison of the features between our proposed system and the reviewed systems. Our new system not only fulfills many advanced features of existing systems, but also introduces novel features such as supporting pedestrians, emergency vehicles, and green wave. Table 2 outlines this comparison in detail.

	SIGSET	**TRANSYT**	**SCOOT**	**RHODES**	**ATCS**(Ours)
Strategy	Fixed-time	Fixed-time	Responsive	Adaptive	**Adaptive**
Coordination	Isolated	Coordinated	Coordinated	Coordinated	**Coordinated**
Architecture	Centralized	Centralized	Centralized	Distributed	**Distributed**
Optimized Parameters	Cycle, Split	Cycle, Split, Offset	Cycle, Split, Offset	Split	**Clique**
Pedestrian	No	No	No	No	**Supported**
Emergency	No	No	No	No	**Supported**
Green wave	No	No	No	No	**Supported**
Oversaturated	No	Yes	No	No	**Yes**
Weather Condition	No	No	No	No	**Considered**
Public Event	No	No	No	No	**Considered**
Lane Closure	No	No	No	No	**Considered**
Traffic Zone	No	No	No	No	**Considered**

Table 2: Comparison between ATCS and notable traffic control systems

Chapter 3

Architectural Design

The architecture that is presented in this chapter is a hierarchical network of traffic managers in a zone. The root of the hierarchy is the *Zone Manager*(ZM), which manages a peer-to-peer network of *Intersection Managers*(IM). Figure 11 depicts this hierarchy. Each *Intersection Manager*(IM) manages a single intersection in a road network with a feed-back loop. The proposed architecture can serve as an essential foundation to develop traffic management systems to achieve several other objectives, such as providing advanced driver assistance, instituting autonomic functioning, and enabling vehicle-to-vehicle communication.

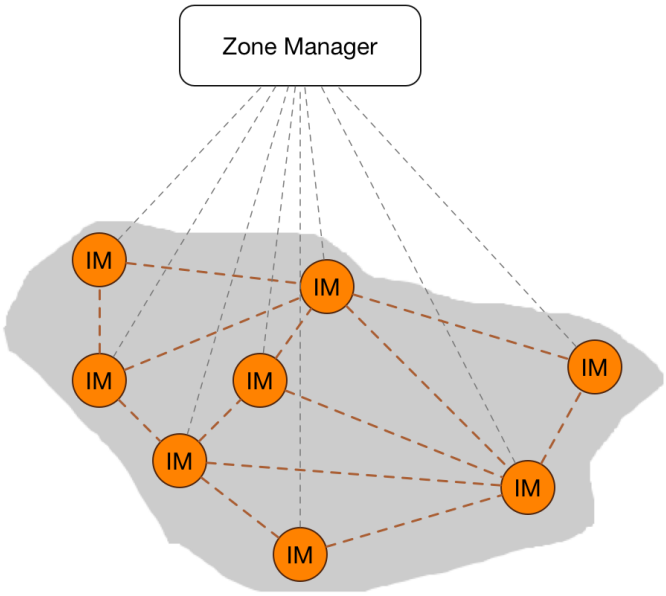


Figure 11: Hierarchy of ATCS

3.1 Objectives of ATCS

The components in different levels of the ATCS hierarchy share the same set of objectives, with varying degrees of emphasis imposed by context constraints. However, their common goal is to ensure dependability and optimize the performance, as described below.

3.1.1 Dependability Objectives: Safety, Liveness, and Fairness

1. *Ensuring safety for vehicles and pedestrians*

   Informally, *safety* means *nothing bad ever happens* in the system. *Ensuring safety* for vehicles and pedestrians at intersections is an important objective of the system. A system which meets all other objectives but fails to ensure safety must not be deployed at all.

2. *Ensuring liveness for traffic participants*

   Liveness means *something good eventually happens in the system.* In [5] liveness property for a traffic control system is defined as "every traffic participant at an intersection eventually obtains a right of way to cross the intersection within a finite amount of time". That is, *no vehicle or pedestrian waits for ever.* If the system does not ensure liveness property, safety property cannot be assured because traffic participants can lose their patience and cross intersections before getting a right of way.

3. *Ensuring fairness between traffic participants*

   Fairness is a constraint imposed on the scheduler of the system that it fairly selects the process to be executed next. Technically, a fairness constraint is a condition on executions of the system model. These constraints are not properties to be verified, rather these conditions are assumed to be enforced by the implementation. Our ATCS system will *ensure fairness constraints* when allocating 'right of way' to vehicles or pedestrians that are competing to cross intersections. That is, by implementing fairness constraints liveness property is achieved.

3.1.2 Optimization Objectives

1. *Minimizing total delays for emergency vehicles*

   Emergency vehicles need to deliver services with minimal delay, preferably with no delay, because human lives depend on their services. That is, enabling the smooth flow of emergency vehicles even during traffic congestion will contribute towards enhancing the safety property. Therefore, the ATCS should *minimize traveling time of emergency vehicles* in the traffic network.

2. *Minimizing total traveling time*

   Total traveling time for a vehicle is the time taken to travel the distance between the origin and destination points in the road network. The ATCS system will *minimize this total traveling time* of pedestrians and vehicles. The interpretation of "minimizing the time" is as follows: "if the normal driving time (under specified speed limits and smooth flow of traffic) from point A to point B is x hours, then the ATCS system should facilitate the trip to be completed in $x \pm \epsilon$ time almost always".

3. *Minimizing total delays of vehicles in network*

   Total delays of vehicles at intersections and in network is the primary reason that cost people time and money. It also increases the emission of *Carbon dioxide* (CO_2) to the environment. Therefore, the ATCS system should *minimize the total delays of vehicles* at intersections, as well as in the entire network.

4. *Minimizing total delays of pedestrians at intersections*

   Most of urban traffic control systems have not factored pedestrian traffic in their design. Some systems give only a minimum amount of importance to pedestrian traffic when making control decisions. This unfair treatment has made the pedestrians unhappy. Therefore, it has been decided to introduce the requirement that the ATCS should *minimize total delays of pedestrians* at intersections.

5. *Maximizing capacity and throughput*

   Maximizing the capacity and the throughput can make a traffic system serve more people without the necessity to expand physical infrastructure.

6. *Minimizing wasted energy & environmental effects*

   Amount of CO_2 emission depends on the pattern of travel of vehicles. It is known [3, 10] that when vehicles travel as smoothly (steadily) as possible, without too many "stop and go", the CO_2 emission is least. Therefore, the ATCS system will maximize the probability of a vehicle traveling smoothly, without stopping.

The *efficiency* of the ATCS system is to be evaluated from the number of objectives achieved, and the level of achievement of each objective. Not all the objectives mentioned are mutually exclusive. For example, minimizing total delays of a vehicle also means minimizing its traveling time and increasing throughput. The arbiter is designed and implemented to meet these objectives. The combined behavior of all arbiters effectively determine the efficiency level of the ATCS . The simulated experiments are analyzed to evaluate the efficiency level achieved for a number of different traffic scenarios.

3.2 Architecture

The distributed architecture proposed in this section emphasizes the above objectives. Figure 12 depicts the main components of the ATCS architecture. The functionality of components are discussed in the following subsections.

3.2.1 Traffic Detector

Traffic Detector component is responsible for capturing traffic data at an intersection in real-time manner. The traffic data includes the presence, speed, position, and direction of vehicles. It also includes the presence and direction of pedestrians. The traffic data will be gathered and synthesized by *Flow Builder* component. At each intersection, one or more of the following traffic detector types can be used.

Inductive Loop

Inductive loop is the most common traffic detector utilized in traffic control systems. In theory, when vehicles pass over or stop at detection area of the inductive loop [2], the inductance of

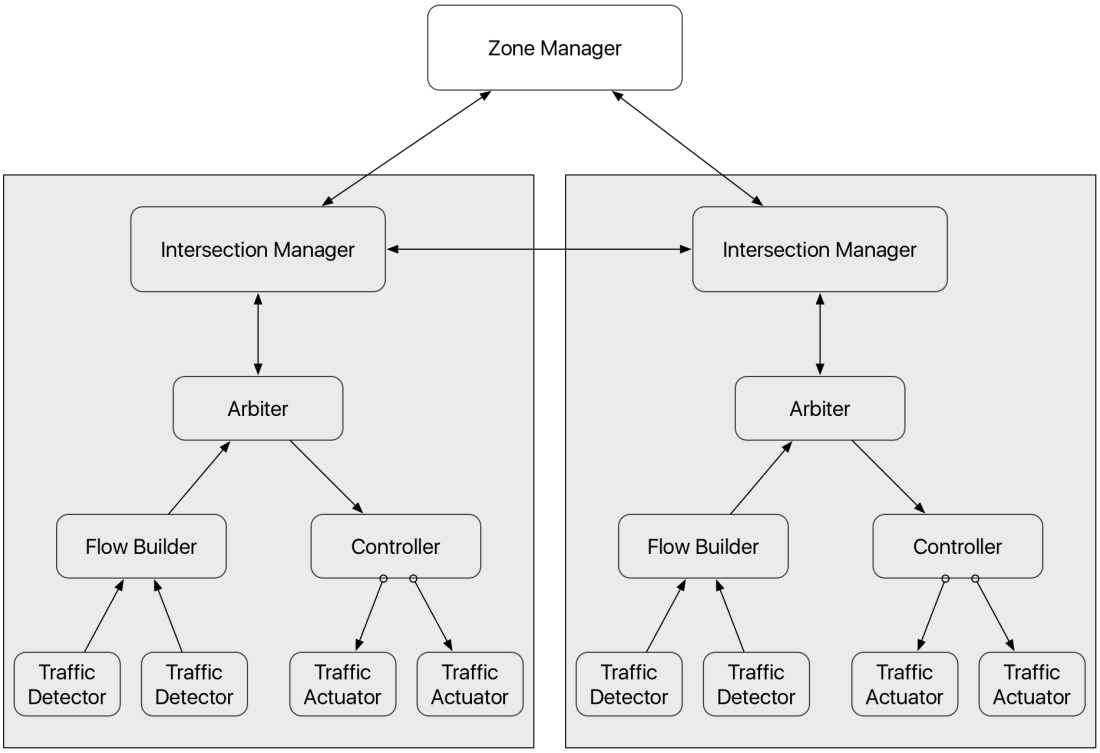


Figure 12: Conceptual Architecture of ATCS

detector decreases. This in turn triggers the detector to send a pulse signal, which indicates either the presence or passing of a vehicle to controller.

Video Image Processor

Video Image Processor technology uses camera to capture images of traffic from which a traffic flow profile is built. This procedure includes the following three steps.

1. A camera captures traffic and stores the digitized images.
2. The traffic data is extracted from the digitized images.
3. The extracted data is synthesized to build a traffic flow profile.

Nowadays, *video image processor* technology is able to detect not only vehicles but also pedestrians. Figure 13 shows FLIR's SafeWalk [22] which is able to detect the presence of pedestrians who are either waiting or approaching or crossing an intersection.

Figure 13: Pedestrian detector using video image processor [22]

Vehicle to Infrastructure (V2I) Interaction

In V2I, the infrastructure plays a coordination role by gathering global or local information on traffic patterns and road conditions and then suggesting or imposing certain behaviors on a group of vehicles. Information and service exchanges in V2I communication use wireless technology, as shown in Figure 14. Most of the recent V2I deployments use Dedicated Short Range Communications (DSRC), Infrared or Wireless LAN. Through V2I, ATCS systems can detect the presence, speed, direction and identifier of vehicles accurately.

Other types of traffic detectors

Other types of traffic detectors include microwave radar, active infrared and passive infrared detectors. Special traffic detectors are deployed to detect special kind of vehicles, such as public transportations and emergency.

3.2.2 Flow Builders

Flow Builder is responsible for building the traffic flow profile at an intersection according to information received from traffic detectors. In the architecture, flow builders are able to

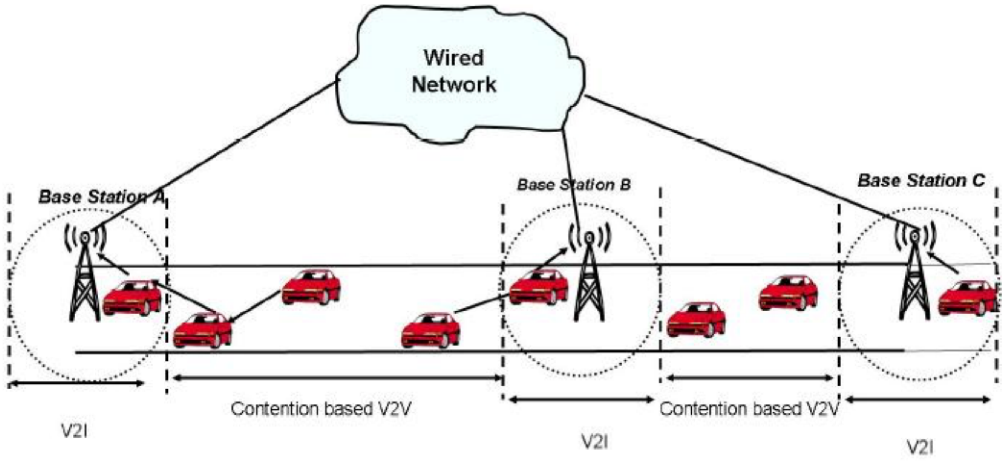


Figure 14: V2V and V2I Communication

gather and synthesize traffic data from different types of traffic detectors through different kinds of connections and communications. Two types of *traffic flow profiles* are defined, one for vehicles and another for pedestrians. These two types of traffic flow profiles are used by the *Arbiter* to make control decisions. The structure of these profiles are described below.

- *Vehicular traffic flow profile* is constructed for each inbound/outbound vehicular lane at an intersection. This profile is a 'queue' in which each element is a vehicle in that lane accompanied with the following information.
  - The time that a vehicle entered to the observed area,
  - The up to date position and direction of a vehicle,
  - And the current speed of the vehicle
- *Pedestrian traffic flow profile* is constructed for each crosswalk at an intersection. Like *vehicular profile*, a pedestrian profile is a queue in which each element is a pedestrian at an intersection accompanied with the following information.
  - The time that a pedestrian approached to the observed area,
  - The approximate position and direction of a pedestrian.

3.2.3 Traffic Actuator

A *Traffic Actuator* component is responsible for either displaying or transmitting traffic control decisions to vehicles and pedestrians. Most of traffic control systems use a traffic light to display traffic commands such as 'Stop' and 'Go' to traffic participants through 'Red' and 'Green' signals. Some others use a barrier or a text-panel to present traffic commands and additional information. A traffic actuator can be a software component instead of a hardware device. For example, a traffic control system can use a software-component to transmit its decisions directly to vehicles which support Vehicle to Infrastructure (V2I) communication.

3.2.4 Controller

At an intersection one *arbiter* will interact with many *flow builders* and one *controller*. In principle, it should be possible to plug-in any actuator type in the system, depending upon the specific context governing the intersection. So, in the ATCS architecture one or more different types of actuators are allowed. The *arbiter* functionality, as described later, is complex and crucial for enforcing the safety, liveness, fairness, and other objectives described earlier. Therefore, it is essential to relieve the *arbiter* from the low-level tasks related to management of traffic actuators. In order to support the diversity and multiplicity of actuators and at the same time relieve the *arbiter* from managing them, controllers are introduced in the architecture. A *controller* component receives control commands from the *arbiter* with which it interacts, communicates them to traffic actuators that it manages in the most appropriate fashion. The addition/deletion of actuators will not affect the *arbiter* functionality, because a controller is enabled to deal with them and communicate through different interfaces. In order that the ATCS may provide a high level of safety, a controller should be able to monitor the status of its actuators to make sure that they are working correctly. In our architecture, every controller will perform this task in both *passive and active way*.

In summary, every controller at an intersection is responsible for the following actions.

- Managing traffic actuators at the intersection
- Receiving traffic commands from the arbiter at the intersection

- Controlling traffic actuators to execute traffic commands
- Monitoring the status of each traffic actuator
- Reporting the abnormal status of a traffic actuator, if detected, to the Intersection Manager

3.2.5 Arbiter

At every intersection of the road network an *arbiter* exists. Essentially, an arbiter at an intersection is responsible for making traffic *control decisions* that are consistent with the objectives (listed earlier). The ultimate purpose of an arbiter at an intersection is to achieve safe optimized traffic flow, not only at the intersection it manages but also in the entire network. In order to achieve this goal, both local and global traffic information must be given to every arbiter. For a given intersection, the traffic information at its adjacent intersections are considered as important sources of the global traffic information. In our architecture, IM gathers the global traffic information and transfers it to the arbiter connected to it. The local traffic information is received from *flow builders*. Based on the traffic policies related to local and global traffic flows, an arbiter instructs the controller associated with it.

Figure 12 illustrates this three-fold interaction of arbiter at every intersection with IM, *Flow Builder*, and *Controller*. The local and global traffic information constitute a time-varying quantity over the physical entities "humans" and "vehicles", expressed in space-time dimension. In order to factor this dynamically changing behavior in ATCS, every arbiter is designed as a *closed-loop system with feedback loop*. In control theory, a closed-loop control system with feedback loop takes external inputs and the current output of the system to produce decisions. This approach provides self-correction capability to the proposed system. *Self-correction* can be a key for the system to obtain the optimal traffic flows at an intersection. Figure 15 illustrates the input-output and the feedback loop at an intersection.

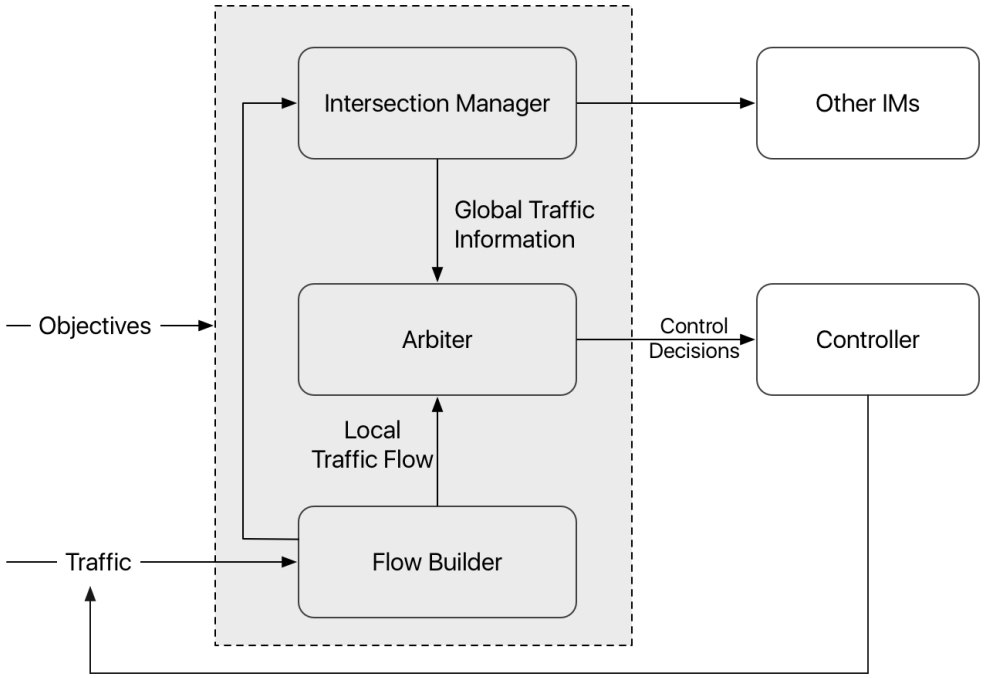


Figure 15: Feedback loop at an intersection

3.2.6 Context Manager

Context Manager(CM) is responsible for collecting and referring context information at the intersection. Collected contexts will be taken into account in selecting an appropriate traffic control policy by the *Intersection Manager*. The following context dimensions [4] will be collected by the CM.

- **Traffic Zone**

  Whereas *Location* may be defined by the coordinates (*longitude, latitude*), a *Traffic Zone* may include a collection of locations. Traffic zones can be classified into school, hospital or commercial zones. For each zone, different traffic control policies will be necessary to optimize the objectives of ATCS. For example, if a traffic zone is a school zone, pedestrians should be given higher priority than vehicles in that zone.

- **Weather Condition**

  Weather Condition impacts the movement of both vehicles and pedestrians. Under good weather condition, it may be that pedestrians can cross an intersection within 3 seconds

but under snowy condition it may take more than 5 seconds for pedestrians to cross it. Thus, weather condition should be taken into account for selecting the traffic policy.

- **Public Event**

  When *Public Event*s happen traffic flow is drastically altered. For example, a parade can interrupt movement of vehicles. If that disruption is not handled well, traffic congestion will result. Hence, different kinds of public events should be considered in formulating traffic policy.

Time has great influence on traffic policy, either directly or indirectly through the mentioned contexts. However, time can be retrieved directly by *Intersection Manager* with minimal effort. Thus, time dimension is not collected by *Context Manager* but is collected by *Intersection Manager*. Figure 16 illustrates factors that determine the selection of appropriate traffic policy.

