Node Reservation Intersection Control Management - A Strategy for Autonomous and Human-Driven Cars Integration.

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Dedication

I dedicate this thesis to the Almighty God for his grace, my wife, children, mum, and my late dad's for their support and prayers.

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My profound gratitude goes to my supervisory team Dr. Julian Kunkel and Dr. Frederic Stahl, for their kindness and commitment to the course of this research, as they usually assigned me overwhelming and challenging tasks and monitored my progress regularly. Dr. Julian Kunkel has explicitly been instrumental in formulating the research topic and supported my progress from the beginning till now.

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Abstract

Driverless cars are emerging slowly but bear the opportunity to improve the traffic system efficiency and user comfort. For the near future, a mix of human-driven and driver-less vehicle co-existence is inevitable. The quest to integrate autonomous and human-driven vehicles has created numerous critical questions in the road traffic system: Should humans remain to navigate the wheel? How can autonomous and human-driven vehicles co-exist efficiently? What are the prospects of breaching traffic data security? How can we address some social driving problems ranging from congestion reduction, communication among traffics, and many more? To a large extent, efficient control and supervision of mix-traffic behaviours at the road intersection will go a long way to ameliorate the concerns envisaged in the autonomous vehicle integration process. Mixed traffic co-existence is associated with lateral and longitudinal direction (2D) behaviour which needs communication among vehicles. These stated mixed-traffic characteristics principle contradicts the car-following model, which only describes longitudinal vehicle interaction in homogeneous traffic. A model predictive control-based node reservation technique is developed to optimise the flow of mixed vehicles at a discrete-time step based on the human-driven vehicles (HVs') estimated driving behaviour. The main contributions of this thesis are employing the existing 1-dimensional homogeneous car-following model strategies to a 2-dimensional heterogeneous traffic system, synchronising the two-vehicle type control communication component (human perception for HVs, and vehicle to X (vehicle and or infrastructure) for autonomous vehicles (AVs)), modelling driving behaviour with vehicle-type-contingency, and a balanced impact assessment of AVs in a mixed-traffic scenario to serve as an integration pattern. To quantify the benefit of the proposed Node Reservation strategy, a simulator is developed, and three traffic management strategies are integrated: traffic light control method, collision avoidance with safe distance method, and the node reservation method. The proposed simulation model is validated, and experiments are conducted with varying traffic intersection control strategies and vehicle type proportions. The obtained results demonstrate that the node reservation strategy has a high throughput with minimal delay and braking.

Declaration of original authorship

I wish to confirm that this thesis is my own work, and the use of all material from other sources has been properly and fully acknowledged.

Frank Ekene Ozioko.

Glossary

1. ADAS = Advanced Driver Assistance System
2. AHS = Automated Highway System
3. AIM = Autonomous Intersection Management
4. AMCA = Automatic Merge Control Approach
5. AV = Atonomous Vehicle
6. AVHVControl = Autonomous Vehicle-Human Vehicle Control
7. CA = Cellular Automata
8. CACC = Cooperative Adaptive Cruise Control
9. CAV = Connected and Automated Vehicles
10. CCP = Cross Collision
11. CV = Centre Vehicle
12. CVIC = Cooperative Vehicle Intersection Control
13. EV = Exiting Vehicle
14. HV = Human-Driven Vehicle
15. IA = Intersection Agent
16. ICCR = Intersection Communication Control Region
17. ICU = Intersection Coordination Unit
18. CIM Cooperative Intersection Management
19. IDM - Intelligent Driver Model
20. I2V = Infrastructure To Vehicle
21. MOE = Measure Of Effectiveness
22. MPC = Model Predictive Control
23. SIS = Shared Intersection Space

24. UML = Unified Modelling Language
25. UTMC = Urban Traffic Management Control
26. VP = Vehicle Platooning
27. VVM = Virtual Vehicle Mapping
28. V2X = Vehicle to Vehicle and or to infrastructure
29. V2V = Vehicle-to-Vehicle
30. V2I = Vehicle-to-Infrastructure.
31. V/C = Volume-to-Capacity
32. 2D = 2-Dimentional

Contents

List of Figures

List of Tables

Chapter 1

Introduction

Chapter Overview

This chapter presents the research background. First, an introduction to traffic control, mixed traffic, road intersection system, autonomous and the human-driven vehicle is presented in Section 1.1. Section 1.2 deals with the motivation for the research in autonomous vehicle integration. The research goal is covered in Section 1.3, The research questions are addressed in Section 1.4. Section 1.5 explains the aim and objectives of the research. The main contributions to knowledge are presented in Section 1.6. The organization and structure of how this thesis is implemented are described in Section 1.7. The research road map is described in Section 1.7. Presented in Section 7.2 is the status of the research.

1.1 Introduction to traffic management

Traffic control is the process of directing traffics along a road intersection to ensure efficiency and safety. Control and predicting traffic uses signal devices, road markers, and signs that are part of the road infrastructure and traffic control parameters. The road system infrastructure design and the traffic control strategy in place drives the traffic system efficiency. The traffic intersection region is generally considered a significant source of traffic congestion. Hence, the control and optimisation of traffic flow behaviour at road intersections are essential as a baseline for the autonomous vehicle integration process. Besides, the control and design of traffic infrastructure are subject to vehicle type characteristics. Autonomous vehicles sense their environment, control and navigate their motion safely from start to destination. Mixed traffic facilities are most appropriate on roads with low traffic volumes operating at low speeds because of the driver's behavioural activities, which may be described by several systems, ranging from simple to complex. The low traffic density allows users to negotiate space in comfort without the need for robust separation.

Recently, autonomous vehicles have been looked at as an alternative way to solve road traffic problems. The emergence of autonomous vehicles (AV) inadvertently makes the co-existence of human-driven vehicles (HV) and autonomous vehicles inevitable. AV will not solve all the HV inefficiencies in a mixed traffic setting but will help a great deal as there are myriad possibilities. The AVHV node reservations method in road-space-time is a perfect example. There is limited road infrastructure to support the growing population of human beings and vehicles in the urban areas. This unchanging situation has given rise to numerous social vices, economic and congestion problems. However, it is a general knowledge and an established worry over road traffic control system due to constant traffic congestion problems associated with the HVs. The AVs to a large extent can mitigate most of the existing city traffic problems ranging from congestion, safety issues, environmental pollution, economic loss, increased travel time, stress, and sometimes loss of life [FN12, WLPH21, KASS21]. Besides the enormous advantages of autonomous vehicles, automated driving raises concerns such as possible loss of situation awareness, over-reliance on automation, and system precision failure. However, the compelling benefits of autonomous vehicles may require prohibiting human-driven vehicles on certain roadways because of the challenges surrounding AVs and HVs co-existence. The road intersection zone is critical (conflict areas) and presents an obstruction to traffic flow while managing traffic streams from different road segments or lanes. A reliable, safe, and efficient road intersection and its associated traffic systems are critical factors to the well-being of the city and businesses in economic growth [CR11, YM16]. These, in turn, enable better social inclusion and quality of life.

The agent-based traffic management system provides a platform for constructing a complex system with multiple agents and mechanisms to efficiently and safely manage independent traffic behaviour. One of the significant challenges in vehicle co-existence is driving behaviour, which is affected by many factors, ranging from structural to situational influence. Human driver's behaviour constitutes a significant percentage of congestion and accidents on the road. Traffic congestion cost the UK over £15 billion/year in 1998, representing about 1.55% of GDP according to [Nas03]. Besides, an investigation released by INRIX in 2014 suggests that this figure would increase to more than £300 billion (a 63% increase in annual cost) cumulatively between 2013 and 2030 [BS17]. Hence, this growth trend, according to [WTG+14, SLL20] reflects the increasing population, which reflects what is obtainable in other countries with estimates of 1.3%, 0.9%, and 0.99% of GDP for France, Germany, and China, respectively. Most current studies reflect this trend and appears to be worse [Lia20].

Norman Bel Geddes of General Motor in [Bim15] in the year 1958 manufactured the radio-controlled electromagnetic fields generated with magnetised metal spikes embedded self-driving car, an electric vehicle whose movement was guided by in the roadway.

Autonomous Vehicles Sensor Feature: The autonomous vehicle makes use of the following sensors feature:

- Autonomous vehicles use their body sensors to develop and maintain a map of their surrounding environment while in motion.
- Uses radar devices to monitor the position of nearby vehicles and other obstacles.
- Uses video cameras to read road signs, track other vehicles, and look for pedestrians or obstacles on the road.

Following the emergence of autonomous vehicles, mixed traffic problems have attracted researchers to develop many related technologies to find solutions associated with the autonomous vehicle integration process. Significant road infrastructure enhancement such as road-vehicle communication needs to be upgraded to accommodate autonomous vehicle integration and future traffic growth.