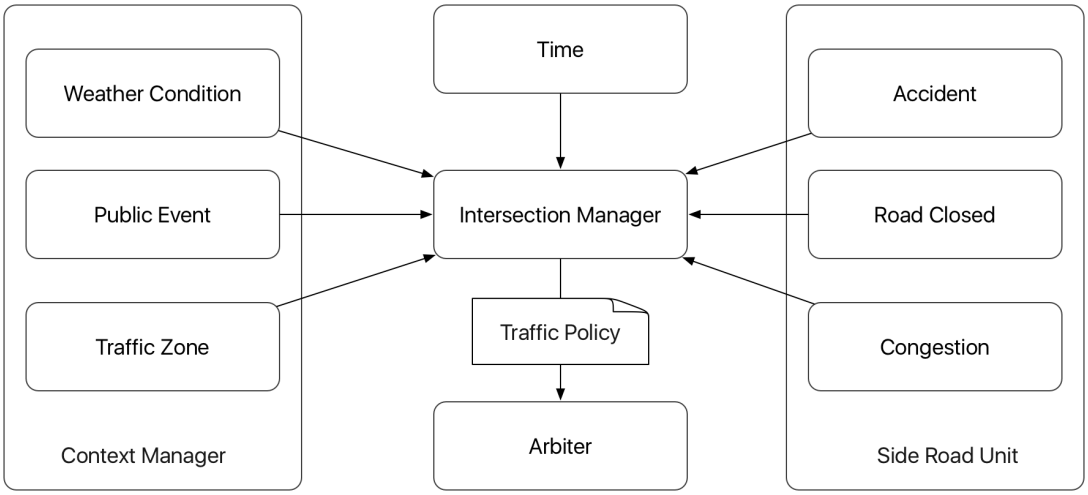


Figure 16: Factors determining traffic policy

3.2.7 Intersection Manager

An *Intersection Manager*(IM) communicates with its adjacent IMs and *Zone Manager* (ZM). It receives traffic policies from ZM and information on traffic patterns from its adjacent IMs. A traffic policy for an intersection defines the structure of linkage lanes and parameters for

control algorithms. It uses this global information for managing components at its intersection. The functionalities of an IM are listed as below.

1. Managing and monitoring components at its intersection
2. Selecting appropriate traffic policy according to current context
3. Exchanging traffic information with its adjacent IMs
4. Reporting the traffic status at its intersection to ZM. The status report includes states of software and hardware components, inflow and outflow traffic information and the current context at its intersection.
5. Receiving current policy from ZM and update its database of policy.

3.2.8 Zone Manager

Zone Manager(ZM) is responsible for managing the entire network of IMs in a specific region such as a district or a city. The functionalities of ZM are listed as below.

1. Defines the traffic control policy the zone managed by it
2. Remotely monitors the network of IMs
3. Receiving and logging reports from IMs for analyzing traffic flow patterns
4. Propagating the changes in road network topology due to road closure or introduction of new roads to the IMs
5. Propagating changes in traffic policy to the IMs

Chapter 4

Arbiter - Algorithm Design

As discussed in Chapter 2, most of adaptive traffic systems are implemented by using dynamic programming which involves Bellman's dynamic programming algorithm [13]. It is well known that algorithms that use Bellman's dynamic programming algorithm will have memory and computation requirements that are exponential in the size of state space, information space and action space. So, when the volume of traffic is high, it is hard to guarantee an optimized solution. It is necessary to overcome this complexity so that the arbiter functions optimally under stressful situations. The adaptive algorithm proposed in this chapter requires memory resource that is directly proportional to the traffic volume at an intersection, and computational resource that is quadratic in the size of the traffic volume at an intersection. The proposed algorithm is called *Rolling Horizon Streams*(RHS). Informally stated, the algorithm has four steps, as shown in Figure 23 during every cycle. RHS algorithm rolls horizon flows at the intersection, then allocates right of ways to a set of lanes that is expected to optimize the traffic flow at the intersection. Allocating right of ways revolves around safety, liveness and fairness properties. Consequently, RHS optimizes while preserving dependable behavior.

The algorithm will be discussed in this chapter as follows. Section 4.1 discusses the structure of an intersection and terminologies that are used in the algorithm. In Section 4.2 the concepts "compatibility of traffic flow" and "clique" are defined. These are fundamental to the RHS algorithm's performance. Section 4.3 discusses the concept "score" that will be assigned to each vehicle when approaching the intersection. Section 4.4 explains the core

steps of the RHS algorithm. Extensions of RHS to deal with the presence of emergency vehicles and pedestrians are discussed in Section 4.5. The influence of contexts on road traffic are considered in Section 4.6 and methods to integrate them in RHS are proposed. The correctness of the algorithm, given in Section 4.7, explains how the objectives of ATCS in Chapter 3 are achieved in RHS. The simulation results and a comparison with the *fixed-time* algorithm appear in Chapter 7.

4.1 Intersection Structure

Figure 17 depicts the structure of a road at an intersection which is governed by the adaptive arbiter. For the sake of clarity in explaining the algorithm, we illustrate in the figures one-way traffic situations. Thus, our figures show 'North-South' and 'East-West' traffic flows. However the algorithm will work for two-way traffic flows, where in each direction many lanes can exist. The following sections explain the terminologies used in RHS algorithm.

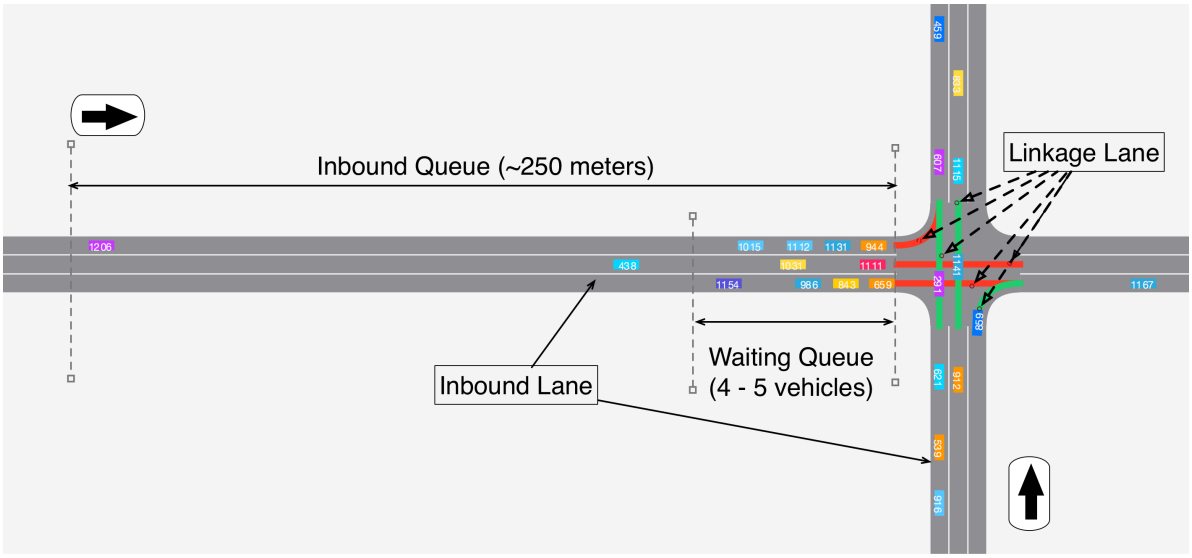


Figure 17: Queues at an intersection

4.1.1 Inbound Queue

The *Inbound queue* in an inbound lane captures vehicles approaching the intersection. The length l of the inbound queue in a lane must be neither too short nor too long. If the queue

is too short, the result of planning will reflect only a part, not the whole state, of the current traffic flow. It must be long enough to allow the execution of the algorithm to be completed and allow planning process to produce a reliable result. However, if l is too long, the accuracy of the algorithm can be downgraded. The reason is vehicles that are far from the stop-line (at the intersection) have a high probability to change lanes which makes the result and the planning process to become invalid. In order that vehicles can travel smoothly without braking in perfect situations l must not be chosen short. A "perfect situation" is the scenario when there is no vehicle at an intersection while only one platoon of vehicles flows through the intersection. In this situation the arbiter will turn on "green" so that all vehicles can go through the intersection without braking. Technically, vehicles can only travel through intersections without braking if green waves occur. In particular, at a moment drivers consider decelerating if the traffic light is red, the arbiter should also consider switching the traffic light to green if possible. Based on these observations the *queue length* l is calculated to satisfy the inequality in Equation 10.

$$l > s \geq \frac{v_0^2}{2d_c} \tag{10}$$

In this equation s is the distance from the stop-line at which vehicles start decelerating if the approaching traffic light is red, v_0 is the desire speed, which is the minimum of "the limit speed on the inbound lane" and "the maximum speed that the vehicle can reach", and d_c is the comfortable deceleration that drivers can deliver.

4.1.2 Waiting Queue

An initial segment of the inbound queue, called *Waiting Queue*, is defined so that vehicles in this queue can be given priority to cross the intersection over vehicles outside this queue. The front of the *Waiting Queue* is at the intersection stop line, as illustrated in Figure 17. The priority mechanism for vehicles in this queue is explained below.

1. The size of waiting queue is to be chosen so that all vehicles in the waiting queue should be able to cross the intersection when the inbound lane receives a new right of way. In other words, the arbiter will allocate a sufficient amount of green time for

'each switching' to the inbound lane to discharge all the waiting vehicles in *Waiting Queue*. The reason behind this strategy is to minimize the total amount of lost time by reducing the number of switchings of traffic lights. When the traffic light is turned to green, drivers usually need 1-2 seconds to react to the change and vehicles also need several seconds to accelerate to a good speed. During these delays, the utility of the intersection is very low, may even be nothing.

2. If a vehicle has been waiting in the waiting queue for θ_t time, depending on the value of θ_t the vehicle is given a higher chance to cross the intersection. The tactic to determine a score based on θ_t will be discussed in Section 4.3

4.1.3 Linkage Lane

An inbound lane at an intersection may or may not be allowed to make a turn at the intersection. Traffic policy for an intersection defines which lanes in a traffic direction are allowed to make turns into which lanes in other traffic directions. Based upon this policy we define *Linkage* as a connection (relation) between a pair of an inbound and outbound lanes at the intersection. The linkage connecting two lanes is called a *linkage lane*. Each linkage is designated for a single and unique pair of inbound and outbound lanes. A set of linkages define all the permitted turns at the intersection. Figure 18a illustrates a set of linkages at an intersection. The set includes N_1W_1, $N_1S_1, N_2S_2, N_3S_3, E_1W_1, E_2W_2, E_3W_3$, and E_3S_3. A linkage lane is *compatible* to another linkage lane if vehicles can pass through both of them simultaneously without collision. Compatibility property can be evaluated by the following rules:

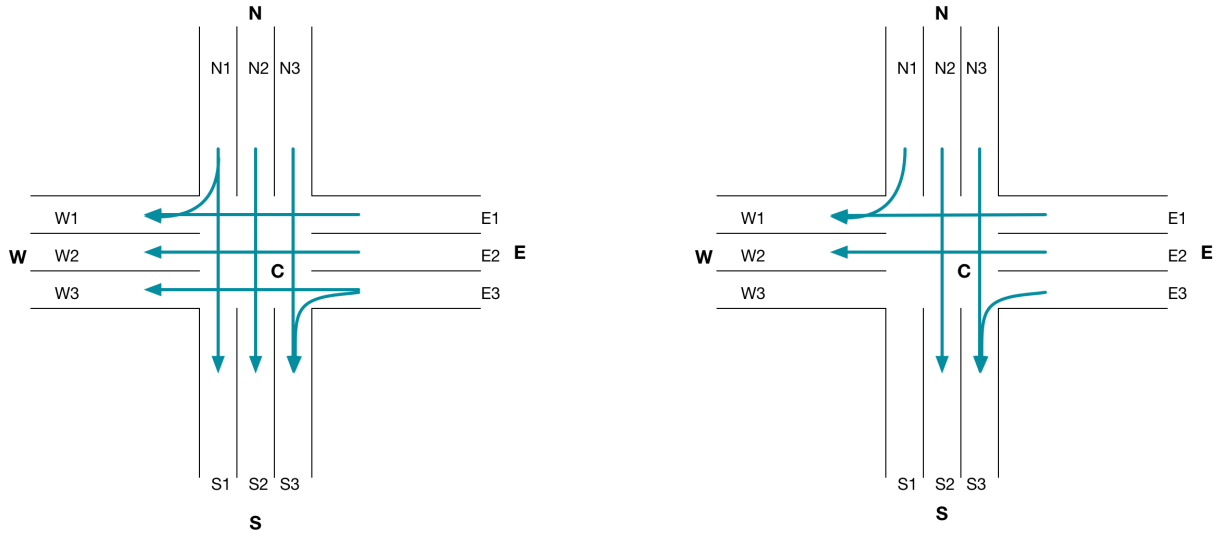
1. If both linkage lanes start from the same inbound lane, they are compatible to one another. For example, in Figure 18a, N_1W_1 and N_1S_1 are compatible to one another.

2. If both linkage lanes end at the same outbound lane, they are incompatible to one another. For example, in Figure 18a, E_3S_3 and N_3S_3 are incompatible to one another.

3. If two linkage lanes intersect, they are incompatible to one another. For example, in Figure 18a, E_1W_1 and N_1S_1 are incompatible to one another.

Turn Prediction

At an intersection it is likely that an inbound lane is connected (through linkage relation) to several outbound lanes. In Figure 18a, the inbound lane N_1 is related by linkage to two outbound lanes W_1 and S_1. It means vehicles approaching the intersection on lane N_1 can either go straight to the lane S_1 or turn right to the lane W_1. An estimation of the ratio between the linkages at an intersection is called *Turn prediction*. Because turn prediction is only an estimate based on "observations or hypotheses", applying turn prediction to regulating the traffic at an intersection can introduce inconsistencies. For example, when the destination of the leading vehicle on lane N_1 is W_1, and the ratio of the link N_1S_1 is much higher than the link N_1W_1 the planning process in Arbiter might favor the link N_1S_1. There will be no progress for vehicles on that lane if the arbiter gives a right of way to only the link N_1S_1 as the leading vehicle needs to be cleared first. This situation can be avoided if every inbound lane is bound to have only one linkage. The road network topology at the intersection needs to be modified to satisfy this restriction. Figure 18 illustrates two versions of an intersection, one without turn restriction and one with turn restriction.



(a) Without turn restriction

(b) With turn restriction

Figure 18: Linkages and turn restriction

In many situations, it is necessary to use *turn prediction*. In particular, when the number of lanes on an inbound road is less than the number of outbound roads at an intersection

many turns are possible. For example, in Figure 19, both inbound roads from East and South have only one lane but are connected to two different outbound roads (West and North). In this scenario, *turn prediction* must be used to estimate flows on each linkage. However, in order to allow traffic flow without blocking, all linkages which started from the same inbound lane must be assigned *right of ways* simultaneously.

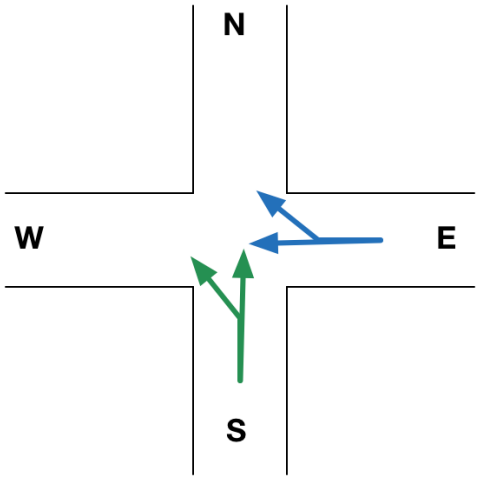


Figure 19: Single Lane Intersection

4.2 Clique

The term *Clique* is introduced to define *"a maximal subset of the set of linkage lanes at each intersection in which all members are compatible to one another"*. In other words, all the members of a clique can be assigned right of ways to cross the intersection at the same time. In general, *clique* holds these important properties.

- *Compatibility property:* All linkage lanes of a clique are compatible to one another.
- *Maximality property:* If any other linkage lane is included in that set the compatibility property will be violated.
- *Completeness property:* The set of cliques form a *cover* for the set of lanes. Hence, the union of all cliques is a set that contains all linkage lanes at an intersection. That

means each linkage lane must be in at least one clique. The completeness property makes sure any movement direction will eventually lead to a right of way.

- *Non-exclusiveness property:* A linkage lane is not required to be in a unique clique exclusively. That means a linkage lane can be in several cliques. Figure 20 shows an example in which linkage lane E_3S_3 belongs to three distinct cliques, whereas cliques C_1 and C_3 have no common linkage.

4.2.1 Constructing a Set of Cliques

Constructing cliques at an intersection is equivalent to the problem [15] of finding a set of maximal complete subgraphs in a graph. The set of cliques can be constructed by the following steps.

1. Create an undirected graph $G = (V, E)$ with V is a set of all linkage lanes of an intersection. For each pair of two distinct linkage lanes a and b, edge $ab \in E$ if only if a and b are *compatible* to one another.

2. Use Bron Kerbosch algorithm [18] with G as the input to find S, the set of *maximal complete subgraphs* of graph G.

3. For each complete subgraph $G_s = (V_s, E_s)$, $G_s \in S$, create a clique $C = (V_s)$ (V_s is a set of linkage lanes).

Although Bron Kerbosch algorithm requires exponential execution time, the process of constructing cliques does not downgrade the performance of the system. The reasons are:

- The set of cliques is statically constructed, once for each intersection. Since each arbiter manages only one intersection the cliques are built once over the lifetime of an arbiter, provided no exceptional situations, such as accidents, cause road closure.

- The number of linkage lanes at each intersection is small. For example, in Figure 20, the number of linkage lanes is only 6.

4.2.2 Example of Clique

Figure 20 shows an example of an intersection which has the four cliques (N_1W_1, N_2S_2, N_3S_3), (N_1W_1, N_2S_2, E_3S_3), (E_1W_1, E_2W_2, E_3S_3), and (N_1W_1, E_2W_2, E_3S_3). In our Arbiter algorithm, at any moment, only the "best clique, chosen from the set of cliques" is favored to receive the right of ways. The "best" clique is one which has the highest "score", a concept that is defined in the following section.

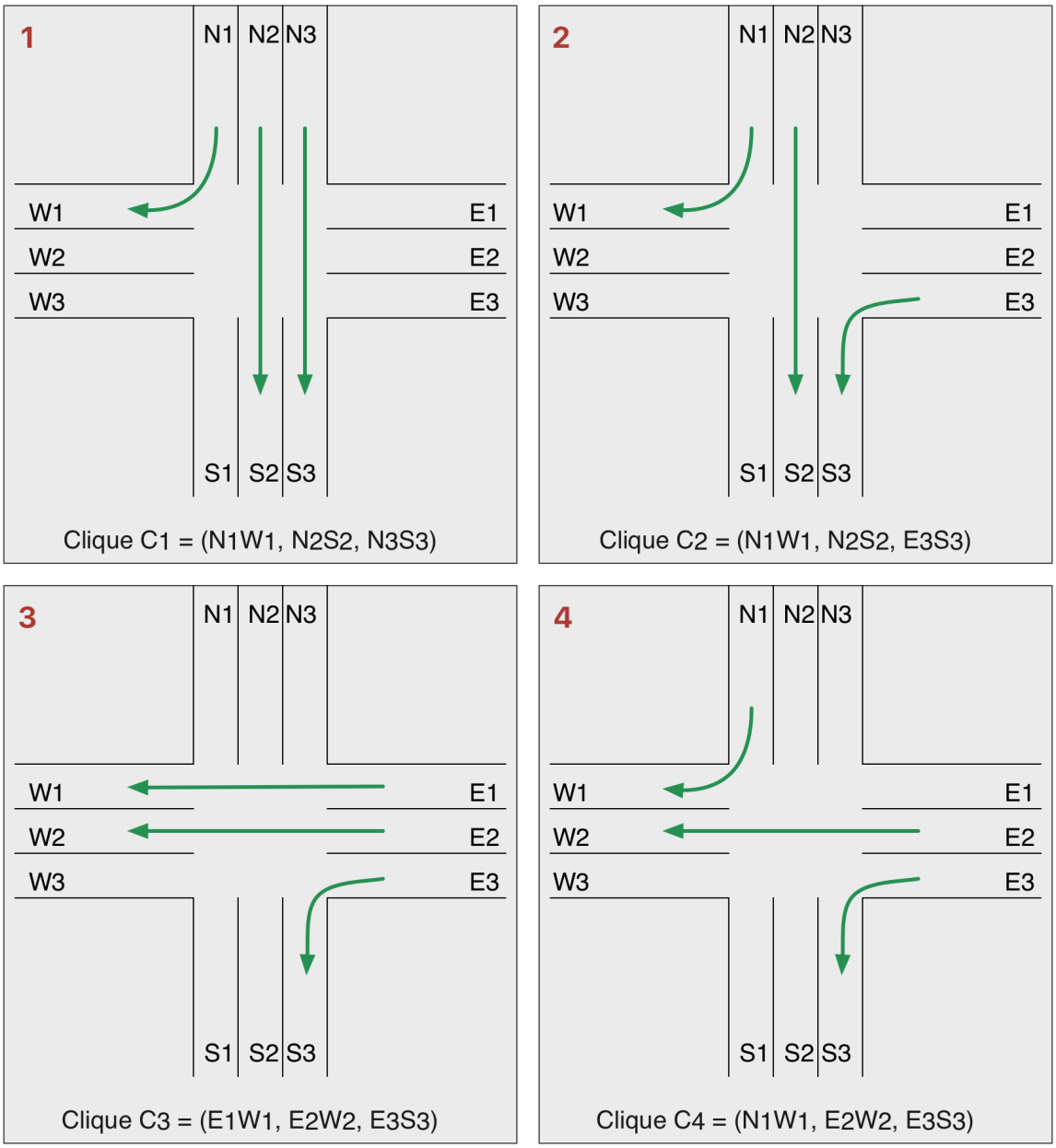


Figure 20: Set of cliques at an intersection

4.3 Vehicle Score

The calculation of route score for a vehicle is explained with respect to an arbitrary intersection I_x shown in Figure 21. Every vehicle approaching I_x in every lane will be assigned a score when entering the inbound queue of that lane in the intersection I_x. This score will be increased monotonically over time as the vehicle keeps approaching the waiting queue (inside the inbound queue). The score $s(t)$ of a vehicle at time t is calculated from the 'base score', 'route score of the vehicle', and 'its aging function'.