Traffic flow theories describes the traffic flow variables of volume, density and speed which correlate with city traffic. These theories' extension gave rise to the interactions between commuters such as vehicles, pedestrians, cyclists, and motorcyclists. Traffic management methods aim to increase traffic peak capacity and ensure a more efficient and smooth-flow of traffic, mainly at intersections and roadways in general. Traffic management strategies application is mainly dependent on the road users' type and characteristics; hence, this research is limited to a traffic mix of human-driven and autonomous vehicles.

The current study by [YWJ+16] predicts growth of more than ten fold in the global autonomous vehicle market worth \$54.23 billion in 2019 to \$556.67 billion by 2026. Though there is a compound annual growth rate of 39.47% during the 2019-2026 [KH16, Wil19], the recent survey shows a rising fear of using driverless cars. The rise in smart city development is expected to drive Autonomous Vehicle penetration significantly. CO_2 emission and the growing number of cars on the road raises an issue of concern concerning environmental pollution and traffic management problems. Autonomous vehicles can share car movement parameter information with a central controller in real-time. This real-time sharing feature makes it possible for AVs to predict their velocities and use it to reserve a node while synchronising the control measure with human-driven cars. In contrast, human-driven vehicles make use of traffic signals with the associated stochastic drivers' behaviour.

Co-existence demands cooperation among participating vehicles, while vehicle autonomy has a varying level, ranging from level 0 to level 5 [GLM19]. Presently, the rolling out of autonomous vehicle-supported functionality such as self-parking or auto-collision avoidance features drives the penetration process. Automation and communications in vehicle advancement has enabled cooperative intersection control involving safe communication between infrastructure, signal control and users to be realisable. One of the main technological barriers in this research area is how to bring about communication between human drivers and autonomous vehicles. With the principle behind cooperative intersection management (CIM) [Shl09], and connected autonomous vehicle (CAVs), groups of vehicles can drive seamlessly. Another objective of cooperation among vehicles is to reduce idling associated with the signalised intersection at red lights, thereby optimising traffic flow. This CAV method improves traffic efficiency with cooperative functionalities such as cooperative sensing, harmonised traffic, adaptive cruise control, dynamic route guidance, improved fuel-efficiency, and cooperative manoeuvring [GLM19, MDF$^+$19, TM16, HKSW12]. The connected vehicle concept supplies useful informed decision making information to a vehicles and driver. The advancement in sensor technology and the adoption of communication technology are increasing the penetration rate of autonomous vehicles. The advantages of the high-precision abilities which autonomous vehicles have over human-driven vehicles are of great importance to feature research in autonomous intersection scheduling scheme. The scheduling method efficiently coordinates the intersection zone by preserving each of the reservation nodes for a single-vehicle at every time instance (successively). The node reservation method ensures a collision-free intersection region and manages the vehicles' turning movements under a safe velocity limit.

However, road intersection being a significant player in traffic congestion management provides for the change of route directions for vehicles from two or more routes and roads. While intersection zones constitute a fragment of a road, it has been identified that significant traffic fatalities occur within the intersection area. These said fatalities are caused mainly by human errors. According to [fT16], over 20% of road accident on EU roads happened at the intersection zone from 2005 to 2014. The co-existence of AVs and HVs may lead to congested traffic conditions at a road intersection, which will require careful handling to avoid a highly complex traffic situation. Communication among traffic participants will go a long way to address this problem and make intersection space sharing seamless. Road intersections vary in complexity subject to the number of roads involved or lane design and the traffic control strategy. In a traffic flow system, road intersections tend to have a high potential for crashes because drivers have to decide which of the alternative routes they wish to take. Besides, city traffic performance is highly dependent to a great extent on the performance of the road intersections within the city because of the delay associated with the sharing of the intersection area with vehicles from other lanes and routes. Undoubtedly, the co-existence of human-driven and autonomous vehicles will complicate this situation if there is no reliable, safe, and efficient integration framework in place. Despite many studies on the autonomous vehicle, [JFM18], one major challenge for its co-existence is the AV communication with HV on the road and other road users like cyclist and pedestrians.