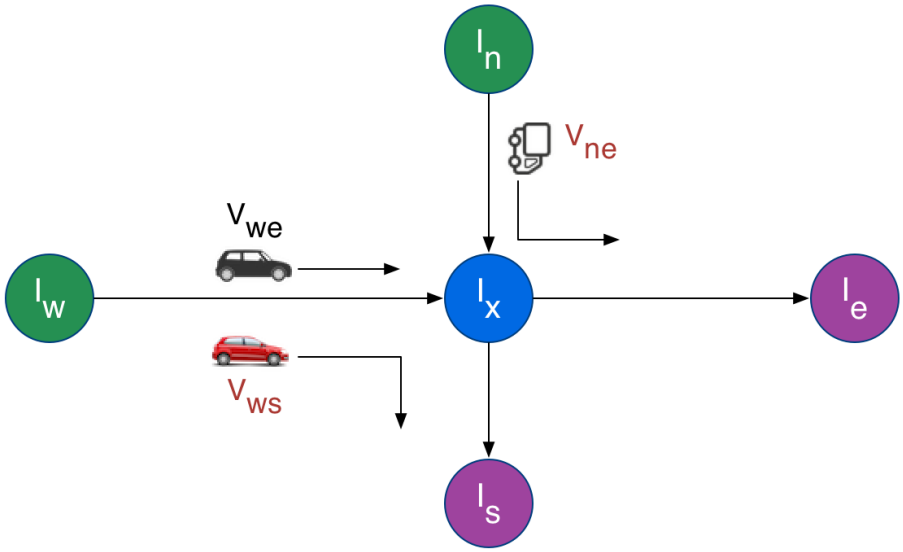


Figure 21: Routes at an intersection

4.3.1 Route Score

A vehicle approaching I_x may come along a lane from any one of the neighboring intersections of I_x. We call this segment of trip the "route" taken by the vehicle. We define *Route score* s_r for a vehicle as a value that depends on this route r. In Figure 21, vehicles v_{we}, v_{ws}, and v_{ne} are shown to approach the intersection I_x and their respective trips are "from I_w to I_e", from "I_w to I_s", and from "I_n to I_e". The assignment of route score at intersection I_x can be explained informally as follows:

- If a vehicle comes from a congested intersection I_i, it is favored to receive right of way than a vehicle that comes from non-congested intersection I_j. The reason is that

assigning a higher priority clearance to vehicles from congested area than to vehicles from a non-congested area we can expect to relieve traffic congestion. That is, we assign $s_{ix} > s_{jx}$.

- If a vehicle that goes through I_x is traveling towards a congested intersection I_j, it is assigned lower priority to receive right of way than a vehicle that is traveling towards a non-congested intersection I_i. The intention is to prevent a congested area from continuing to build up more congestion. That is we assign $s_{xj} < s_{xi}$.

The primary idea behind the calculation of route score is to let the Arbiter at an intersection cooperate with its neighbor intersections to *minimize the maximum* values of 'intersection densities' in the network. The reasons to minimize the maximum value of density at an intersection are explained below.

- The relation between flow rate and density (see Section 1.1.1) states that both flow speed and flow rate decrease when density increases (when $k > k_c$). That means if we minimize the density, we can maximize the flow rate and flow speed.

- Traffic jam happens when density of an area reaches to the jam density value k_{jam}. If we can minimize the maximum of density, the traffic system can handle a higher volume of vehicles without causing traffic congestions.

We define the mathematical expression in Equation 11 and use it to define the score s_{we} for a vehicle at intersection I_x as it takes the route from I_w to I_e crossing the intersection I_x. Let there be n "inbound" lanes and m "outbound" lanes at I_x. The "inbound value" in Equation 11 is the proportion of inbound density of vehicles that flow into I_x from I_w, and the "outbound value" is the proportion of outbound density of vehicles that flow out from I_x to I_e. Every density value in Equation 11 is chosen to be "the maximum of {the critical density and the real density value}". In other words, if the real density at an intersection is less than the critical density, the critical value is selected.

$$s_{we} = \underbrace{\beta \times \frac{k_w}{\sum_{i=1}^{n} k_i}}_{\text{inbound value}} - \underbrace{\gamma \times \frac{k_e}{\sum_{j=1}^{m} k_j}}_{\text{outbound value}} \tag{11}$$

where:

- β is a parameter assigned to the inbound traffic flows,
- γ is a parameter assigned to the outbound traffic flows,
- s_{we} is the route score for a vehicle taking the route I_w to I_e,
- k_w is the density at intersection I_w,
- k_e is the density at intersection I_e,
- k_i is a density at I_i, an intersection which feeds traffic into I_x,
- k_j is a density at I_j, an intersection to which traffic flows out from I_x,
- n is the number of inbound lanes at intersection I_x, and
- m is the number of outbound lanes at intersection I_x

] The values for β and γ are chosen by the TMs depending upon the contexts, such as accidents and road closure. If β is greater than γ, the inflow traffic is favored. This implies that the congestion at the source from which the traffic flows into the intersection will be cleared. If γ is greater than β, the outflow traffic is favored at the intersection. This implies that the congestion at the destination to which the traffic flows out will be reduced.

4.3.2 Aging Function

The primary purpose of the aging function is to guarantee liveness property or prevent starvation from happening. That is, every vehicle eventually passes the intersection. Consider the scenario when many vehicles keep approaching an intersection in the direction NS, and a single vehicle is waiting at the intersection on the direction WE. If Arbiter emphasizes only "traffic density" and "route scoring" it may not allocate the right of way for the vehicle in the direction WE. This will lead to "starvation" of that vehicle. The aging function is introduced to solve this problem. Aging function gradually increases the score of vehicles in the waiting queue as time passes in order to increase the opportunity for vehicles to be

granted a right of way. Hence liveness property is ensured. Using the aging function, the arbiter ensures fairness property that every vehicle in a lane will have a chance to cross the intersection within a finite amount of time. Therefore, the aging function should be a monotonically increasing function of time.

However, if the aging function is not appropriately defined there is a chance that the efficiency of the arbiter to optimize traffic flow is reduced significantly. For example, If the aging function increases too fast with (waiting) time, the arbiter will tend to favor a lane with longer waiting vehicles than a lane with more number of vehicles. On the other hand, if the aging function increases only too slowly it may not create any significant change for the score of a vehicle in a waiting queue. For example, if aging function increases only too slowly the score after waiting for 10 seconds and 60 seconds may not be different, thus making vehicles to wait longer. Furthermore, the aging function should not be a simple linear function, because the slope of the function should also increase over time especially when the waiting time is greater than the defined threshold. Based on these considerations, in our algorithm we have selected the aging function as a parabolic function $g = at^2 + bt + c$. Figure 22 shows the plot of our selected function with $a = 1/900$, $b = 0$ and $c = 1$, and compares the region governed by it with linear functions that correspond respectively "fast" and "slow" growth rates.

4.3.3 Definition of Vehicle Score s(t)

This score $s(t)$ at time t for a vehicle in a lane at an intersection is calculated by the following equation.

$$s(t) = \begin{cases} (s_b + s_r) \times g(t - t_0) & \text{if the vehicle is in the waiting queue} \\ s_b + s_r & \text{otherwise} \end{cases} \tag{12}$$

where t_0 is the time when the vehicle entered the waiting queue, s_b is the base score of the vehicle assigned when entering the inbound queue, s_r is the route score for route r taken by the vehicle in arriving at the intersection, and g is the aging function. Without bias and for the sake of simplicity the base score s_b for every regular vehicle can be chosen as 1 under normal circumstances. For other vehicles such as ambulances, firetrucks, and diplomatic cars,

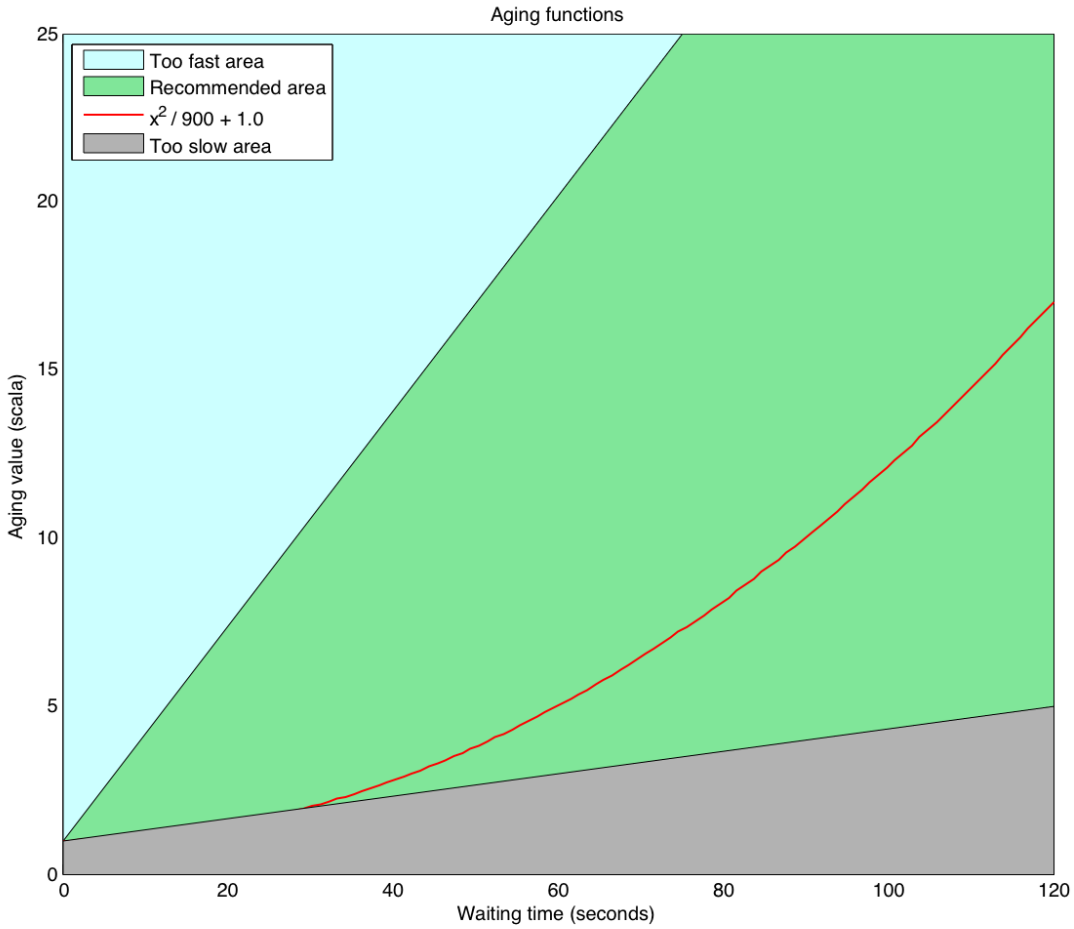


Figure 22: Aging function: $g = t^2/900 + 1$

the value of s_b, assigned by the TMs, will be greater than 1.

4.4 Rolling Horizon Streams(RHS)

The centerpiece of Arbiter algorithm, called RHS algorithm, is explained in this section. In traffic prediction studies "forecasting horizon" refers to a time window T, such that for a starting observation time t_0 and for $i \geq 0$, the traffic flow for the duration $[t_i, t_i + T]$ is predicted with a step size $\delta_t = (t_{i+1} - t_i)$. The general idea of RHS algorithm is to "roll horizon flows" at the intersection, then allocate right of ways to a set of lanes in order to optimize the performance. The optimization is done for those parameters that are selected for optimization at the intersection. Figure 23 outlines the four main steps *Rolling flows*, *Ranking*

cliques, *Deactivating non-member lanes*, and *Activating member lanes* of RHS algorithm.

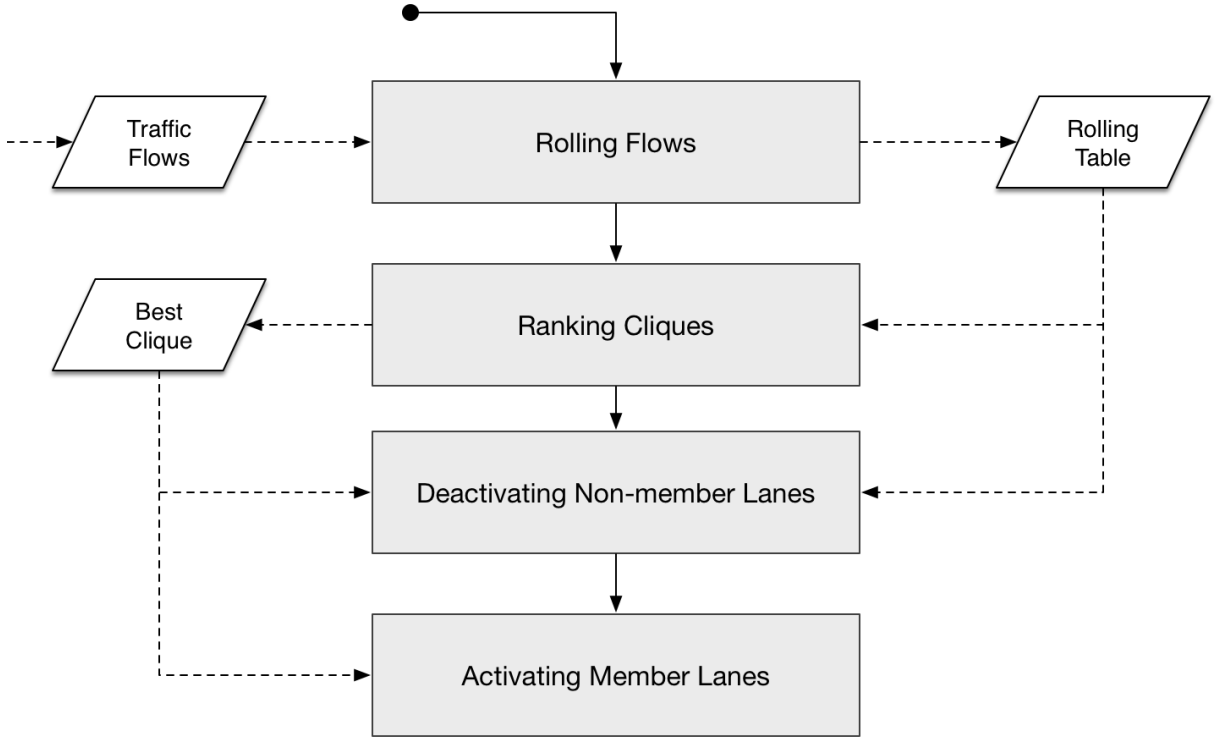


Figure 23: Four steps of RHS

4.4.1 Rolling Flows

Process *Rolling Flows* is responsible for predicting locations of approaching vehicles in the next K intervals *if its inbound lane was given a right of way*. This process uses an instance of microscopic traffic simulation roll of every vehicle in flows from the FlowBuilder. Rolling vehicle means updating the speed and location of the vehicle in the next interval with respect to its current speed and location, and driver behaviors. This feature of the simulation can be implemented by using *Car Following* models such as GIPPS [23] and IDM [52]. The detail of this model will be discussed in Section 6.1, as part of the simulation study. The output of this process is L *rolling tables* with size $N \times K$, where L is the number of inbound lanes, N is the number of vehicles in inbound queue l, and K is the number of rolling steps. Each row of the table illustrates the locations of a vehicle through the current time t to $t + K \times \delta_t$,

where δ_t is the interval of each rolling step. The window time for observing the horizon is $K \times \delta_t$. Hence the choice of K and δ_t are to be chosen based upon the window time.

4.4.2 Ranking Clique

Ranking Clique process is responsible for selecting the clique that is expected to produce the highest accumulated discharge rate in the next K intervals. It relates the rolling tables in the previous process to evaluate the mean values of the accumulated discharge rate for each lane (MDRPL) and for each clique (MDRPC).

Mean Discharge Rate Per Lane (MDRPL)

We calculate $l_k(n)$, the *Mean of discharge rate per lane* (MDRPL) of lane k at the rolling step n, by the following formula.

$$l_k(n) = \frac{\sum\limits_{v_i \in q_k} u_i}{n} \tag{13}$$

where v_i is a vehicle in the inbound queue q_k of lane k, u_i is an utility that vehicle v_i can produce at the step n. This utility function $u_i(n)$ for vehicle i at the rolling step n is measured by the expression

$$u_i(n) = \begin{cases} s_i & \text{if } v_i \text{ is expected to cross the intersection at step } n \\ 0 & \text{otherwise} \end{cases} \tag{14}$$

where s_i is the score of vehicle v_i. The formula states that a vehicle score at step n is contributed to MDRPL if and only if the vehicle is expected to cross the intersection. The values of MDRPL can be presented in a table of size $L \times K$, where L is the number of inbound lanes and K is the number of rolling steps. Each row of this table demonstrates the values of MDPRL throughout the N rolling steps.

Mean Discharge Rate Per Clique (MDRPC)

The *Mean of discharge rate per clique* $c_k(n)$ is the mean of discharge rate of clique q_k at the rolling step n, calculated as the sum of the MDRPL of all the members of clique q_k at step n

by the following equation.

$$c_k(n) = \sum_{i \in q_k} l_i(n) \tag{15}$$

where l_i is an inbound lane is a member of clique q_k, and $l_i(n)$ is MDRPL of lane l_i at step n. The result of this step is a table with size $C \times K$ with C is the number of cliques at the intersection and K is the number of rolling steps. Each row of the table shows the values of MDRPC throughout N rolling steps.

Best Clique and Periods

The best clique is the one that has the highest MDRPC value throughout the rolling steps. The moment when the selected candidate reaches the highest rate is called the *peek period* (t_p), and the moment when the MDRPC value of the selected candidate falls below other cliques is *end period* (t_e). If there is more than one peak, the earliest peak will be selected. End period is the end of rolling time when the values of MDRPC of the selected candidate are always greater than values of other cliques at the same step. The output of this process is a 3-tuple of (c, t_p, t_e) where c is the best candidate clique, and t_p and t_e are respectively the peek period and the end period of the selected clique.

4.4.3 Deactivating Non-member Lanes

Process *Deactivating non-member lanes* is responsible for efficiently and safely terminating running lanes (changing a traffic light from green to red) which are not members of the selected clique. Figure 24 shows the flowchart of this process.

Termination Conditions

Switching to RED in a lane is safe if and only if all the following conditions are satisfied:

1. The green time that the lane has used is greater than the minimum green time that the arbiter allocated when the lane was switched from red to green, or all vehicles in the waiting queue (at the moment switching happened) crossed the intersection.

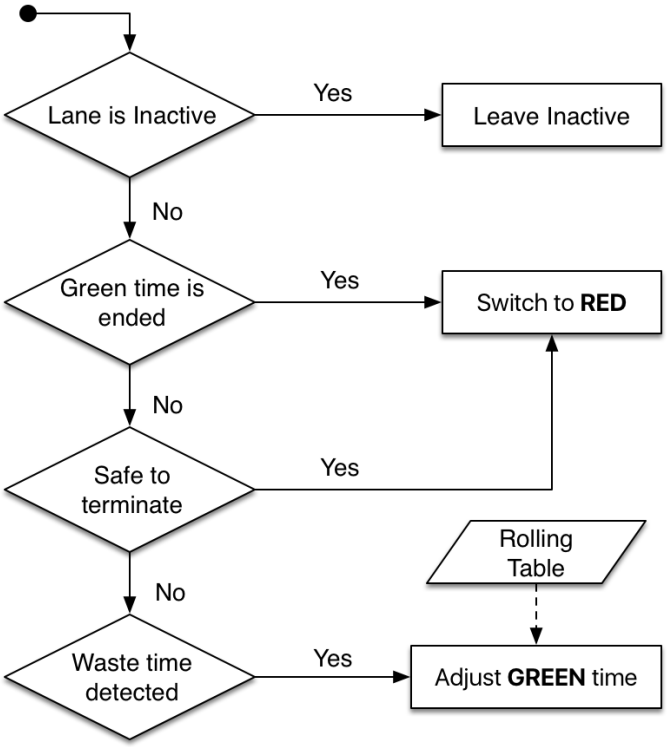


Figure 24: Flowchart of deactivating non-member lanes

2. All the remaining amount of green time will be wasted time because no vehicle can use that time to cross the intersection.

3. The leading vehicle must be able to stop safely without any hard braking. This condition can be checked with this inequality $d > \delta_t \times v_c + (v_c^2/2d_b)$, where d is the distance of the leading vehicle from the stop line, δ_t is a reaction time of drivers, v_c is the current speed of the leading vehicle, d_b the minimum value of deceleration that is considered as hard braking.

Adjust Green Duration

Adjust Green Duration is a correctness process that adjusts the remaining amount of green time that the arbiter has allocated to a lane. If the remaining green time is used wholly, the arbiter will leave the value without any update. However, if the arbiter detects a wasted time it will shorten the remaining green time. This strategy is an explicit *feedback loop* which helps to improve the performance by minimizing the total amount of *Wasted time*, a leftover

amount of green time after the last vehicle can utilize. Figure 25 indicates that the amount after vehicle v_3 crosses the green light is a wasted time. The last utilizing vehicle can be found by iterating over the rolling table which is produced in the Rolling Flows process.

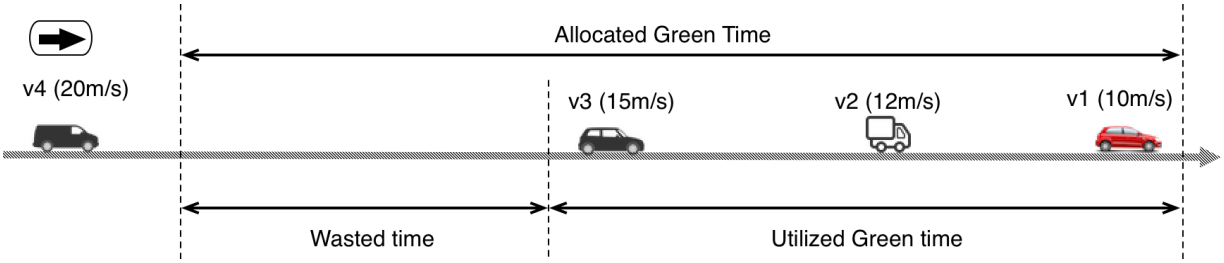


Figure 25: Detecting wasted Time

4.4.4 Activating Member Lanes

Process *Activating member lanes* is responsible for activating lanes which are members of the selected clique safely and efficiently. Figure 26 depicts the flowchart of this process which is described as below.

- If a linkage lane is in inactive status, the arbiter will assign it a right of way if and only if that linkage lane is fully compatible to all other active linkage lanes. If it is safe to turn on the traffic light to GREEN, the arbiter will assign that linkage lane an amount of green time via 'Turn On' procedure, explained below.
- If a linkage lane is in active status, the arbiter will maintain and adjust its green time duration via 'Maintain Green' procedure, explained below. Since the linkage lane is active already, there is no need to check the compatibility condition.

Turn On Procedure

The procedure *Turn On* is used to allocate a new green time for inactive lanes. The amount of green time should be at least sufficient to clear all vehicles that are waiting in the waiting queue of that lane. Technically, this amount t_l allocated to lane l is calculated by the equation

$$t_l = max(t_e, t_l^c) \tag{16}$$

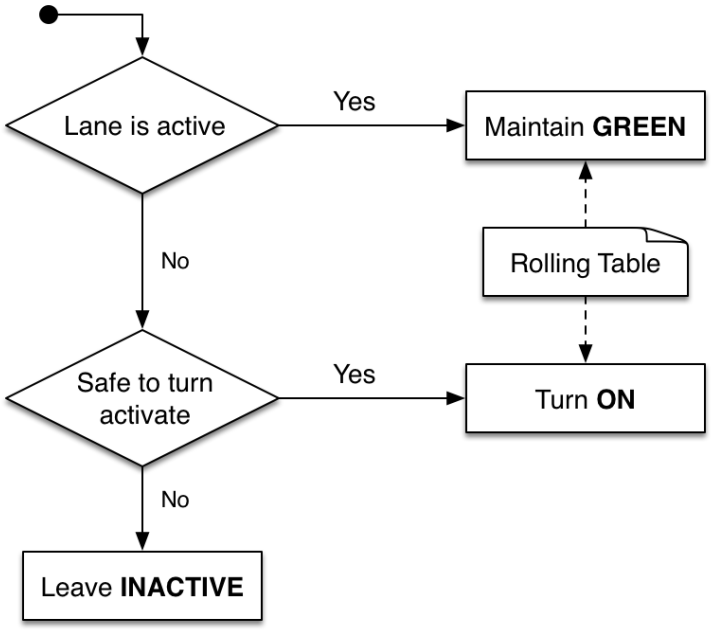


Figure 26: Flowchart of activating member lanes

where t_e is the 'end period' of the selected clique, and t_l^c is the *clearance time* for lane l. *Clearance time* is defined as the minimum amount of green time that is long enough to discharge all vehicles in the waiting queue. It can be calculated by iterating over the rolling table to find a moment when the last vehicle in the waiting queue crossed the intersection.

Maintain Green

The procedure *Maintain Green* is used to maintain or extend the remaining amount of green time. This procedure is only applied to a lane which is in active status and is a member of the selected clique. The new amount of green time t_l for lane l is calculated according to the expression

$$t_l = max(t_e, t_l^r) \tag{17}$$

where t_e is the 'end period' of the selected clique, and t_l^r is the remaining amount of green time of lane l.

4.4.5 Update Interval

Update Interval(Δ_t) is an amount of time between two successive executions of the algorithm. This update interval should not be too long because the current control decisions can be invalid over a long period. In our algorithm, we select the update interval to be 0.5 seconds which equals to the recommended interval step of IDM model [52].

4.5 Extended RHS

The RHS version of the arbiter described in the previous section will manage only regular vehicles. In this section, we consider two exceptional situations, namely those caused by emergency vehicles in the traffic and pedestrians in crossings.

4.5.1 Emergency Vehicles

The arbiter can support emergency vehicles seamlessly if the infrastructure is able to distinguish them from regular vehicles in captured traffic flows. Emergency vehicles can be detected by hardware sensors or through V2I communication. The following two simple modifications to the algorithm RHS will prioritize the right of way of emergency vehicles in the traffic flows.

1. **Car Following with Emergency Vehicles**
   Emergency vehicles often do not follow another vehicle as regular vehicles do. Strictly speaking if a priority vehicle, such as ambulance or police car, is following regular vehicles, then the regular vehicles will eventually be forced to make way for the priority ones to by pass them. Car Following models that are used to roll vehicles in RHS do not consider this special scenario. Therefore, the car following models in RHS should be extended to include the factors described below.

   - Regular vehicles make way for emergency vehicles. Instead of keep moving up the regular vehicles the emergency vehicles may be allowed to bypass them.
   - Emergency vehicles are not restricted by the speed limit imposed on the lanes.

- Emergency vehicles should be assigned a higher acceleration value, but a lower time-headway value (reaction time) than those assigned for regular vehicles.

2. **Emergency Vehicle Score**

   Emergency vehicles should be assigned a much higher base score (s_b) than a regular vehicle. The base score of an emergency vehicle will be set by the TMS so that when it enters an inbound queue, the arbiter at that intersection immediately favors that lane to receive a right of way. This allows emergency vehicles cross an intersection without any 'delay'. The route score of an emergency vehicle can be chosen as 0. Finally, RHS can prioritize different kinds of emergency vehicle such as fire-fighting engines, ambulances and police cars by assigning them different base score values.

With these modifications in RHS, the arbiter can fully preempt traffic signals to allow emergency vehicles to cross an intersection with a minimum delay, while maintaining traffic safety and smooth traffic flow without any significant halt and go interruptions.

4.5.2 Pedestrians

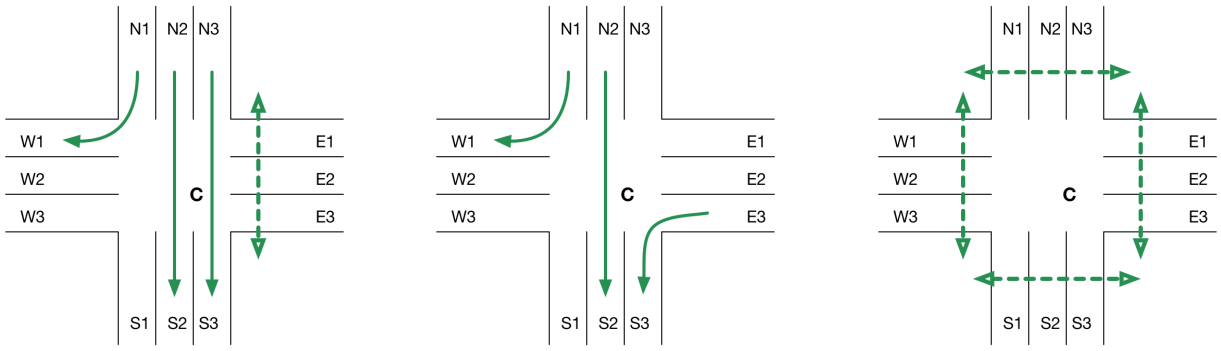
Like emergency vehicles, in order to support pedestrians, the traffic infrastructure system must be able to collect the presence of pedestrians at intersections. Pedestrians can be detected through camera detectors [16], although the direction of their crossings can be approximately predicted. The RHS algorithm will be extended to include the following factors in order to support safe crossing for pedestrians.

1. **Crosswalk**

   Crosswalk is defined as a place designated for pedestrians to cross a road. In this extended model, a crosswalk is considered as a regular linkage. Thus, a clique may contain both regular linkages and crosswalks, or just only linkages, or just only crosswalks (see Figure 27).

2. **Pedestrian Crossing Model**

   The way people cross a road on a crosswalk at an intersection is completely different from the way a vehicle follows another vehicle on a road. That is, a pedestrian need



(a) A clique contains both linkages and crosswalks

(b) A clique contains linkages only

(c) A clique contains crosswalks only

Figure 27: Cliques in the extended RHS

not follow another pedestrian while crossing. Therefore, we can not use a car following model to estimate 'pedestrian crossings'. Pedestrian crossing model such as [45] should be used to 'roll' pedestrians in the rolling procedure of RHS.

3. **Pedestrian Score**

   Pedestrian score should not include the route score because the route score is specified to congestion rates of vehicles not related to pedestrians. The base score for a pedestrian is assigned by the TM at that intersection. The value of the base score will be determined by the traffic control policy for pedestrian crossing. In certain contexts, the base score of a pedestrian may be chosen less than the base of a regular

4.6 Integrating Context Parameters in RHS

As stated in Chapter 3, context parameters such as *weather conditions*, *public events*, *time*, *traffic zone*, and *road closure* can be taken into account in regulating traffic flows. In our proposed architecture (see Chapter 3), when *Intersection Manager*(IM) receives the up to date values of these parameters, it 'transforms' them to a traffic policy. From the perspective of RHS algorithm, a traffic policy is just a 3-tuple consisting of (1) result of *Car Following* model, (2) value of *aging function*, and (3) a set of allowed *linkages*. Table 3 outlines the influences of the context parameters to arbiter parameters. These relations are explained as follows.

Context Parameter	Arbiter Parameter
Weather Condition	Car Following
Public Events	Car Following
Time	Aging Function
Traffic Zone	Base Score
Lane Closure	Clique

Table 3: Influences of the context parameters to RHS

- **Weather Condition:**

  Weather condition affects directly the way people drive. In dry weather condition, drivers usually keep the *time headway* to be around 1-2 seconds. However, in wet or snowy condition, they prefer to keep a larger headway, say around 5-7 seconds. If RHS algorithm fails to capture this value, the *rolling produce* procedure will produce inaccurate rolling tables. Consequently, the performance of the algorithm can be downgraded. Therefore, the parameters that match weather conditions are integrated in *Car Following* model of RHS algorithm.

- **Public Events:**

  When a public event, such as music festival or soccer game, ends, the cars will try to drive out of that place as soon as possible. In this situation the drivers are willing to accept a higher level of risk, which means "they may keep a smaller *gap* and *time headway*" when following another vehicle. Consequently, the parameters in *Car Following* model of RHS algorithm need to be adjusted.

- **Time:**

  Although the proposed algorithm reacts efficiently to dynamic traffic flows, its performance can be further improved if the "time factors on traffic patterns" is also factored into it. For example, when the volume of traffic is low the performance of the algorithm can be upgraded with a 'fast increasing' *aging function*, and when the traffic volume is high, the algorithm will perform well with a 'slow increasing' *aging function*. From traffic statistics gathered by traffic enforcing authorities, it is known that traffic volumes

at a specific area “vary over time within a day” as well as “ vary over certain days in a week”. By integrating time contexts and the traffic volumes in each time context in the choice of aging function the performance of the algorithm can be improved.

- **Traffic Zone:**

  Different traffic zones in a city have different vehicles-to-pedestrians ratios, which can vary over time contexts. With a knowledge of these ratios in different time contexts, base score values for vehicles and pedestrians can be computed in RHS. These scores, which vary from context to context, can improve the efficiency of the green time allocation for vehicles and pedestrians.

- **Lane Closure:**

  Lane closure contexts are observed by sensors and communicated to the nearest IMs. The IM that receives the lane closure information will select the traffic policy for “turn” at the intersection and communicate to the module that computes the cliques. This model recomputes the set of cliques and send it to the Arbiter managed by the IM. In this manner, the set of cliques used by RHS algorithm will match the real-world configuration of compatible lanes. Consequently, RHS algorithm will meet the dependability objectives.

4.7 Correctness and Complexity of RHS

The two criteria for evaluating an algorithm are *correctness* and *complexity*. The correctness problem is related to the presence of a stated property in the algorithm. Time complexity refers to the worst case execution time taken by the algorithm to terminate, and is often expressed as a function of the input size to the algorithm. Space complexity refers to the maximum intermediate storage, measured as a function of input size, during the entire execution of the algorithm.

4.7.1 Correctness of RHS

The three core properties of the arbiter are safety, liveness and optimization. A formal correctness proof, such as verification by model checking, is beyond the scope of this thesis, because the arbiter interacts with physical processes in a dynamic environment and formally modeling them is extremely hard [7]. However in this section, we outline how these properties are achieved in the algorithm.

Safety

The arbiter guarantees the safety property at an intersection because it never grants right of ways to two incompatible linkage lanes simultaneously. This ensures collision-free passage of vehicles at an intersection. In the algorithm, this behavior is enforced in the following procedures.

- The algorithm always grants right of ways to *one and only one* clique at any moment.
- The linkage lane can be switched from RED to GREEN *if and only if* all linkage lanes that are incompatible to it are turned off and vehicles on those linkage lanes have crossed.
- The linkage lane can be switched from GREEN to RED *if and only if* vehicles approaching it can safely stop.

Liveness

The liveness property is promoted by the introduction of the aging function. The principle of the aging function emphasizes that *the longer vehicle stays in the waiting queue, the more likely it will be assigned the right of way.* The two key characteristics of the aging function that achieve liveness are the following:

- It is a monotonically increasing function of waiting time. That means the chance (of vehicle in a waiting queue) to get a right of way will always increase over time.
- The slope of the aging function also increases over time especially when the waiting time is greater than the defined thresholds. This prevents a vehicle from starvation.

Optimization

In the algorithm, the best clique is always selected to grant right of way to vehicles in it. The best clique is expected to deliver the highest number of vehicles through the intersection in the next interval of time. The best clique is more likely to

1. maximize the flow rate (throughput),
2. minimize the total waiting time at an intersection, and
3. minimize the total traveling time in network (inferred from (2))

Moreover, a clique that has vehicles traveling with high speed is favored to receive right of ways than others. The reason is the algorithm estimates that the high speed group of vehicles will complete crossing within a shorter amount of time, which leads to choosing that clique as the best clique. Favoring the high speed group of vehicles will significantly reduce the total number of "stop-and-wait". It is known that the fuel consumption is [3] a monotonically increasing function of a traveling time and a number of "stop-and-go". Since the traveling time and the number of "stop-and-go" are both minimized by the arbiter, it also minimizes the total fuel consumption of vehicles while in the intersection as well as while traveling in the network.

The route score in the algorithm minimizes the maximum value of density for road segments in the network. This strategy leads the traffic system managed by the arbiter and other managers to be able to serve a high traffic volume. However, in exceptional situations when the density approaches "the jam density" in a large number of intersections, traffic flow will be stalled at intersections which in turn will trigger deadlock situations.

4.7.2 Complexity of RHS

Algorithm RHS has a preprocessing state in which the cliques are computed. They are used in all the cycles for regulating the traffic. The number of linkages at an intersection is a constant, which is also the number of vertices in the graph to construct all the maximal cliques. Although computing cliques is NP-complete, because the graph size is small and we compute the cliques only once, this cost is still is a constant, not dependent on the volume of

traffic flow. Therefore, in this section we focus only on the complexity of the dynamic part of the algorithm.

Since the number of arithmetic operations dominate over the number of comparisons in RHS, the complexity of RHS is measured in term of the number of multiplications required in order to calculate the tables and selecting the best clique. The algorithm computes three tables. The size of the first table is $N \times K$, where N is number of vehicles observed in window time T. Each entry in this table is calculated by using Equation 28. A computation of this equation involves 10 multiplications and 1 square root (ignoring additions). Therefore, the cost of computing this table is $\Theta(N \times K)$. The second table computes only the column sums of the first table, there is no multiplication involved. The size of the third table is $C \times K$, where C is the number of cliques. The calculation of each element in this table requires only one division of each corresponding entry in the second table. Therefore, the multiplication cost for constructing the third table is $\Theta(C \times K)$. Hence, the total complexity to find the clique to assign a right of way in one cycle is $\Theta(N \times K) + \Theta(C \times K)$. In principle, the number of cliques C is a constant because the number of linkages at an intersection is bounded. Therefore, the total complexity is $\Theta(N \times K)$. The number of vehicles N is bounded K/r_t, where r_t is an average reaction time. Typically, reaction time is greater than 1 second, thus we conclude $N < K$. Hence, the total complexity is $\Theta(K^2)$. In transportation study, it is found that the value of K should be small, otherwise inaccuracy is introduced in prediction. The worst case complexity of our algorithm is polynomial in K(and hence polynomial in N, number of vehicles observed in window time T). Compared to other approaches which are based on Bellman's Dynamic Programming approach which has exponential time complexity, we have a quadric time algorithm.

Chapter 5

Road Network Topology

The goal of this chapter is to introduce a formal model of road network topology and explain how it is arrived at. This model is a necessary input to the microscopic simulation developed as part of this thesis. The simulation environment provides a solid platform to implement, verify, and evaluate a part of the ATCS presented in the thesis. The simulation environment imitates the two important characteristics of *Road Network Topology Model* and *Vehicle Driver Behavior* of the transportation system. In this chapter the modeling of road network is discussed. The driver behavior model will be presented in Chapter 6.

5.1 Overview

The *Road Network Topology* (RNT) model that we introduce is a complete description of a physical road network and this model is used as an input to the simulation platform. This model provides a detailed presentation for the roads and the intersections in a physical road network. Although the model is readable and editable, it is time-consuming for humans to create this model from scratch. To reduce this complexity another model, called *Road Network Description* (RND), is introduced. The RND model is more abstract than the RNT model created from it. The tool 'netbuild' is constructed to generate the RNT corresponding to the RND input by users. Moreover, RNT is designed so that importing real world data from OpenStreetMap [40] will require only minimal effort. Figure 28 illustrates the different modes of creating a RNT model for the simulator.

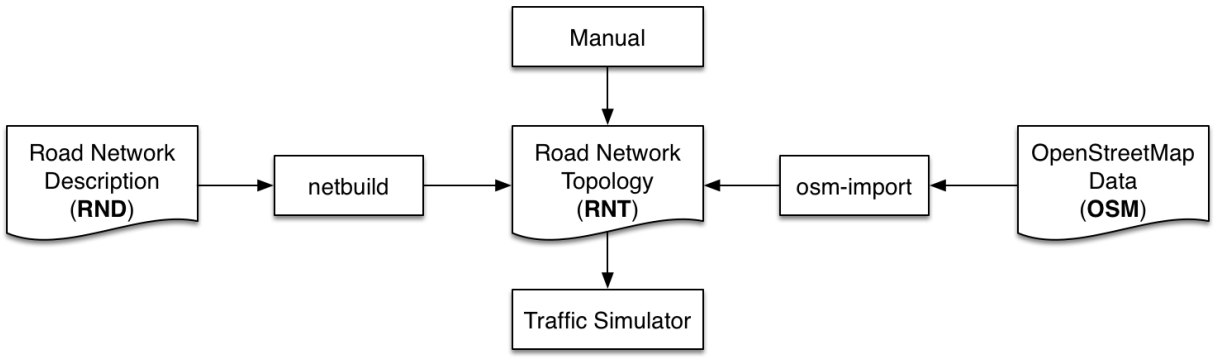


Figure 28: Converting to RNT from RND and OSM

5.2 Road Network Description

Road Network Description (RND) is the descriptive model of a road network. Conceptually, the skeleton of the model is a directed graph in which road segments are edges and intersections are vertices. The primitive elements of the model are *node*, *road*, and *lane*.

5.2.1 Node in RND

In the descriptive model, a *node* typically represents a physical intersection. Each node consists an identifier and a pair of coordinates. Table 4 outlines these attributes in detail.

Attribute	**Type**	**Option**	**Description**
id	String	Required	The identifier of an intersection
x	Double	Required	The x-coordinate of an intersection
y	Double	Required	The y-coordinate of an intersection

Table 4: Node attributes in RND model

5.2.2 Road in RND

In the descriptive model, a *road* represents a physical road segment between two successive intersections. The description of a road segment is a 6-tuple consisting of "an identifier, an origin node, a destination node, a road shape, lanes, and a control type". Table 5 outlines these attributes in detail.

Attribute	Type	Option	Description
id	String	Required	It is the identifier of a road segment. If an *id* is provided in the format of 'α to β', α and β can be inferred as the identifiers of the origin and destination nodes respectively.
from	String	Optional	It is the identifier of the origin node of a road segment. If an origin node is not provided, it can be inferred from the identifier of the road.
to	String	Optional	It is the identifier of the destination node of road segment. If a destination node is not provided, it can be inferred from the identifier of the road.
via	Array	Optional	It is an array of intermediate points that a road segment gets through. Those points are used to construct the shape and the length of a road segment. The value of *via* attribute can be provided in string with the format "$x_1, y_1\ x_2, y_2\ x_n, y_n$".
shape	Structure	Optional	This attribute is used to specify the shape of a road segment. The structure of the shape is discussed later. If the shape is not provided explicitly, it is assumed that the shape of the road is a polyline of $N+2$ endpoints, where N is a number of intermediate points.
lanes	Array	Optional	This is an ordered list of lane specifications. The order of *lanes* attribute is the rightmost order - it starts from the rightmost lane and ends at the leftmost lane (see Figure 29). If a value for this attribute is not provided, the default value of lanes attribute is used.
control	Enum	Optional	This attribute describes how a road segment operates at the destination node. Possible values of *control* attribute are *signaled* and *unregulated*. If this attribute is not provided, the control type of the road segment will be *unregulated* if there is no conflict in traffic flow at the destination node; otherwise it will be *signaled*.