Over the years, research on traffic management has been on the increase [KR18, FK15]. This increase in traffic research is due to the advancements in-car technology, an increase in population growth, with a corresponding increase in the number of cars on the road, without the right compliment of road infrastructure

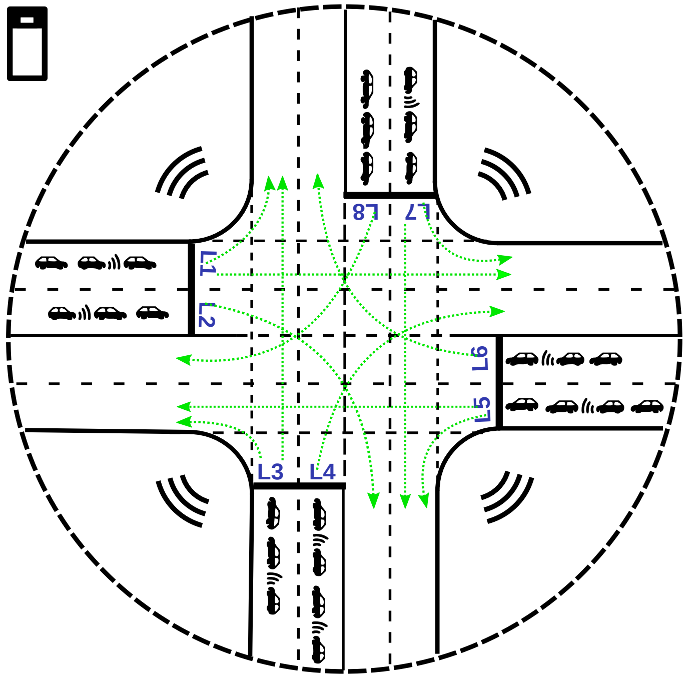


Figure 1.1: A 4-way road intersection with double lanes

and traffic management techniques[LAS+19, BBKHK18]. Drivers are sometimes forced to wait at the intersection for several minutes before accessing the intersection facility. Based on different car behaviours associated with mix-traffic, autonomous vehicle integration will increase the intersection delay without an efficient traffic control scheme, which will cause the under-utilisation of the benefits of autonomous vehicles. A flawed traffic management scheme has been identified as the root cause of traffic gridlock at intersections, which has led to frustration, the incidence of road rage, traffic build-up in other intersections within the city, to mention but a few.

At road intersections, traffic flow naturally occurs bidirectionally: lateral and longitudinal, which brings about bidirectional traffic behaviour. This 2-dimensional behaviour contradicts the typical traffic stream behaviour in a vehicle platoon or car-following models, which are one-dimensional lane-based traffic flows. Autonomous vehicles are emerging while conventional (human-driven) vehicles are on the ground, hence the need for the change in control scheme features of a varying proportion of HVs and AVs before realising such a full traffic autonomy. Based on the preceding, there is a need to address the efficiency and safety issues in a hybrid system for a seamless co-existence of HVs and AVs at a road intersection. The pilot investigation in the field of vehicle autonomy started with the Automated Highway System (AHS) research program [HV00], which focused on improving the capacity and the safety of highway traffic. The efficient scheduling of the traffic lights system at road intersection can only guarantee an optimal utility of the road infrastructure at the intersection [SEL12]. The advent of automated vehicles led to the birth of vehicle-to-vehicle and vehicle-to-infrastructure communication systems, which inadvertently led to road intersection settings without traffic lights but has smooth and efficient flows of traffic with suitable safety measures in place. The social-psychological issues surrounding the anticipated adventure necessitated by autonomous vehicles has so far underscored the timely demand for research directed towards the well-being of its integration process.

Road intersections may be categorised by the following factors: traffic control measure in use, the number of lanes involved, and the geometric design that is associated with it. Subject to the model of traffic control means, there are two types of intersections:

- Signalised intersection which is equipped with traffic lights.
- Non-signalised intersections without traffic light, but vehicles interacts with each other and the road infrastructure.

Besides, in categorising road intersection based on the number available umber of road lanes, we have:

- 3-Way intersection
- 4-Way intersection and
- Scatter intersection

Figure 1.1 is the proposed 4-way road intersection model with vehicle trajectories indicated with green arrows. AVs are vehicles with wireless communication sign; as both AVs and HVs share the same intersection space. L indicates the lane identifiers; the wireless communication sign is located outside the intersection, while the control units is the box located outside the circle. These intersection cross collision points are where the green trajectory lines cross each other from different road lanes or trajectories from which they depart to their destination after crossing the intersection region. The primary responsibility of intersection control is to direct vehicles and platoons of vehicles seamlessly without collision. A 3-way intersection model extracted from the 4-way model is represented in Figure 1.2, where the merging section of the road joined the major road in continuous one-directional traffic flow. Traffic intersection management strategy is highly driven by the type of intersection determined by the number of road systems and lanes involved. For this research, the investigation is based on two types of intersections: 3-way and 4-way intersections. There is a variation in the number of vehicle trajectories considered in the intersection management strategies to apply. In this case, depending on the vehicle's goal or destination, drivers must decide on a trajectory based on the intersection management rule. A little mistake at the intersection point in judgement on path trajectories has a high-risk value of causing multiple accidents. Vehicles experience delays at the intersection, but it depends on the model of the road and intersection control strategy. By and larg, activity stream depends on the execution of the convergences road system. Road intersection investigations are essential for optimal city traffic engineering investigation.