Table 5: Road attributes in RND model

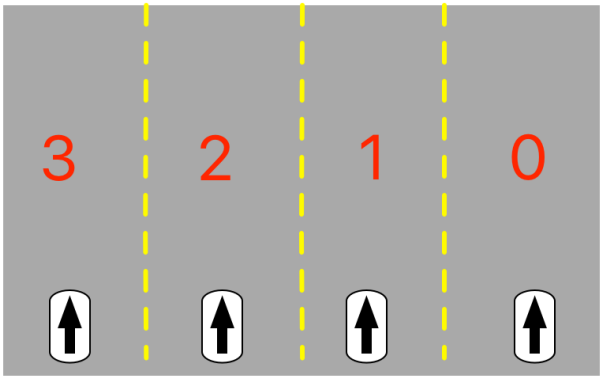


Figure 29: Lane Index

5.2.3 Lane in RND

In descriptive model, a *lane* is a specification for a physical lane segment of a road. Its attributes are illustrated in Table 6.

Attribute	Type	Option	Description
id	String	Required	The identifier of a lane specification
width	Double	Required	The width of a lane segment
speed	Double	Required	The limited speed of a lane segment

Table 6: Lane attributes in RND model

5.2.4 Intersection in RND

In the descriptive model, each node represents an intersection. To keep the descriptive model simple, other detailed attributes such as *turns* and *shape* of an *intersection* are not included in the model. The 'netbuild' utility will generate the internal structure of intersections automatically according to road segments defined in the network.

5.2.5 Road Network Description Model Example

YAML [14] has a human-readable data serialization format and it takes concepts from programming languages such as C, Perl, Python, and XML. The syntax of YAML is designed to be easily mapped to common data types such as list, associative array, and scalar. Figure 30

demonstrates an example of the descriptive model in YAML format of the 16-nodes road network shown in Figure 31. The network in the example is explained as follows:

- *Line 1-2* defines an array of lane specifications which has only one element 'r' with its width is 3.7 $meters$ and allowed speed is 60 km/h.
- *Line 3-4* defines default attributes for the network. By default, each road in the network has 3 lanes of type 'r'.
- *Line 5-21* defines an array of 16 nodes. Each node is specified in format 'id: x,y'.
- *Line 22-49* defines a set of roads in the network. Each road is specified in format 'road-id: road-attribute'. In YAML, character '∼' means 'NULL', thus a road with '∼' inherits the default attributes.

5.3 Road Network Topology

Road Network Topology (RNT) is a detailed presentation of a road network. Unlike the descriptive model, every element in this model is defined explicitly without any assumption or inference. The core elements are node, road, lane, and intersection.

5.3.1 Node in RNT

In RNT a *node* no longer represents a physical intersection, but it is an endpoint of the road segment. The attributes of a node are given in Table 7.

Attribute	**Type**	**Description**
id	String	The identifier of an endpoint
x	Double	The x-coordinate of an endpoint
y	Double	The y-coordinate of an endpoint

Table 7: Node attributes in RNT model

```
lanes:
  r: { width: 3.7, speed: 60 }
defaults:
  lanes: [r, r, r]
nodes:
  1: 100,200
  2: 500,200
  3: 1000,200
  4: 1500,200
  5: 100,600
  6: 500,600
  7: 1000,600
  8: 1500,600
  9: 100,900
  10: 500,900
  11: 1000,900
  12: 1500,900
  13: 100,1200
  14: 500,1200
  15: 1000,1200
  16: 1500,1200
roads:
  5to2:
    via: 100,200 # Node 1
  2to3: ~
  3to8:
    via: 1500,200 # Node 4
  8to7: ~
  7to6: ~
  6to5: ~
  9to10: ~
  10to11: ~
  11to12: ~
  12to15:
    via: 1500,1200 # Node 16
  15to14: ~
  14to9:
    via: 100,1200 # Node 13
  9to5: ~
  2to6:
    lanes: [r,r] # Two lanes
  6to10:
    lanes: [r,r] # Two lanes
  10to14:
    lanes: [r,r] # Two lanes
  15to11: ~
  11to7: ~
  7to3: ~
  8to12: ~
```

Figure 30: RND Model Example

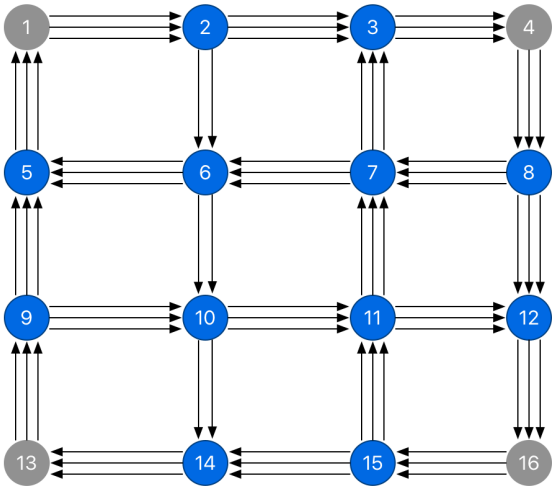


Figure 31: Road Network of Figure 30

5.3.2 Road in RNT

In the detailed model, *road* still represents a physical road segment. The attributes of a road segment are given in Table 8.

Attribute	Type	Description
id	String	The identifier of a road segment
from	String	The identifier of the origin node of a road segment
to	String	The identifier of the destination node of road segment
lanes	Array	The ordered list of lanes from the rightmost to the leftmost (see Figure 29)

Table 8: Road attributes in RNT model

5.3.3 Lane in RNT

In the detailed model, each lane is assigned an index and accompanied with an ordered list of segments. The attributes of a lane are outlined in Table 9.

Attribute	Type	Description
index	Integer	Lanes are ordered from right to left, with the rightmost lane assigned 0 as the index and the leftmost lane assigned index $N-1$ if N is the number of lanes of the road segment. So, *index* is the index of a lane in the above ordering.
segments	Array	It is the ordered list of lane segments of a lane.

Table 9: Lane attributes in RNT model

5.3.4 Lane Segment in RNT

Lane segment is a part of a lane along its driving direction. The length and the location of a segment are calculated based on its shape attribute. The attributes of a *segment* are given in Table 10.

Attribute	Type	Description
width	Double	The width of a lane segment
speed	Double	The limited speed on a lane segment
shape	Structure	The shape of a lane segment

Table 10: Lane segment attributes in RNT model

5.3.5 Shape in RNT

The shape at an intersection is important to accurately calculate the position of vehicles in the rolling tables. The syntax of the *shape* of a lane segment is borrowed from SVG [21]. Currently, the model supports the following kinds of shapes.

- *Polyline* with n endpoints $p_1 \dots p_n$ can be specified in a string with syntax "Polyline $x_1, x_2\ x_2, y_2\ x_n, y_n$".
- *Quadratic curve* with endpoints e_1 and e_2 and control point c can be specified in a string with syntax "Quad $x_{e_1}, y_{e_1}\ x_c, y_c\ x_{e_2}, y_{e_2}$".
- *Cubic curve* with endpoints e_1 and e_2 and control points c_1 and c_2 can be specified in a string with syntax "Cubic $x_{e_1}, y_{e_1}\ x_{c_1}, y_{c_1}\ x_{c_2}, y_{c_2}\ x_{e_2}, y_{e_2}$".

5.3.6 Intersection in RNT

In the detailed model, an intersection is no longer represented by a single node but a graph. The internal structure of an intersection is illustrated explicitly in the RNT model. The 'netbuild' utility automatically generates the internal structure of an intersection according to road segments sketched in the descriptive model. Figure 32 depicts the internal graph of Intersection 7 of the road network in Figure 31. The attributes of an intersection in RNT are illustrated in Table 11.

5.3.7 Linkage in RNT

Linkage is an extended lane segment whose purpose is to allow crossing at an intersection. The attributes of linkage are outlined in Table 12.

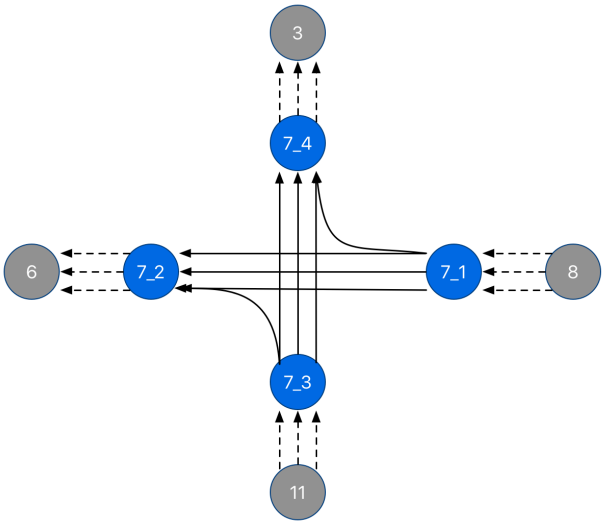


Figure 32: Internal structure of Intersection 7 of Road Network in Figure 31

Attribute	Type	Description
id	String	The identifier of an intersection
control	Enum	It is the control type of an intersection. Possible control values are: *signaled* and *unregulated*.
center	SVG	It is the shape of an intersection. This attribute is solely used in the *Traffic Viewer*.
links	Set	It is a set of linkages(which are described in Table 9) that indicates all allowed movements at an intersection.

Table 11: Intersection attributes in RNT model

5.4 Shape of an intersection

The shape at the center of an intersection is generated automatically according to the number of inbound/outbound lanes and their width and direction. The boundary of a shape is composed by a combination of several Bezier quadratic curves and straight lines. For example, the shape of Intersection 7 in Figure 31 is composed by a path of (L1, C1, L2, C2, L3, C3, L4, C4) (see Figure 33). The path can be represented in SVG *"M1012.0 605.45 L1012.0 594.55 Q1005.45,594.55 1005.45,588.0 L994.55 588.0 Q994.55,594.55 988.0,594.55 L988.0 605.45 Q994.55,605.45 994.55,612.0 L1005.45 612.0 Q1005.45,605.45 1012.0,605.45"*. Our shape representation in Figure 33 is sufficiently expressive to capture real-world intersections.

Attribute	Type	Description
fromRoad	String	The identifier of the inbound road of a linkage
toRoad	String	The identifier to the outbound road of a linkage
fromLane	String	The index of the inbound lane of a linkage
toLane	String	The index of the outbound lane o a linkage
segments	Array	An array of lane segments of a linkage (see Table 9)
peers	Set	A set of compatible linkages at an intersection

Table 12: Linkage attributes in RNT model

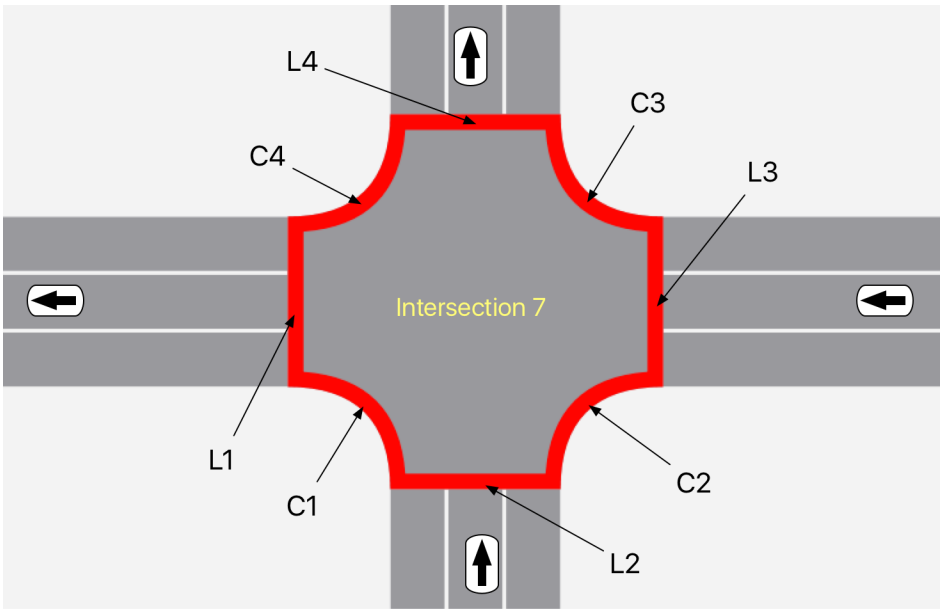


Figure 33: Shape of intersection

Chapter 6

Vehicle Driver Behavior

A macroscopic traffic flow model is a mathematical model that formulates the relationships among traffic flow characteristics like density, flow, and mean speed of a traffic stream. Microscopic traffic flow models the behavior of vehicular traffic dynamics. That is, in microscopic traffic flow the dynamic variables represent microscopic properties like the position and velocity of single vehicles. The term '*Vehicle Driver Unit* (VDU)' is defined as the combined behavior of a vehicle and a driver driving that vehicle. While traveling, each VDU keeps changing its *dynamic variables* over time including acceleration, speed, direction, and location. These dynamic variables are explicitly determined by two core decisions of a driver: *accelerating* and *steering*. *Accelerating* means adjusting the current speed of a vehicle. *Steering* in the microscopic model refers to lane changing. Accelerating and steering decisions are respectively formalized in *Car Following* and *Lane Changing* models.

6.1 Car Following Models

Car Following models describe the way a vehicle driver unit follows another unit on the same lane while traveling. These models have been studied for more than 60 years [42] and have played an extremely important role in traffic engineering studies such as microscopic simulation, modern traffic flow theory, and autonomous cruise control(ACC) [17]. Figure 34 outlines the three main steps of *Car Following* models [46].

1. **Perception**

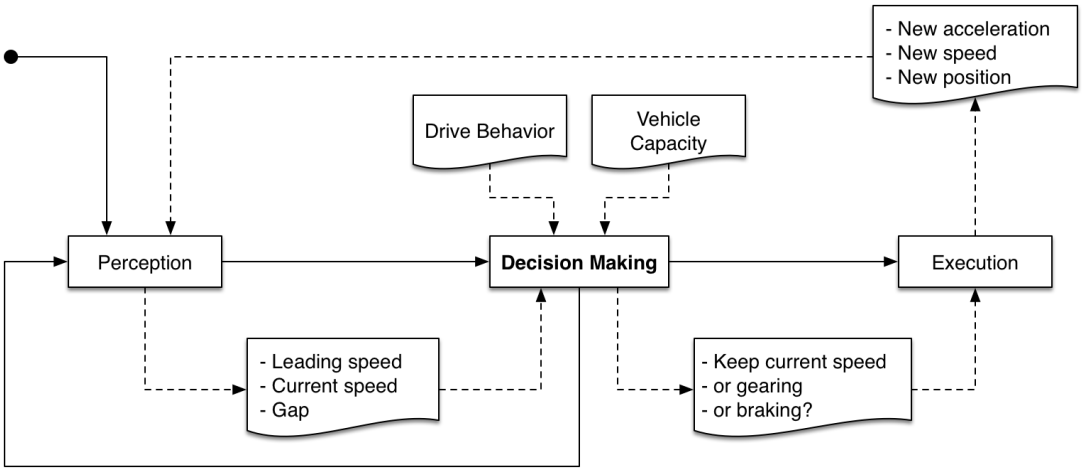


Figure 34: Main steps of *Car Following* models

In this step, a driver collects relevant information including the current speed of his vehicle, the leading vehicle's speed, and the gap between the two vehicles.

2. **Decision Making**

   A driver interprets the collected information, then decides a control command which estimates the acceleration or the speed of the vehicle in the next interval. The decision is influenced not only by the perceptive information, but also by the driver behavior, driving experience, and the capacity of the vehicle.

3. **Execution**

   In this step the driver is delivering the selected control command, while observing the roadway and repeating these steps. Strictly speaking, *Execution* and *Perception* steps happen simultaneously.

6.1.1 Elements of Car Following Models

The primary principle of *Car Following* models is to assume that a vehicle-driver unit, when following another unit, always attempts to

- *Keep up with the leading vehicle,*
- *Avoid collision with the leading vehicle.*

Mathematically, *Car Following* model is a function that estimates the speed of a vehicle in the next interval according to its current states and the state of the leading vehicle. The mathematical expression in Equation 18 demonstrates the general form of *Car Following* models. Following the notation of Figure 35, the subscript n is associated with the vehicle that follows the vehicle with subscript $n-1$. The meanings of velocities, distance between vehicles, and car lengths are also illustrated in this figure.

$$v_n(t + \Delta t) = F(v_n(t), v_{n-1}(t), s_n(t)) \tag{18}$$

Thus, $v_n(t + \Delta t)$ denotes the estimated value of the speed of vehicle n at time $t + \Delta t$, $v_n(t)$ and $v_{n-1}(t)$ are respectively the speeds at time t of the "following" and "leading" vehicles, and $s_n(t)$ is the gap between the two vehicles at time t.

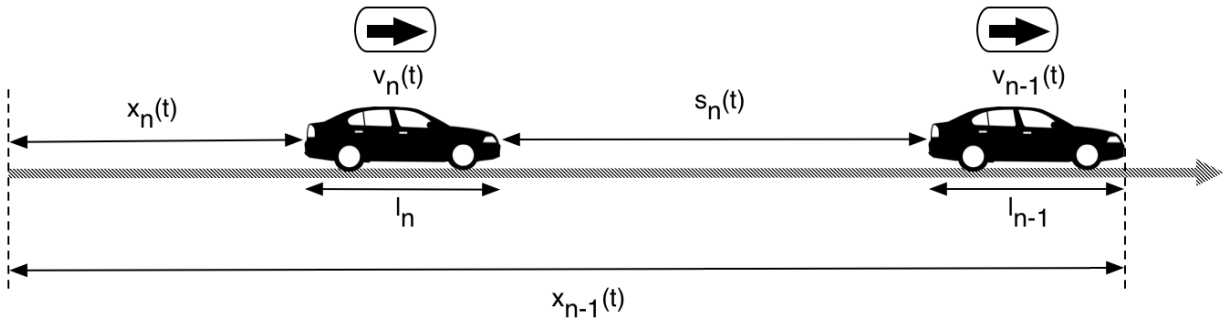


Figure 35: Notations of *Car Following* models

6.1.2 Gipps' Model

The *Car Following* model proposed by Gipps [23] in 1981 is considered as a major development in modeling vehicle-driver behavior. This model is built upon the following assumptions.

- There is an apparent reaction time τ for all drivers. In other words, a driver may not react to a change of the preceding vehicle at time t until $t + \tau$.
- Drivers always maintain a safe speed so that they can stop their vehicle safely even when the leading vehicle suddenly stops (the worst situation). To prevent collision, Gipps requires the gap between two successive vehicles on the same lane must be greater

than or equal to the minimum gap s_0 (safe distance to avoid collision) even when those vehicles are standing. This condition is called 'safety condition'.

- When a driver of vehicle n executes braking, it is done with a constant value of deceleration b_n.

Safe speed

Safe speed is defined as the maximum speed that a following vehicle can maintain and with which the safety condition is satisfied. Safety condition can be evaluated when the leading vehicle suddenly stops. When that happens, the leading vehicle will be at position x^*_{n-1} given by

$$x^*_{n-1} = x_{n-1}(t) + \frac{v^2_{n-1}(t)}{2b_{n-1}}, \tag{19}$$

where x^*_{n-1} is the expected position of the leading vehicle at time $t+\tau$, $x_{n-1}(t)$ and $v_{n-1}(t)$ are the position and speed of the leading vehicle respectively at time t, and $b_{n-1} > 0$ is the constant deceleration of vehicle $n-1$.

The following vehicle won't react to the change of the leading vehicle until $t+\tau$ and it will be at position x^*_n, given by

$$x^*_n = x_n(t) + \Big((v_n(t) + v_n(t+\tau)\Big)\frac{\tau}{2} + \frac{v^2_n(t+\tau)}{2b_n}, \tag{20}$$

where τ is the average reaction time for all drivers, and b_n is the maximum deceleration that the driver of vehicle n can execute. The other variables in the equation are as defined in Figure 35.

However, this equation does not allow any margin of error from driver behavior. To ensure safe reaction time, θ is introduced as the margin of error and the above equation is rewritten as follows:

$$x^*_n = x_n(t) + \Big(v_n(t) + v_n(t+\tau)\Big)\frac{\tau}{2} + \frac{v^2_n(t+\tau)}{2b_n} + \underbrace{v_n(t+\tau)\theta}_{\text{margin error}} \tag{21}$$

The safety condition requires the gap between two vehicles must be equal to or greater than

the minimum gap s_0.

$$x^*_{n-1} - l_{n-1} - x^*_n \geq s_0, \tag{22}$$

where l_{n-1} is the length of the leading vehicle. Replacing the values of x^*_{n-1} and x^*_n, in 22 we get the inequality

$$x_{n-1}(t) + \frac{v^2_{n-1}(t)}{2b_{n-1}} - l_{n-1} - x_n(t) - \Big((v_n(t) + v_n(t+\tau)\Big)\frac{\tau}{2} - v_n(t+\tau)\theta - \frac{v^2_n(t+\tau)}{2b_n} \geq s_0 \tag{23}$$

Referring to Figure 35, we write $s_n(t) = x_{n-1}(t) - l_{n-1} - x_n(t)$ which is the gap between two vehicles at time t. Using this expression in inequality 23 we rewrite it as

$$s_n(t) + \frac{v^2_{n-1}(t)}{2b_{n-1}} - \Big((v_n(t) + v_n(t+\tau)\Big)\frac{\tau}{2} - v_n(t+\tau)\theta - \frac{v^2_n(t+\tau)}{2b_n} \geq s_0 \tag{24}$$

In the *perception* stage, the driver following vehicle $n-1$ can observe all parameter in Equality 24, except the constant deceleration b_{n-1} of the leading vehicle. Thus an estimated value $\hat{b}$ is used. Substituting this estimated value $\hat{b}$ for b_{n-1}, the safety condition becomes

$$s_n(t) + \frac{v^2_{n-1}(t)}{2\hat{b}} - \Big((v_n(t) + v_n(t+\tau)\Big)\frac{\tau}{2} - v_n(t+\tau)\theta - \frac{v^2_n(t+\tau)}{2b_n} - s_0 \geq 0 \tag{25}$$

Safe speed of vehicle n at time $t+\tau$ written as $v^{safe}_n(t+\tau)$ is the maximum value that still satisfies the inequality 25. In other words, $v^{safe}_n(t+\tau)$ is the maximum value of the solutions of the equation when equality holds. If θ is equal to $\tau/2$ and $\hat{b} = b_n$, the safe speed of vehicle n at time $t+\tau$ is given be the following equation.

$$v^{safe}_n(t+\tau) = -b_n\tau + \sqrt{b^2_n\tau^2 + 2b_n\Big(s_n(t) - s_0\Big) + v^2_{n-1}(t) - b_n v_n(t)\tau} \tag{26}$$

Gipps Formula

Besides the safety condition, the speed of a vehicle at the next interval must not exceed the desired speed V^0_n and the amount of change caused by accelerating. The speed at time $t+\tau$ is given by

$$v_n(t+\tau) = min\Big\{v^{safe}_n(t+\tau),\ V^o_n,\ v_n(t) + a\tau\Big\} \tag{27}$$

where $v_n(t+\tau)$ is the expected speed of vehicle n at time $t+\tau$, $v_n^{safe}(t+\tau)$ is the safe speed, V_n^o is the desired speed, which is the minimum of 'the allowed speed on the current lane' and 'the maximum speed that vehicle n can reach', and a is the maximum acceleration vehicle n can execute.