There is no doubt that connected and automated vehicles (CAVs) can enhance security by reducing and mitigating traffic accidents with a seamless flow of traffic and suitable safety measures. Traffic lights manage the traffic flow at an intersection in a conventional traffic control model, while signs limiting the highest traffic control capacity and increasing inconveniences of frequent stops and idle time. In a traffic light control system, vehicles mostly are required to decelerate at the intersection stop signs prior to crossing over the intersection zone and then start accelerating to its destination. In most cases, vehicles are bound to stop for the right to be granted to it, even if no other vehicle is present at the other road segment, thereby causing traffic delay. Similarly, vehicles crossing the roundabout obey the vehicles already using the roundabout when there is no traffic light or sign. For busy signalised traffic intersections, traffics arriving at the intersection are managed using green, amber, and red lights that eventually increase the stop delays.

Traffic-light signal control has been appraised as the most common and effective method of traffic control measure. Sequel to this assertion, many states of the art strategies that use traffic light signal has been developed with advanced signal [PDD+03, THH00, KIO+12]. Besides, traffic light signal strategies could relatively enhance traffic flow if the traffics at an intersection are not congested. Traffic light cannot remove

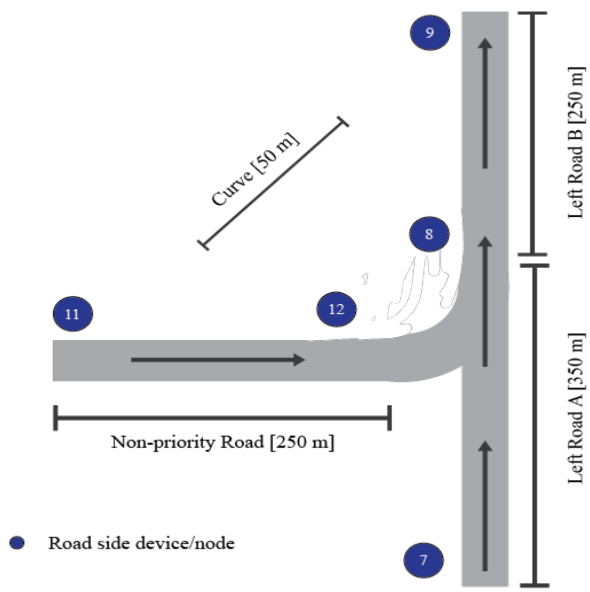


Figure 1.2: A 1-way traffic T-road intersection

the stop delay associated with arriving vehicle irrespective of the traffic volume. For the vehicle advancement technology and consolidation in the moden road transport system, innovation in the traffic control regime may eliminate or improve the delays associated with a traffic light.

1.2 Motivation

The delay in autonomous vehicles' emergence is mostly caused by the fact that the state-of-the-art system in traffic management mainly deals with homogeneous traffic behaviours [HMPR59, WKVB17, BTAO16]. In contrast, the traffic mix is being affected by the complex driving behaviour involved. There is a need to bridge the gap between safe driving and efficient mix-traffic control for the next generation mix-traffic scheduling method involving human-driven and autonomous vehicles. This method moves away from the global same vehicle type traffic management involving either vehicle-to-roadside or vehicle-to-vehicle traffic management to a vehicle mix scheduling system involving AVs and HVs. Autonomous vehicles will gradually change the road traffic system and become part of our daily lives. Sequel to this expected change in traffic system occasioned by the emergence of autonomous vehicles, fully intelligent road traffic systems will makes their way to traffic autonomy. The deployment of autonomous vehicles will naturally increase traffic performance significantly because AVs can perceive the surroundings and possibly navigate through some challenging road conditions for humans, though with enormous challenges. The full vehicle automation trend still has some challenges in the human being's role along the path to meet up with both driving psychology and commensurate with user requirements.

According to [SEL12], traffic is controlled naturally by reducing vehicles number and increasing the shared intersection space. AVs and HVs co-existence will affect the traffic control system's efficiency and deserve creating different control schemes and roads for each vehicle type instead of hybrid vehicle sharing the standard road system. Building a separate road and scheme for each vehicle type is not feasible because of cost and space constraints. Traffic management agencies tasked with controlling traffic systems are frequently challenged with moving traffic in congested road conditions. In the current situations where the traffic demand exceeds the road system's capacity, there is no doubt that the integration of autonomous cars will compound the problem more irrespective of the advantages of the autonomous vehicles [DKH+16, EW16]. Autonomous vehicles are emerging while the conventional human-driven vehicles cannot be automatically phased-out from the road; hence the need for a mixed traffic co-existence on-road system at the intersection point is a must.

In summary, the key motivation for this research is as summarized below:

1. Integration of autonomous vehicles with human driven vehicles is an excellent idea, but not without concern, as these careful automated vehicles, and aggressive human drivers will have to figure out behavioral rules for coexistence.

2. Currently, millions of pounds are being invested in smart roads system research, which involves defining and creating technological frameworks for the mix-traffic integration process.

3. The integration process will help society appreciate the enormous advantages AV has over HV and fastrack its emergence.

4. Building a new smart road for AVs is not feasible and will be faced with many challenges; hence a seamless integration process appears to be a reliable approach to this problem facing AV emergence.

5. Need to put in place standards to ensure safe operation, and right compliment of data flow between mix-vehicles and its environment.

6. Newell's in [DBC08] made an effort to address the challenge encountered by addressing the 2-dimensional (lateral and longitudinal directions) traffic model because it deviates from the car-following traffic theory. This is equally affected by the non-possibility of actual mix-traffic data.

It has become challenging for traffic controllers to provide optimal road traffic management strategy for the ever-increasing vehicle and human population. The connectivity of different road lanes builds up the road intersections, which is vulnerable to vehicle collision without suitable traffic control measures. Traffic congestion frequently happens when traffic density exceeds the road intersection maximum capacity. The optimal use of the available road infrastructure by applying an innovative traffic intersection control scheme is a solution for the city traffic problems where additional expansion or creation of roads are challenging. Conventional drivers create traffic congestion due to the various types of disturbances ranging from the driver's state of mind to roadside distractions. Therefore, people daily waste a considerable amount of fuel and time, which is why the cost of traffic increases day by day. Traffic congestion usually occurs when the number of vehicles on a particular road system exceeds the maximum number meant for the road system capacity; in this case, traffic density is higher than the road network capacity. In this situation, if the existing road system is used in a very innovative and efficient way, then this problematic situation can be solved. Management of intersection using various controlling strategies for a human-driven car traffic intersection is the feasible solution to a hybrid vehicle situation. Human-driven vehicles use intersection control with traffic light systems. In contrast, autonomous vehicles came in with new technology for accessing the road facilities involving a vehicle-to-vehicle and vehicle-to-infrastructure communication, while human-driven vehicles involve driver-to-road infrastructure communication. The introduction of new technology is not automatic, while replacing old technology takes a gradual process. This is because of the social and economic challenges.

There is a need to integrate autonomous vehicle and human-driven vehicle movement parameters to drive and midwife the smooth transition to a fully automated road system. This is necessary because conventional vehicles currently occupying the road cannot just be phased out sooner based on the following constraints: cost, choice, infrastructure. Realistically, technology is evolving and advances once it replaces the old. The integration and migration period is usually gradual because the technology advancement trend is not automatic. There is the possibility of acceptance challenge for most human-drivers who believe in the way they used to do it and cannot afford to do away with their private vehicle immediately, even with some government incentives if available. Gradual transformation to a fully automated road transport system can seamlessly be achieved by integrating automated vehicles' attributes into the human-driven vehicles bearing in mind the human driver's attribute on-road (tracking user's stochastic behaviour) and communication parameters.

The proposed model assumption is based on an idle traffic management system with a central control unit that manages AVs through wireless communication and HVs with traffic light signals control. There is synchronisation between the two traffic control behavioural parameters (traffic signal and vehicle-to-vehicle and vehicle to infrastructural communications) to control the traffic mix method. However, this thesis focuses on modelling and optimising a mix of traffic intersection techniques to improve the throughput and safety of light-controlled intersections in combination with vehicle-to-vehicle and vehicle-to-infrastructural communications.