Driver Behavior

In Gipps model, the driver behavior can be modeled by providing different values for parameters θ and s_0. Aggressive drivers usually have small values for both θ (the margin error time) and s_0 (the minimum gap), whereas careful drivers have bigger values for both θ and s_0.

6.1.3 Intelligent Driver Model

Intelligent Driver Model (IDM) [52] was developed by Treiber, Hennecke, and Helbing in 2000 with the aim to improve the realism of the braking manner. In Gipps' model, the driver of vehicle n is assumed to brake with the constant of deceleration b_n. However, this assumption is not true because in the real traffic, drivers usually execute a soft braking then gradually increase the value of deceleration. IDM provides a function which helps to estimate the acceleration for a following vehicle in the next interval. The speed in the next interval can be calculated by using Runge - Kutta methods [19]. Equation 28 illustrates that the acceleration in the next interval is the difference between 'the desired acceleration' (of the vehicle n) and 'the gap deceleration' (which introduced by the leading vehicle $n-1$ in order to avoid collision). The desired acceleration indicates that drivers want to accelerate their vehicle to the desired speed, however it is restricted by the gap deceleration.

$$a_n(t+\Delta t) = A_n \left(\underbrace{1 - \left(\frac{v_n(t)}{V_n}\right)^{\delta}}_{\text{desired acceleration}} - \underbrace{\left[\frac{s^{\star}(v_n(t), \Delta v_n(t)}{s_n(t)}\right]^2}_{\text{gap deceleration}} \right) \tag{28}$$

where:

- $a_n(t+\Delta t)$ is the estimated acceleration of vehicle n for the next interval,

- A_n is the maximum acceleration vehicle n can execute,
- $v_n(t)$ is the current speed of vehicle n,
- V_n is the 'desired speed of vehicle' n on the current lane,
- s_0 is the minimum gap,
- $s^\star(v_n(t), \Delta v_n(t))$ is the desired dynamic distance of vehicle n at time t,
- $s_n(t) = x_{n-1}(t) - l_{n-1} - x$ is the gap between vehicles $n-1$ and n at time t,
- and $\Delta v_n(t) = v_n(t) - v_{n-1}(t)$ is the difference between speeds of vehicles n and $n-1$.

The desired dynamic distance can be calculated as follows:

$$s^\star(v_n(t), \Delta v_n(t) = s_0 + max\left(0,\ v_n(t)\,T + \frac{v_n(t)\,\Delta v_n(t)}{2\sqrt{A_n b_n}}\right), \tag{29}$$

where T is the 'time gap' that drivers usually keep, depending on road and weather conditions, b_n is the comfortable deceleration the driver of vehicle n can execute, and s_0 is the minimum gap between two successive vehicles.

Driver Behavior

IDM model does not require the reaction time explicitly, however it requires a 'time gap' between two successive vehicles. In IDM, the driver behavior can be modeled by providing different values for parameters b_n - comfortable deceleration, T - time gap, and s_0 - the minimum gap. Aggressive drivers usually use small values for T and s_0 but a large value for b_n; whereas careful drivers usually use larger values for T and s_0. Another advantage of IDM model is that it can be easily used in Autonomous Cruise Control (ACC). The difference between ACC and human driver only is the 'time headway'. ACC requires a much smaller value for T than human drivers.

6.1.4 Special Situations

Car Following models only discuss the regular situation in which a vehicle follows another vehicle on the same lane. There are other special situations which are not mentioned, however they can be easily transformed to the regular case.

- **Vehicle without a leading vehicle**:
  When a vehicle is traveling without following another vehicle, we can use the regular situation discussed above, by assuming that there is a vehicle at the *horizon* running with the desired speed. The term *horizon* is used in Traffic Engineering to denote the region that is visible while facing the traffic flow direction.

- **Vehicle approaching a traffic light**:
  When a vehicle approaches a traffic light which is RED, we can use the regular situation discussed above, by placing a standing (static) vehicle (speed = 0) at the position of stop line at the minimum gap distance s_0.

6.2 Lane Changing

Lane Changing is a process of transferring a vehicle from one lane to an adjacent lane. Like *Car Following* model, *Lane Changing* is one of the cornerstones in the study of microscopic traffic flow. According to the study [51], *Mandatory lane change* (MLC) and *Discretion lane change* (DLC) are the two types of *Lane Changing* model. MLC happens in three scenarios, namely (1) when the current lane is not connected to the next road segment, (2) the current lane merges with another lane, and (3) the current lane is blocked due to accidents or lane repairs. DLC takes place when a driver wants to improve driving condition, such as avoiding to follow slow vehicles or gaining speed or enter a shorter queue.

In 1986, Gipps [24] introduced the first *Lane Changing* model which covers various urban driving scenarios such as traffic signals, obstructions, and presence of slow vehicles. In Gipps model, lane changing selections are influenced by a combination of necessity, desirability, and safety. *Necessity* is governed by the reasons cited for MLC. *Desirability* is governed by DLC criteria, which can be evaluated by driving condition. *Safety* means 'Is it possible to change

lane without collision?' which is determined by a 'gap acceptance' criterion. Gap acceptance will be discussed later in this section.

Gipps model is incomplete in the sense that it models only regular lane changes and not forced lane changes. Although it is incomplete, it provided a starting point for the development of most of modern lane changing models such as SITRAS [35], Integrated Lane-changing Model [51], and MOBIL [31]. After analyzing these models, we have selected SITRAS (*Simulation of Intelligent TRAnsport Systems*) to integrate into our traffic simulator because the other two are less adequate. However, during the process of integrating SITRAS model it was discovered that in many situations (1) safety can be violated, and (2) liveness cannot be guaranteed in 'forced change lane'. To remedy these two vital flaws, we corrected the logic of lane change process and introduced *Following Graph* model. With this graph model, liveness violations are detected. We discuss this improved SITRAS model next.

6.2.1 Improved Model of SITRAS

The improved version of SITRAS is developed to promote liveness and safety which are not fully guaranteed in the original model. Figure 36 outlines the main flow chart of a lane changing process.

Determine Lane Change Situation

Procedure *Determine Lane Change Situation* is defined, with the behavior explained below, for determining the current lane change situation of a vehicle and target lanes. This procedure evaluates the following conditions in the order of their importance.

1. *Turning movement:* If a vehicle is on intended lanes, a lane change is 'Unnecessary'. Otherwise, a lane change situation depends on the distance to the turning point. If the distance to the turning point from the current position of vehicle is such that it requires more than 50 seconds to reach it, then a lane change is 'Unnecessary'. If the distance to the turning point from current position of the vehicle is such that it will require between 10 and 50 seconds to reach the turning point, a lane change is considered

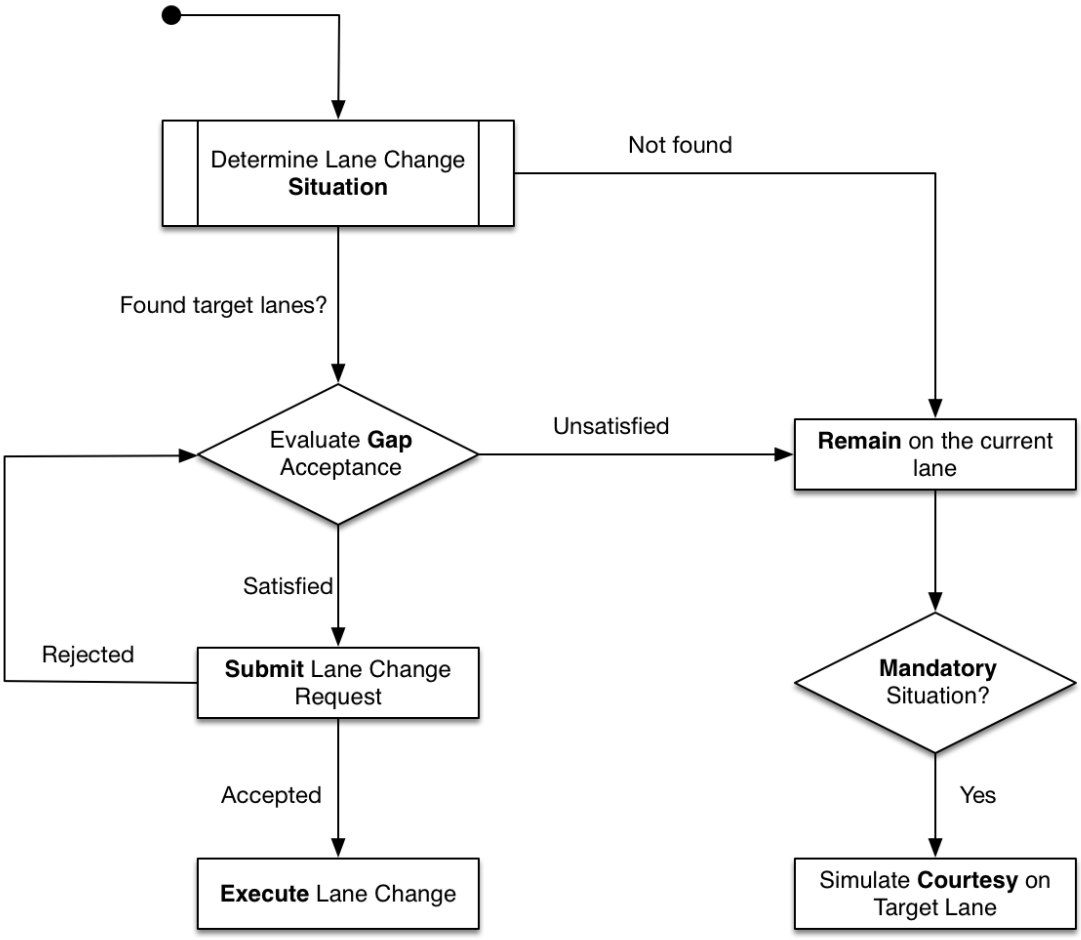


Figure 36: Flowchart of *Lane Changing*

'Discretionary'. If the distance to the turning point from the current position is such that it requires less than 10 seconds to reach it, the situation is 'Mandatory'.

2. *End of lane:* If a vehicle is on a lane which is about to end (because of merger or blocking), the lane change situation depends on the distance to the endpoint. This is evaluated using the same criteria as in the 'turning movement' situation.

3. *Speed advantage:* If the current speed is less than the desired speed and other lanes can provide a higher acceleration (which means higher speed), a lane change is 'Discretionary'. Moreover, to prevent a vehicle performing lane change many times within a short interval, the difference of accelerations must be large enough to consider it as 'Discretionary'.

4. *Queue advantage:* When approaching a waiting queue, a lane change is 'Discretionary'

if the queue in the target lane is at least 10 m shorter than the one in the current lane. The target lane must be one of the intended lanes.

Evaluating Gap Acceptance

Gap acceptance is a safety criterion which determines whether or not a lane change process should be executed in order to guarantee safety. In other words, a driver is allowed to perform lane change only if a gap acceptance meets the safety requirement. Technically, a gap acceptance is determined by a combination of acceptable accelerations a_s and a_f (see Figure 37).

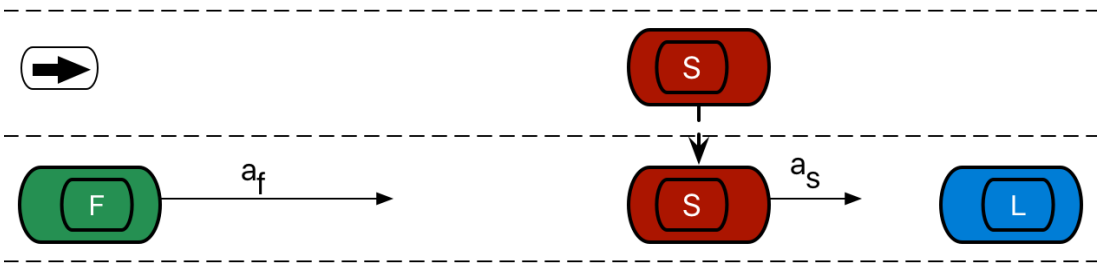


Figure 37: Notations for Gap Acceptance

- The subject vehicle S(the one that is trying to perform a lane change) must be able to follow a new leader L on the target lane safely. Mathematically, the condition is $\alpha = a_s/A_s < 1$ where a_s is the acceleration of S when it follows L and A_s is the maximum deceleration of the subject vehicle S.

- The new follower F on the target must be able to follow the subject vehicle S safely if lane change occurs. The requirement is $\beta = a_f/A_f < 1$ where a_f is the acceleration of F and A_f is the maximum deceleration of F.

The value of accelerations a_s and a_f are calculated using *Car Following* model. The values of α and β indicate the risk level that the driver of a subject vehicle is willing to accept. If either α or β is greater than 1, a gap acceptance is not satisfied for the safety requirement, because collision is certain to occur. According to Gipps [24], these values depend on the distance to the turning point and the driver behavior.

Submit Lane Change Request

Submit Lane Change Request is a new procedure which is introduced into the improved model in order to promote the safety property. In the improved model, a driver has to submit a lane change request to a 'navigation system'. If the request is approved then only the driver executes a lane change. However, if the request is rejected, the driver has to reevaluate the safety criterion. If it is satisfied then the driver can resubmit the lane change request to the navigation system. However, if the safety condition is not satisfied the driver has to stay on the current lane. The reason for enforcing this mechanism is to prevent a collision that might happen when two vehicles switch to the same area of the same lane at the same time. Figure 38 demonstrates that such a scenario might happen. In SITRAS model, both vehicles L and R will eventually be on lane L_1, which certainly leads to a collision. In our improved model, only one of the vehicles (either L or R) will be on lane L_1. Assume that the request from vehicle L arrives to 'navigation system' earlier than the one from vehicle R, the navigation will grant permission for vehicle L. However, when processing the request from vehicle R, if the navigation detects a change in that lane area it refuses the request from vehicle R. Our improved algorithm successfully handles this type of scenario, which might happen frequently when many vehicles are approaching intersections.

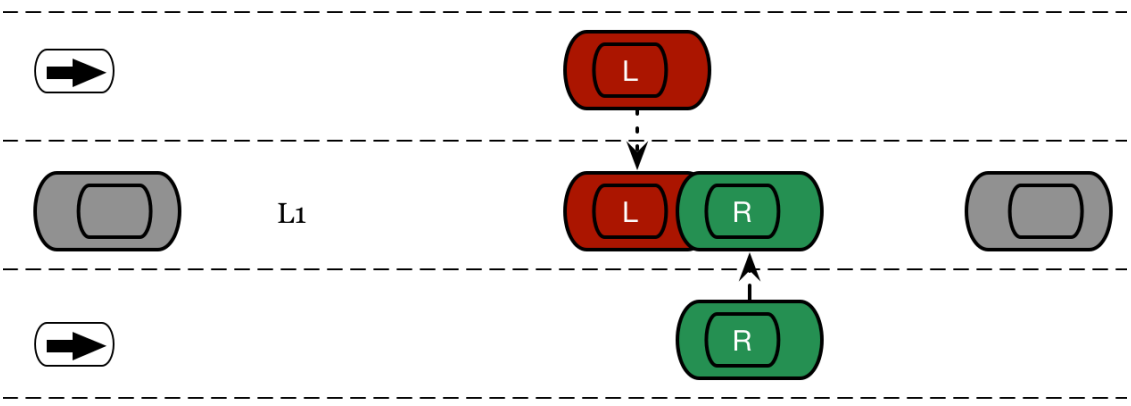


Figure 38: Collision when two vehicles performing lane changes

Lane Change Execution

In SITRAS model, lane change execution happens instantaneously. That is, when it occurs the subject vehicle will be on the adjacent lane immediately (with no time lapse). However, in real traffic a vehicle will be transferring gradually from the current lane to the adjacent lane. In our improved model, a path of a vehicle when performing a lane change is a Quadratic Bezier curve (see Figure 39) as suggested in [28]. Thus, lane change execution is not instantaneous, and is smooth.

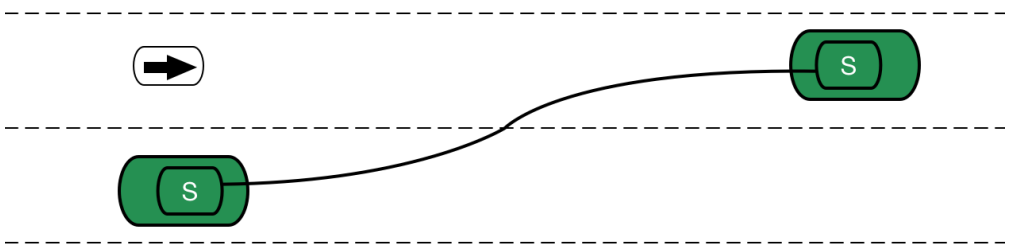


Figure 39: Path of vehicle when performing lane change

Request Courtesy on Target Lane

Procedure *Requests Courtesy on Target Lane* is defined for use in 'forced lane change' situation in which a vehicle must perform a lane change but can not because the current gap does not satisfy the safety condition. A driver sends a 'courtesy' request to subsequent vehicles on the target lane. Those vehicles will evaluate the request with respect to the differences of speed and distance with the requesting vehicle to determine whether to accept or reject the signal. If a vehicle offers a courtesy to another vehicle, it will slow down so that it can follow the requesting vehicle, and meanwhile the requesting vehicle also adjusts its speed so that it can follow the potential leader. Once the gap is sufficient (eg. a gap acceptance is satisfied), the subject vehicle performs lane change, then turns off the signal. Figure 40 illustrates the forced lane changing situation. In that scenario, vehicle S signals a request of courtesy, and vehicle F accepts that courtesy. Then F adjusts its speed so that it can follow S safely, meanwhile S also adjusts its speed so that it can follow L safely. If everything happens as explained, vehicle S will eventually change its lane to be in-between vehicles F and L on the target lane.

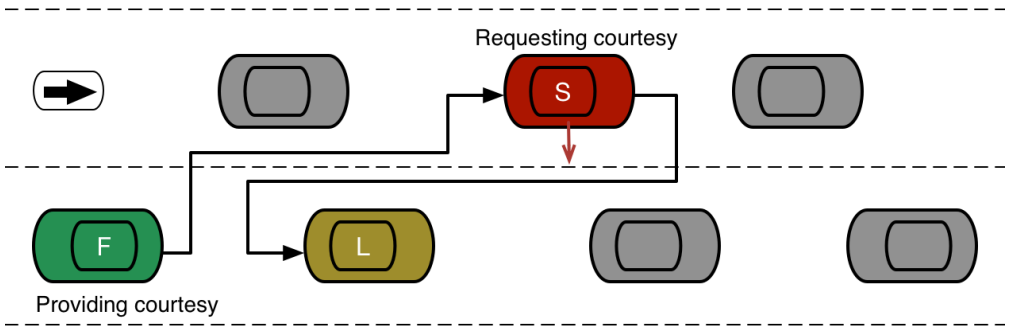


Figure 40: Forced lane changing model

6.2.2 Following Graph

We found that in SITRAS model, liveness cannot be fully guaranteed in the forced lane changing mode. Figure 41 demonstrates an example of the forced lane change in which a deadlock occurs. In the example, both vehicles A and B are signaling courtesies to change lane and these courtesies are accepted by D and C respectively. Below we enumerate the possible "follows" ($\rightarrow$) relations in the example.

1. Vehicle C accepts a courtesy from B, therefore B "follows" D which is the leader of C.
2. Vehicle D accepts a courtesy from A, which means D "follows" A.
3. Vehicle A "follows" vehicle B on its current lane.

From 1, 2, and 3, we have '$B \rightarrow D \rightarrow A \rightarrow B$'. This cyclic relation indicates a "deadlock", because it leads all vehicles A, B, and D to brake, then even stop completely.

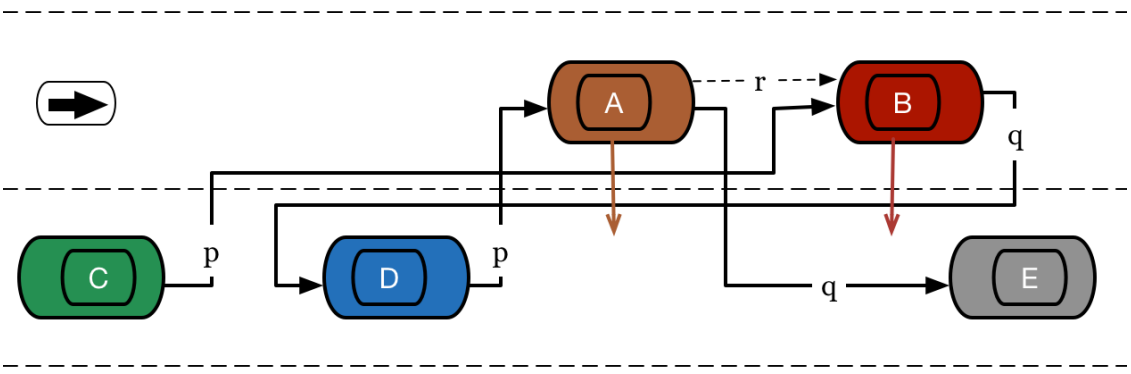


Figure 41: Deadlock in forced lane changing

In order to detect such deadlocks, we introduce the *Following Graph* model. It is a directed graph in which the vertices are vehicles on a road segment and its edges are "following" relations between vehicles. Three types of "following" relations are defined to label the edge types in *Following Graph*. These are as follows:

- *Regular Following* ($\rightarrow_r$) is a relation between two successive vehicles on the same lane when one follows another. In Figure 41, $A \rightarrow_r B$, $C \rightarrow_r D$, and $D \rightarrow_r E$ are regular following relations.

- *Provider Following* ($\rightarrow_p$) is a relation between a vehicle that accepts a courtesy and another vehicle which requests that courtesy. In Figure 41, $C \rightarrow_p B$ and $D \rightarrow_p A$ are provider following relations.

- *Requester Following* ($\rightarrow_q$) is a relation between vehicle R that requests a courtesy and the leader($\hat{P}$) of a vehicle which accepts that courtesy. This following relation exists because $\hat{P}$ will be a leader of R when lane change happens. In Figure 41, $A \rightarrow_q E$ and $B \rightarrow_q D$ are requester following relations.

Constructing Following Graph

A following graph for a given road segment at any moment can be constructed by the following steps.

1. For each vehicle v in a road segment, creates a vertex called v.

2. For each lane of the road segment, for each pair of two consecutive vehicles f and l, creates an edge $f \rightarrow_r l$. This step collects all regular following relations.

3. For each courtesy c requested by r, and accepted by p, create

   - An edge $p \rightarrow_p r$ which is a provider following relation
   - An edge $r \rightarrow_q \hat{p}$ if $p \rightarrow_r \hat{p}$. This edge is a requester following relation.

Figure 42 illustrates the *Following Graph* which is constructed from the road segment scenario in Figure 41.

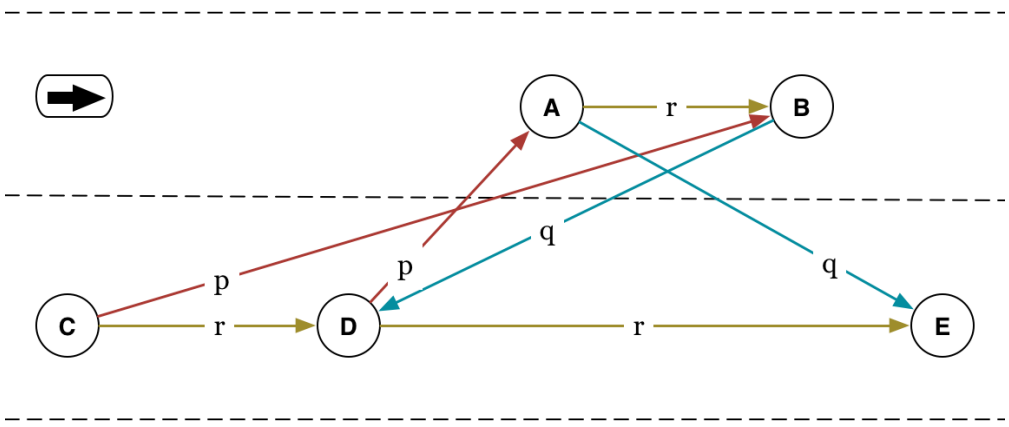


Figure 42: Following Graph of Figure 41.

Integrating "Following Graph" in the Improved Model

In the 'forced lane change' mode of the improved model, when a vehicle is willing to provide a courtesy for another vehicle, it has to submit a request to the 'navigation system' and waits for a feedback. The 'navigation system' will reject a proposal which can produce a deadlock in the traffic flow. A deadlock is detected if the 'following graph' which is constructed from the current snapshot of a road segment plus the proposed relation contains any *cycle*. The cycle can include any type of following relations. If the proposal is approved, the requesting and providing vehicles can form a courtesy relation.

By performing a depth-first search [50] on the *Following Graph* a cycle can be found in time $\Theta(|V| + |E|)$ where V is the number of vehicles involved in lane changing and E is the number of edges. In practice, both $|V|$ and $|E|$ are small numbers. Consequently, the cost of dynamically finding cycles in a *Following Graph* will be small.

Chapter 7

Implementation

We have developed **CMTSim** (**C**oncurrent **M**icroscopic **T**raffic **Sim**ulator) whose primary objective is provide an environment to evaluate the performance of the traffic control system (ATCS) proposed in this thesis. The simulator is implemented in Scala [38], a language in which Object-Oriented and Functional Programming paradigms are integrated. Scala is fully-compatible with Java, and interacts back and forth seamlessly with Java. Scala code of the simulator is compiled to Java byte-code and then executed as a regular Java program on JVM. Therefore the simulator will be able to run on most of the platforms, such as Windows, OSX, and GNU/Linux. We use Akka Framework [53] which is a standard implementation of the actor model on Scala. Akka supports the location transparency, thus actors in Akka can be deployed either in the same process, or in different processes on the same host, or even on different machines without changing the code.

7.1 Toolchain

The simulation process includes thee main stages. These are *Preprocessing*, *Operating*, and *Analyzing*. Figure 43 and Table 13 describe a set of utilities that we have developed for the simulation tool. We use the terms CLI and GUI in the table to respectively denote *Command Line Interface* and *Graphical User Interface*.

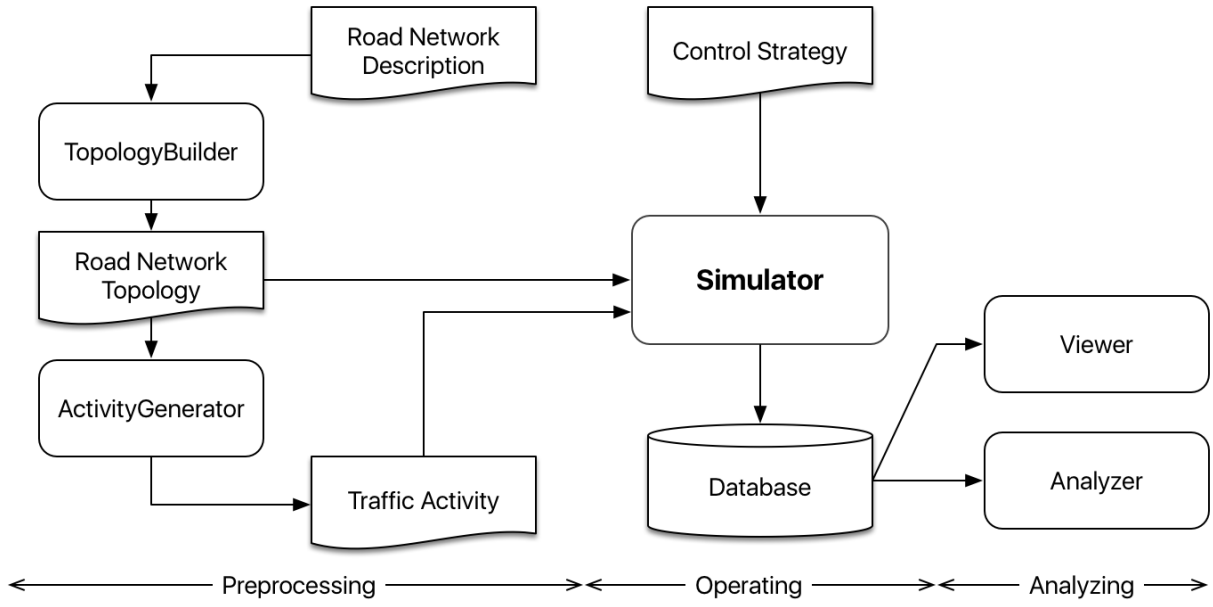


Figure 43: Toolchain of CMTSim

7.1.1 Preprocessing Stage

In *Preprocessing* inputs are prepared for the simulating process. These tasks, if manually done, can consume a lot of time. The utilities in this stage free users from that burden.

- *Topology Builder* converts a road network description(RND) to a detailed internal representation of road network topology(RNT) (see Chapter 5).
- *Activity Generator* generates traffic demands for a given network, according to specified demand rate. We define *demand rate* as the number of cars that enter the network every second.

7.1.2 Operating

Operating stage is the central piece of the simulation process. In this stage, an utility *'Simulator'* simulates all scheduled vehicles with respect to vehicle driver behavior on the roadway, road network topology and traffic control strategy. Different traffic control strategies can be programmed into the utility. The output of the operating stage including states of vehicles and arbiters is stored in a database.

Utility	Stage	Type	Description
Topology Builder	Preprocessing	CLI	Converts a road network description to a detailed presentation (RNT)
Activity Generator	Preprocessing	CLI	Generates traffic activities(trips) for a given road network and demand rate
Simulator	Operating	CLI	Center-piece of CMTSim. It simulates scheduled vehicles and stores the output including vehicles and arbiter states to a database
Viewer	Analyzing	GUI	Displays road network and animates states of vehicles and arbiters with data from the database
Analyzer	Analyzing	CLI	Provides statistics for all vehicles in the macro level

Table 13: Set of utilities of CTMSim

7.1.3 Analyzing

Analyzing stage can be started anytime once *Operating* stage tasks are completed. *Viewer* and *Analyzer* are two tools developed for this stage. They both query data from the database to accomplish their tasks.

- *Viewer* is the only GUI application (uses JavaFX [39]) in the set of CMTSimutilities. When users start Viewer, it first shows the selected road network topology, then animates scheduled vehicles step by step according to their locations and direction. Traffic lights are also displayed visually according to their states (eg. red, yellow and green). By default, the progress of vehicles and states of arbiters will be displayed chronologically; however users can control it. Playback controls such as 'pause', 'resume', 'go next', 'go previous' and 'goto to a specific time' are fully supported in the *Viewer*. Users can also zoom in and zoom out of selected areas of a road network without lost of image quality. Figure 44 shows a snapshot of Viewer on OSX.

- *Analyzer* provides the statistics for all scheduled vehicles in the macro level. The details on the statistic will be discussed in the last section of this chapter.

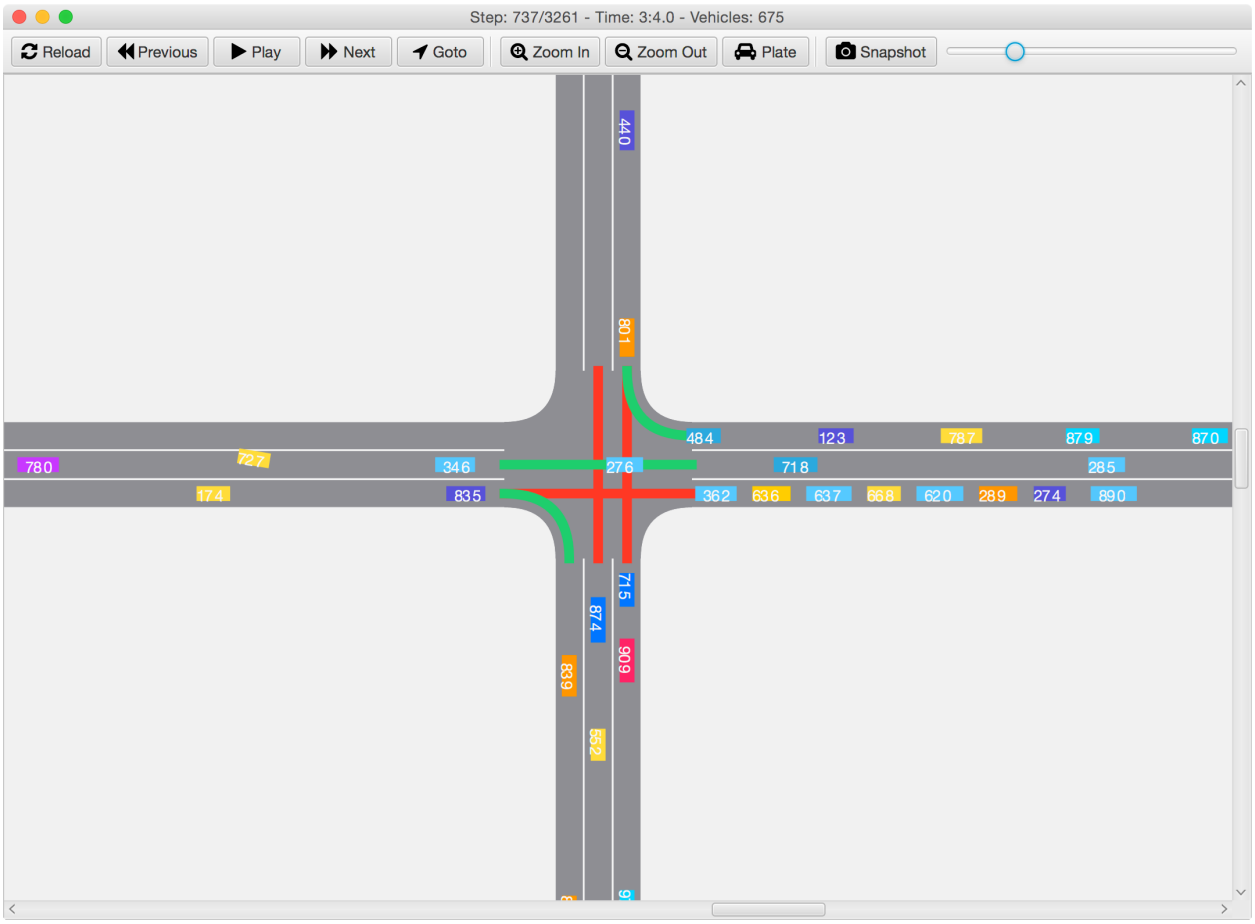


Figure 44: Snapshot of Viewer on OSX

7.2 Features

In this section, we highlight two major advanced features of CMTSim when comparing with other popular microscopic simulators such as SUMO [12], MITSIM [54], and SITRAS [27].

7.2.1 Nondeterministic

Most traffic simulators maintain an ordered list of *vehicle-driver units* (VDU) according to their positions on a roadway. For each interval update, a simulator will process VDUs with the order from the head to the last. Consequently, the simulation is a deterministic process. Technically speaking, with the same traffic demands, these simulators always yield the same output. However, this simulation behavior does not conform with realistic traffic situations. The reason is in this approach, the 'first vehicles' always yield a favor to perform

their decisions such as lane changing. This behavior also may also hide traffic problems which may occur if the system is deployed in the real-world. In contrast, each VDU in our simulator is modeled by an actor [26] which runs concurrently in its own execution context. Therefore, our simulator resolves the nondeterministic behavior that arise in real world traffic situations.

7.2.2 Scalable System

In CMTSim, we use Akka as the implementation of Actor model. Akka allows scaling out and scaling up easily by changing configuration file. *Scaling up* (vertically) means upgrading the resources of the current computer including CPU and memory; whereas *scaling out* (horizontally) means adding more nodes to the current system. Therefore, our simulator can be easily deployed as a distributed system. This is a significant advantage when simulating a large number of vehicles. A scaled distributed system can reduce a lot of running time.

7.3 Simulation Results

In this section, we provide the simulation results of the two control strategies *Fixed Time Signal Coordination* (FTSC) and *Rolling Horizon Streams* (RHS). FTSC is the most popular traffic control which is being used in most of traffic systems, while RHS is our proposed adaptive algorithm. The simulation results involving a variety of data sets (number of vehicles, network topology, number of tours) focus only on the macro level in terms of *mean speed*, *low speed ratio*, and *congestion*. The network topology used in the simulation has 9700 meters of road length and 12 intersections. Each road has either two or three lanes, each lane having the standard width. We ignored roads with single lane because the structure of linkages at each intersection is trivial. Therefore four main types of data sets can be constructed.

- **FTSC-2** is constructed using FTSC, with each road in the network having two lanes.
- **RHS-2** is constructed using RHS, with each road in the network having two lanes.
- **FTSC-3** is constructed using FTSC, with each road in the network having three lanes.
- **RHS-3** is constructed using RHS, with each road in the network having three lanes.

The simulation computes "mean speed", "low traveling speed ratio", "fuel consumption", and "congestion rate" for each data set. In all simulated results we observe that there is a 'sudden jump' in the calculated values when the number of vehicles in the network increases from 3000 to 3500. The most likely reason for this jump is that the density of the network has reached the critical density level when the number of vehicles is around 3000. These simulated results are explained next.

7.3.1 Mean Speed

Mean speed is the total traveling distance divided by total traveling time of all vehicles. Mean speed is the most important factor that determines the performance of a traffic system. Higher mean speed means lower traveling time and higher throughput. Figure 45, and Table 14 illustrate the simulation results for mean speed. From these results we conclude the following results.

1. For each dataset, the *mean speed* of RHS is greater than the *mean speed* of FTSC algorithm. When the number of vehicles is 1000, the mean speed for RHS-3 is 20% higher than the mean speed for FTSC-3. At the number of vehicles increases, the difference between the mean speeds calculated for the two datasets also increases. Consequently, the RHS algorithm has higher *throughput*.

2. There is traffic congestion in FTS-2 dataset when the number of vehicles is 5000 or higher. For FTS-3 dataset the congestion starts when the number of vehicles reaches 6000. However for RHS-2 dataset, the congestion starts at 6500 vehicles. For RHS-3 dataset, we are able to calculate the mean speed even when the number of vehicles is 9000, although as shown in Table 16, congestion starts when there are 8000 vehicles in the network.

7.3.2 Low Traveling Speed Ratio (LTSR)

LTSR is the ratio x/y, where x is the number of vehicles with mean speed less than 30% of the desired speed, and y is the total number of vehicles. The smaller this ratio is, the

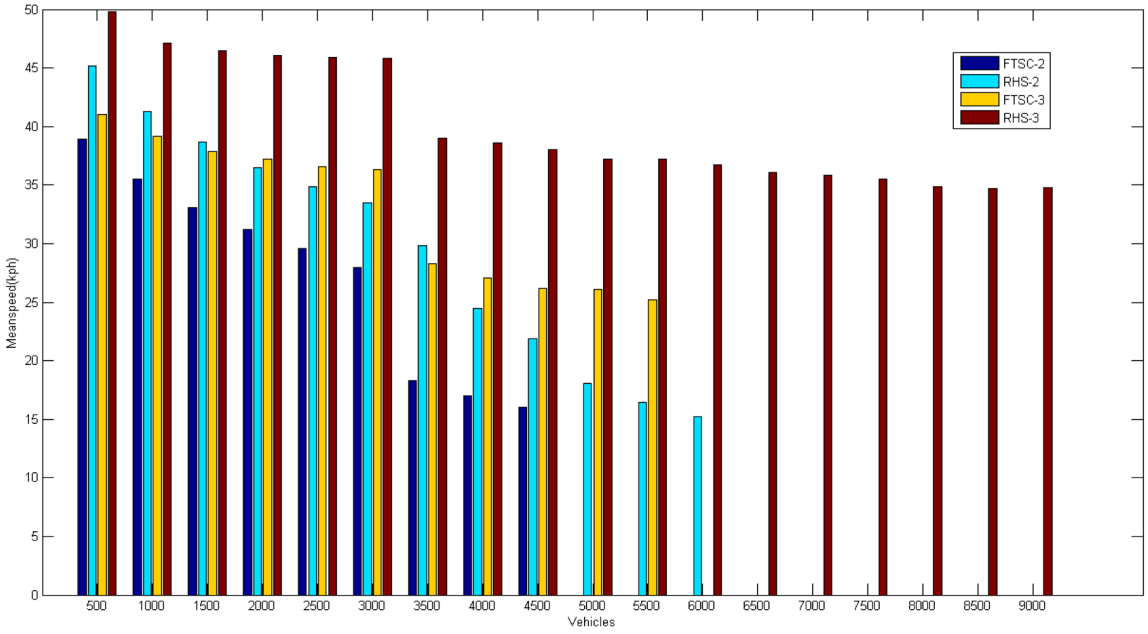


Figure 45: Simulation Result - Mean Speed

more reliable a traffic system in the sense that the number of trips in which the traveling time exceeded the expected value of traveling time will be small. Thus, lower values of LTSR mean 'the probability of exceeding the expected time of travel is low'. Therefore, minimizing this value is extremely important. Table 15 illustrates the simulation results for all data sets. We make the following observations.

1. There is a big jump in LTSR values when the number of vehicles increases from 3000 to 3500 in all cases except for RHS-3. We believe that this jump is due to the fact that the mean speed has to decrease at a faster rate once the density has reached the critical level.

2. LTSR values increase at a much slower rate for RHS-3 when the number of vehicles increases. We believe that this behavior is due to the combined effect of the efficiency of RHS algorithm and the availability of more lanes in each direction.

Vehicles	Distance(km)	**FTSC-2**(kph)	**RHS-2**(kph)	**FTSC-3**(kph)	**RHS-3**(kph)
1000	1643.5	35.5	41.3	39.2	47.1
1500	2465.8	33.1	38.7	37.9	46.5
2000	3291.1	31.2	36.5	37.2	46.1
2500	4110.4	29.6	34.9	36.6	45.9
3000	4934.6	28	33.5	36.3	45.8
3500	5760.2	18.3	29.8	28.3	39
4000	6608.4	17	24.5	27.1	38.6
4500	7435.7	16	21.9	26.2	38
5000	8225.1	-	18.1	26.1	37.2
5500	9001.2	-	16.4	25.2	37.2
6000	9806.2	-	15.2	-	36.7
6500	10684.8	-	-	-	36.1
7000	11455.7	-	-	-	35.8
7500	12262.8	-	-	-	35.5
8000	13081.7	-	-	-	34.9
8500	13891.8	-	-	-	34.7
9000	14714.9	-	-	-	34.8

Table 14: Simulation Result - Mean Speed

7.3.3 Congestion Rate

Traffic congestion at an intersection is characterized by the length of waiting queue in each direction and the amount of time that these vehicles wait. In between two consecutive intersections, traffic congestion is characterized by slower moving vehicles, often braking to avoid collision. For our simulation, we consider a road network to be congested if vehicles in that network are unable to make a significant progress in more than 10 minutes. It is highly desirable if a traffic system can manage a traffic flow without congestion. Traffic congestions increase traveling time and fuel consumption, while decreasing throughput and reliability. So, it is necessary to minimize, if not totally eliminate, traffic congestions in road networks. The simulation results for traffic congestion rates for different data sets are shown in Table 16. For each 'entry' of Table 16 we conducted 100 test cases, and observed the number of test cases for which congestion occurred. We make the following observations.