1.3 Research Goals

This research aims to test traffic theories and use the proposed model to solve the co-existence of human-driven and autonomous vehicles problems at a road intersection. When intersection nodes are reserved for traffic, AVs and HVs could co-exist seamlessly. This method will enhance the performance of the human-driven vehicle when the distance headway of AVs are adjusted. The proposed model aims at optimising the performance of the driver behaviour in a mix-traffic environment. Cooperation among participating vehicles in mix-traffic poses the chance to enhance the efficiency of the traffic flow. The vehicle cooperation made the human-driven vehicles benefit from autonomous vehicle competence such as harmonious driving speeds and keeping an informed distance between vehicles to minimse needless braking and re-acceleration in a car-following model. However, the scheme integrates fully automated vehicle intersections to improve traffic operations. Access precedence is granted to human-driven vehicles whenever it comes into access request conflict with autonomous vehicles. The proposed model will be appraised through statistical simulation, and its results compared with the conventional signalised and mixed traffic scheme. Under the various traffic-flow conditions, the critical interest to observe is that the stop delay of vehicles at intersections is possibly gotteb rid of, and vehicles flow and the intersection capacity are significantly improved.

The communication between AVs and HVs needs to be synchronised seamlessly though they have different communication channels. A Human-driven and autonomous vehicle intersection scheme in a signalised and non-signalised co-existence that conquer the constraint of the current methods is proposed. The proposed scheme novelty is the simultaneous control and considerations of the states of all routes and the aggregates of vehicles at real-time. However, considering the growing trends of vehicle innovation and advancement in road transportation systems, a success story in the intersection control methods, with optimal efficiency, is highly expected.

1.4 Research Question

AVs are evolving; while HVs are not to be eradicated any time soon, it is therefore evident that AVs and HVs co-existence for a while is inevitable. This thesis uses the proposed methodologies to investigate mix-traffic flow at road intersections using traffic theories and dramatisation and compares it with alternative strategies. Several issues are still the focus of research in the integration of human-driven and autonomous vehicles. Some of these challenges include the following:

- The worry surrounding autonomous vehicle integration has been growing, and the need to design a method and regulations for its co-existence is vital. Answering the above question will help society know how feasible and safe the co-existence of autonomous and human-driven vehicles will be when intersection nodes are reserved.

- Mix-driving requires many complex social interactions with an expected impact on traffic; how do we deal with investigation?

By addressing the above research probes, we present the weakness in the microscopic simulation of hybrid traffic, propose a solution, and show future research directions. The advanced traffic simulator appears realistic from the validation conducted while addressing the research questions. Currently, a couple of all-encompassing experiments have been conducted with the different 3-ways and 4-ways road intersection scenarios. While the research in this area is still ongoing, this research approach is shaped to be competitive and contribute reasonably to the research field.

1.5 Research Aim and Objectives

This research's aim at developing an efficient algorithms for mix-traffic management at a city road intersection. This could be achieved through the following specific objectives:

- Model mix-traffic with the human-driven vehicles benefiting from autonomous vehicles potentials such as harmonious driving speeds, reaction, and safe distance in a car-following scheme.
- Develop a driving behavioural model with an aggressive factor capturing human driving behaviour physically and psychologically.
- Investigate the model's performance based on the percentage mix of HVs and AVs to serve as a guide for the transition period.

Modeling mix-traffic is an important goal as reliance on autonomous vehicles is ever increasing. This thesis objectives have been identified as "autonomous vehicles co-existence with human-driven vehicles is a feasible direction to reap the immediate befit of autonomous vehicles". Towards this, a promising method of managing mixed traffic is inevitable. Besides, this work's objective also involves the review of the different traffic control strategies applied to a mixed traffic environment, which will reduce traffic congestion, increase road safety measures, and drive the transition period to a fully autonomous intersection system.

1.6 Contribution Computing and Computation to Knowledge

This work builds on the existing approaches by employing 1-dimensional homogeneous traffic control strategies into a 2-dimensional complex traffic behaviour of the mix-traffic environment. The work combined both traffic lights and vehicle-vehicle/road infrastructure communications for controlling the human-driven vehicle and autonomous vehicles, respectively, at a road intersection. However, the main areas of the contributions are as follows:

- Investigating the complicated behaviour involved in a mix of AV and HV to fastract autonomous vehicle integration process.
- Conduct as many simulated experiments to develop optimal data as a basis for the AV and HV integration process.
- Development of a 2-D traffic model with the concept of car-following models to comprehensively simulate both lateral and longitudinal mix-traffic behaviour.
- Modelling driving behaviour with vehicle-type-contingency and human psychological driving characteristics.
- The method of adjusting the distance headway improves the performance of a human-driven vehicle. This makes the HVs yield to much smoother trajectories.
- A method for speed harmonisation algorithm for a traffic-mix setting.
- A centralised traffic control method that controls both AV and HV using one control unit with different proportion of vehicle types to serve as an integration of autonomous vehicle pattern.