Vehicles	Distance(km)	**FTSC-2**(%)	**RHS-2**(%)	**FTSC-3**(%)	**RHS-3**(%)
1000	1643.5	0.3	0.0	0.2	0.0
1500	2465.8	1.0	0.1	0.7	0.0
2000	3291.1	2.2	0.4	1.3	0.0
2500	4110.4	3.8	0.8	1.8	0.0
3000	4934.6	5.5	1.3	2.0	0.0
3500	5760.2	42.8	9.1	21.2	0.5
4000	6608.4	48.9	10.7	29.8	0.5
4500	7435.7	54.5	24.0	35.2	0.8
5000	8225.1	-	29.1	43.9	1.3
5500	9001.2	-	56.0	51.7	1.2
6000	9806.2	-	43.1	-	1.6
6500	10684.8	-	-	-	2.0
7000	11455.7	-	-	-	2.2
7500	12262.8	-	-	-	2.3
8000	13081.7	-	-	-	3.0
8500	13891.8	-	-	-	3.1
9000	14714.9	-	-	-	3.0

Table 15: Simulation Result - Low Traveling Speed Ratio

1. Traffic congestion happens more than 50% of the time for FTSC algorithm when 3500 or more vehicles travel in either two or three lanes.

2. For RHS algorithm with two lanes, congestion occurs more than 50% of the time when 4000 or more vehicles travel.

3. For RHS with 3 lanes, there is no traffic congestion until the number of vehicles exceeds 7500. If the number of vehicles is 8000 or higher, congestion happens at a low rate.

4. RHS can handle a high traffic volume without causing traffic congestion.

7.3.4 Fuel Consumption

Fuel consumption is an estimate of the total amount of fuel that all scheduled vehicles consumed to complete their trips. We could have used the fuel consumption model [3] to

Vehicles	Distance(km)	**FTSC-2**(%)	**RHS-2**(%)	**FTSC-3**(%)	**RHS-3**(%)
1000	1643.5	0.0	0.0	0.0	0.0
1500	2465.8	0.0	0.0	0.0	0.0
2000	3291.1	0.0	0.0	0.0	0.0
2500	4110.4	1.0	0.0	0.0	0.0
3000	4934.6	0.0	0.0	0.0	0.0
3500	5760.2	84.0	20.0	47.0	0.0
4000	6608.4	97.0	53.0	66.0	0.0
4500	7435.7	99.0	80.0	91.0	0.0
5000	8225.1	100.0	87.0	95.0	0.0
5500	9001.2	100.0	94.0	98.0	0.0
6000	9806.2	100.0	97.0	100.0	0.0
6500	10684.8	100.0	100.0	100.0	0.0
7000	11455.7	100.0	100.0	100.0	0.0
7500	12262.8	100.0	100.0	100.0	0.0
8000	13081.7	100.0	100.0	100.0	3.0
8500	13891.8	100.0	100.0	100.0	8.0
9000	14714.9	100.0	100.0	100.0	19.0

Table 16: Simulation Result - Congestion Rate

estimate this value in simulation. However, we argue that RHS algorithm optimizes the fuel consumption, based on the simulated results on mean speed, LTSR, and congestion rate.

- RHS algorithm has a higher mean speed compared to FTS algorithm. Hence, the throughput is increased in RHS algorithm. This implies that there will be less number of 'stop-and-go' in the traffic. The amount of fuel consumed will be optimal because of the smooth traffic flows.

- RHS algorithm has lower LTSR values than FTS algorithm. Thus, the probability of exceeding the expected travel time is low. This implies most of the time, vehicles complete their travel within the estimated time and only rarely the travel time will be higher than the expected time. Hence, the total fuel consumption for all vehicles will exceed the expected fuel consumption only by a small value.

- RHS algorithm has almost eliminated congestion. Thus, vehicles may not be stuck in

the traffic and therefore fuel consumption will be low.

The above observations have a few limitations, because the fuel consumption model is not explicitly used and only two road network topologies are used in this simulation.

Chapter 8

Conclusions and Future Work

The primary objective of the thesis is to develop a traffic control system that optimizes the performance of traffic flows in both macro and micro levels, while maintaining safety, liveness, and fairness properties. In Chapter 4 we have explained how safety, liveness, and fairness properties are achieved in RHS algorithm. The simulation results in Chapter 7 convincingly demonstrate that the algorithm optimizes the traffic flow patterns in all simulated scenarios. In the following summary we emphasize the major contributions in the thesis as well as its limitations, provide some suggestions for future work, and comment on the challenges to overcome in further extensions.

8.1 Contributions

Without an efficient traffic control algorithm that can dynamically adapt to time-varying traffic scenarios the full benefits of ATCS cannot be realized. With this in mind, adaptive traffic control algorithm was designed, analyzed, and implemented. The algorithm satisfies the dependability and optimization properties. This major contribution is novel and new. Below a summary of results achieved in the thesis are enumerated and their significance emphasized.

1. **Adaptive Traffic Control Algorithm for Arbiter**

   In Chapter 4, we have proposed Rolling Horizon Streams(RHS) algorithm, a new

adaptive traffic control algorithm for the Arbiter. This algorithm is distinctly different from all existing traffic control algorithms. It gathers inflow traffic volume, the path information for each vehicle at an intersection, calculates compatible linkage lanes, and discharges the out-flowing traffic without collision and without waiting for ever. While the current well-known algorithms [47, 35, 44] did not consider "pedestrian traffic", and "context" the RHS algorithm design did consider pedestrian crossing and context-dependent policies in the calculation of cliques and allocation of green time. Context-dependent policies are formulated by the Zone Manager (ZM) and communicated to Intersection Managers (IMs). The IM at an intersection calculates the parameters for the Car Following model and Aging Function. It communicates these parameters and the structure of linkage lanes to the Arbiter. Consequently, the behavior of RHS algorithm is adaptive to contextual changes.

Safety property is ensured in the RHS algorithm, because only compatible linkage lanes are allowed simultaneous crossing at an intersection. Both liveness and fairness properties are also integrated in RHS design through judicious choices of parameters in the design of "aging function" and in allocating "green time". Thus, all dependability requirements stated in Chapter 3 are fulfilled. Optimization properties of ATCS, stated in Chapter 3 have been verified through simulation. The inflow traffic pattern was simulated using "Car Following Model". In Chapter 7 the performance of RHS algorithm against the performance of FTCS (Fixed-Time Coordination Signal) algorithm was compared, based on the four measures "mean speed", "low traveling speed ratio", "fuel consumption", and "congestion rate". The RHS algorithm has performed much better than FTCS algorithms in all simulated scenarios. These results convince us that optimization properties are completely fulfilled by the adaptive algorithm for all simulated data sets.

2. **Improved Model for Lane Changing**

   We found that the original version of lane changing model in SITRAS [27] does not guarantee safety and liveness properties. We have solved the safety issue by adding the "two-phases lane change procedure" in our algorithm. This procedure avoids collision

of vehicles during lane change. We introduced "*Following Graph*" model to detect deadlock in the "lane change signaling process". Consequently, liveness property is enforced. We claim that our improved lane changing model and its implementation can optimally detect deadlocks in real-life traffic situations.

3. **Traffic Engineering Domain Knowledge**

   Although traffic domain knowledge is not claimed as a direct contribution in the thesis, we identified the core concepts, such as *platoon*, *green-wave*, and *fundamental relation between density and flow*, and integrated them in different phases of the construction of the adaptive algorithm. A good understanding of traffic domain models helped in creating new "lane change model", and introduce the concept of "vehicle scores" and "aging function" that contributed to the efficiency of RHS algorithm. The domain knowledge integration plays a vital role in all aspects of the development of the thesis. In particular, the "car following model" is crucial to develop the traffic simulator, because the "dynamic traffic in-flow" cannot otherwise be captured.

4. **Architectural Design for Traffic System**

   The architectural design, presented in Chapter 3, is a good starting point towards achieving some of the future traffic management goals, as explained in Section 8.3. In the current design, we have emphasized the importance of distributed property, context integration, and feedback loop. Arbiter algorithm employs the feedback loop (the out-flow is factored in) and context-aware monitoring. Arbiters that are under the management of traffic managers are distributed across the intersections in a road network, share "traffic flow information with adjacent intersections", and efficiently diffuse traffic congestions from occurring at the intersections.

5. **Road Network Topology**

   Theoretically, a road network topology can be modeled as a directed graph. However, to use the topology in an application requires an enormous amount of data processing. To simplify this task we introduced two models for road network topology and an utility to convert their abstract models to detailed concrete models. These models are explained in Chapter 5. This approach is really handy as it lifts users and traffic engineers from

the difficulty of defining a road network for an application.

6. **Concurrent Microscopic Traffic Simulator**

   Although, there are several open source traffic simulators [12, 48], they can not be adopted immediately for simulating the traffic arbiter designed in this thesis. It is justified to claim the new traffic simulator discussed in Chapter 7 as an essential contribution. Without this tool it is not possible to validate the optimization properties stated in Chapter 3. The toolkit that has been developed to run the simulator and view its output can be used with other existing control algorithms. A complete implementation of the new simulator has been provided. Besides including the common features of traffic simulators, our simulator includes two advanced features that are not available in others. These are *nondeterminism* and *scalability*.

8.2 Limitations

In this section, we comment on the scope of current simulator and analysis of simulated results, to bring out the limitations of current analysis as well as the features not part of the current simulator implementation.

1. **Studying special characteristics from the simulation results**

   Our analysis was narrowed down by our goal in simulation, which is to use it as a benchmark to compare the performance between RHS and FTSC algorithms. For both algorithms, there is a sudden big jump in observed values when the number of vehicles increase from 3000 to 3500. Because of our goal, we did not scientifically analyze to determine the cause for the sudden jump in values. We only speculate that the "critical level" of the density of the network has been reached when the number of vehicles is 3000. This issue needs further analysis.

2. **Simulating and analyzing over-saturated situations**

   In principle, in a road network many RHS arbiters will cooperate, using route scores, to prevent high density areas from occurring. The simulation results indicate that RHS algorithm can handle a large volume of traffic with a very low rate of congestion.

However, we did not simulate and analyze traffic situations in which congestions occur at multiple intersections, as shown in Figure 46.

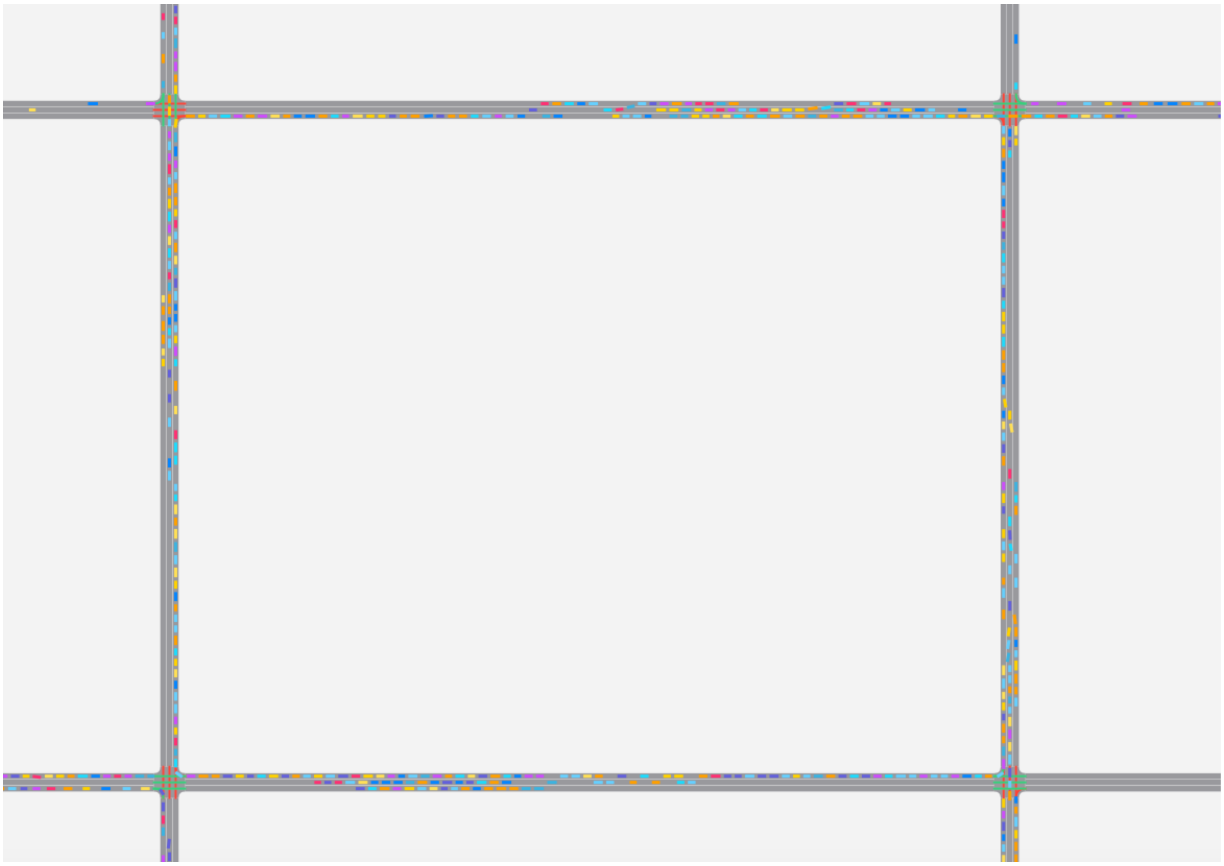


Figure 46: Congestions occur at multiple intersections

3. **Simulating with different types of road networks**

   Simulation results highlight that RHS algorithm provides better results (in terms of mean speed, low speed ratio, congestion, and fuel consumption) than FTSC in all simulated scenarios. However, the simulation scenarios are conducted in only one road network. If the simulations are conducted with different road networks and traffic control policies, the conclusion will be more convincing.

4. **Supporting pedestrian and emergency vehicles**

   In Section 4.5, we explained how to extend RHS to support pedestrians and emergency vehicles. Although the extension is quite straightforward, it requires a modified version of car following model for emergency situations. The reason is that in emergency

situations cars do not follow one another as in regular situations, but make ways for emergency vehicles. Unfortunately, there is no car following model for emergency situations available for us to use in our simulator. Consequently, we could not provide this feature in our simulator.

5. **Integrating with context**

   In section 4.6, we provide a guideline to integrate RHS with context information, such as weather, special zone, and public events. However, this feature is not part of the current version of simulator.

6. **Extending `netbuild` to support different road networks**

   In Chapter 5, we introduced two models as representations of a physical road network. These are Road Network Description(RND) and Road Network Topology (RNT). In principle, both representations can be used to model any physical road network. However, the current version of `netbuild` utility only supports one-way roads. That is, a two-way road network must be defined directly in RNT.

8.3 Future Work

The two important directions for future work are (1) formal verification of RHS algorithm, and (2) architecture extension for supporting any future development of a dependable *Transportation Cyber Physical System*, in which vehicle-to-infrastructure (V2I), vehicle-to-vehicle (V2V) cyber communications, and advanced assistance to driverless vehicles are enabled.

8.3.1 Formal Verification

Formal verification is required to prove the safety property in a safety-critical system. The adaptive traffic controller intimately interacts with its environment to determine in-flow and out-flow of vehicles. A formal verification is necessary to verify the safety property "no collision occurs at the intersection" while Arbiter and its controllers are monitoring and actuators are executing their commands. The cyber objects, such as arbiter and controllers,

operate under "discrete time". The physical objects, such as vehicles and actuators, are governed by "real-time" actions. Thus, a formal model of these cyber and physical objects will require "a hybrid approach", in which the objects interact in discrete as well as in real time. The challenge is in formally modeling this hybrid behavior and choosing the appropriate verification method for that model. Following the technical challenges succinctly brought out by Alur [8] and several others [9, 7] it becomes clear that constructing a hybrid automata to synthesize the discrete timing behavior of the controller and the continuous timing behavior of the environment (vehicles) is an ongoing research problem. Moreover, it is known that model checking such a hybrid model for safety property will necessarily lead to exponential time (and space) complexity.

8.3.2 Architectural Extensions for Supporting Transportation Cyber Physical System

In the current system, the interaction between infrastructure and vehicles (V2I) is rather limited. Infrastructure facilities are used for only detecting the presence of vehicles. In "Following Graph" model V2I support has been brought in for detecting deadlocks while "lane changing". V2I interaction in the thesis is allowed only in the presence of drivers. The development of driverless vehicles, such as Google's Self-Driving Car [25], opens a great opportunity to build more 'intelligent' traffic control systems in which infrastructures can interact to transmit driving suggestions or even enforce the vehicles to follow its instructions. According to the recent news from BBC [11] "two robot cars (driverless vehicles), one made by Delphi Automotive and one by Google, met on a Californian road in Palo Alto. The Google car pulled in front of the Delphi vehicle making it abandon a planned lane change.". This article also reports "Delphi and Google's autonomous vehicles have been involved in several minor accidents and incidents during testing. However, before now all of those have involved the robot cars and human-driven vehicles. In almost all cases, the firms have said, the fault lay with human drivers". Regardless of "who is responsible" it is most important to devise mechanisms that ensure that such accidents do not occur. The arbiter implemented in this thesis can be a plug-in for controlling "driverless vehicles either in the presence or absence of

drivers in vehicles" in urban or in highway traffic. Below we explain a few extensions to our ATCS architecture that will enable future transportation systems operate in a dependable manner.

Although the algorithmic details used in controlling driverless vehicles are not made public, it is safe to assume that the three pillars necessary to accommodate such a system of vehicles are *Context-awareness* (CA), *Autonomic Computing Principles* (ACP) [30, 33, 49], and *Cyber-Physical System* (CPS) [37, 32]. With context-awareness fully enforced in the system, both V2I and V2V communications can be enabled. Since we have included context as an element in our design, we need to extend the architecture to include features, such as dynamic context builders and reasoners, to meet the full potential of context-awareness. We already have feed-back loop in the architecture, although it is limited to sensing the outflow (context-awareness involved here) at an intersection. The scope and functionality of the feed-back mechanism can be extended to include "interaction with any physical device" in the environment of an intersection. Such a physical device can be either a vehicle (with or without driver) or radar or a "railway gate". As stated in the NSF program description [37], CPS is a large distributed network, typically including embedded computers that monitor and control physical processes based upon local and remote computational models. A CPS interacts directly with the physical world with feed-back loops. The current adaptive behavior has to be scaled up by the introduction of "adaptation policies for events observed in the environment". With such an extension, the current intersection architecture will become a CPS which adapts itself to changing environmental situations, as measured by the physical devices in the proximity of the intersection. Both efficiency and faults can propagate only upwards in the current architecture. Thus, by ensuring the correctness of the subsystem under each intersection manager we can aim to achieve efficiency in traffic control even when some IMs are faulty. The current architecture can be extended to empower the traffic managers possess resources, knowledge, and skills they need in assisting themselves as well as in assisting the subsystems they manage. In order to effectively deal with system deployment failures, correct hardware and software issues, and avoid human errors that might be introduced by a manual intervention of IT professionals, IBM [30] introduced ACP. The principles are the following:

- *Self-configuring:* This refers to the ability to dynamically adapt to changing environments, using policies defined by IT professionals. So, the system must be aware of the changes happening both internally and externally. An adaptation can be the deployment of new components or the removal of existing ones, consistent with component behavior and safety/security policies.

- *Self-healing:* This refers to the ability to discover, diagnose and correct itself to disruptions caused by either system components or through external attacks. Corrective actions are adaptations to reactions triggered by the discovery of disruptions. Policy-based corrective actions will ensure system dependability, without disrupting the IT environment.

- *Self-protection:* This refers to the ability to anticipate, detect, identify and protect against hostile attacks. The hostile attacks can include unauthorized access and use of system resources, and denial-of-service attacks on some of its components that provide vital services. The system will monitor itself and its environment to detect hostile behaviors. Both prevention and corrective actions are done according to the security and privacy policies instituted in the system.

- *Self-optimization:* This refers to the ability to monitor its resource utilization and tune its resources automatically to meet end-user needs in providing timely services. Without resource optimization, service denials might happen. The tuning of actions could mean reallocating resources from contexts to contexts as well as from user to user in order that all pending transactions are completed in a timely fashion. *Self-optimization* helps to enhance service availability and hence system dependability.

The autonomic computing principles, which necessarily include context-awareness, can be integrated in the current architecture, mainly in the design of traffic managers. Not all principles of ACP are independent. For example, self-protection mechanism may need to invoke self-healing, self-configuring, and self-optimization. The traffic managers at all levels of the architecture must be empowered with mechanisms necessary to enforce ACP. As an example, an IM can be given the ability to self-configure hardware/software components at

an intersection. Both IM and ZM may have to coordinate their efforts for self-healing when a disruption is observed at an intersection, because traffic policies may have to be re-formulated. In general, a thorough investigation of methods and mechanisms to integrate ACS, CPS, and context-awareness in different layers of the current architecture is required to find solutions that can meet the challenges faced in creating a safe transportation system.

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