The innovative method above will differentiate this approach from coordination algorithms or schemes and demonstrate the unique contribution to knowledge. The abstraction of the car following model with a minimum gap in cooperative adaptive cruise control (CACC) could be extended to provide an innovative intersection control scheme. The proposed method simultaneously allows traffic from different lanes to traverse the intersection keeping a marginal gap with traffic signals. Such a paradigm of intersection control measure would potentially eliminate stop delay, reduce travel time, increase intersection capacity, and address the issue of steady speed for the human-driven vehicle.

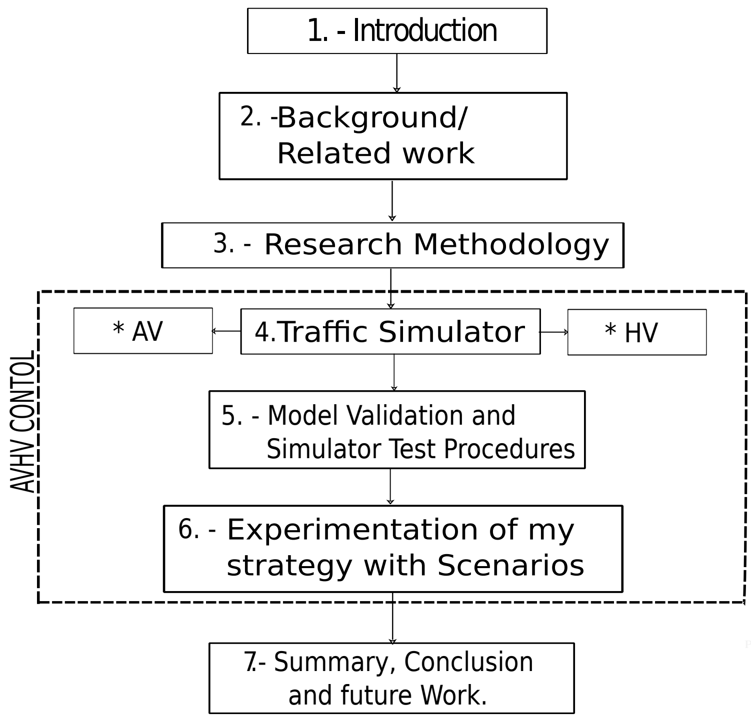


Figure 1.3: A road map for the chapters

1.7 Thesis Organisation

This section of this chapter discuss the structure of this thesis as designed in Section 1.7, providing a summary of the contributions made by the contents of each chapter of the thesis. The organisation and relationships between the chapters of this thesis are represented in the flow chart - road map Figure 1.3. This presents readers with a guide in understanding the thesis's structure. This thesis is organised as follows:

Chapter 1: covers the general background introduction to the topics dealt with in this thesis - state-of-the-art traffic management strategies, emphasising the research problem and goals. Within this same chapter 1, we have the motivation for the research, research questions, research aims and objectives, contribution to knowledge, the research status, and conclusion.

Chapter two: This chapter presents an overview of the state of the art in traffic management strategies and control architecture. These reviews are mostly in traffic management schemes involving human-driven vehicles and autonomous vehicles (mixed-traffic environment). A few pieces of literature deals with mixed traffic control schemes containing different road users: such as a pedestrian, cyclist, and motorist. This review's focus was based on analysis of traffic management strategies of the human-driven vehicle or autonomous vehicles separately, which can be adaptable to manage a mix of human and autonomous vehicles considering their behavioural characteristics. Based on this survey, comparative analysis of these traffic control schemes involving human-driven vehicles on one side and autonomous vehicles on the other side is presented. Besides, a review of the current research progress in AV and HVs mixed traffic management was critically analysed. The review involves centralised and decentralised traffic control strategies for both human-driven and autonomous vehicles, with each method's pros and cons. This analysis developed a relationship table on how different traffic management approaches could work for a mixed-traffic scenario involving AV and HV at a road intersection. One of the significant considerations of the review was based on the means of communication between human-driven vehicles, autonomous vehicles, and the road infrastructure, respectively, to bridge the compatibility gap between the AVs and HVs communication means.

Chapter three: This chapter presents the proposed mixed-traffic solution, covering the research framework, research design methods, and strategy for mixed-traffic management. It covers the research background idea, design procedure, methodology, and fundamental assumptions and explaining the problem investigated through experimentation. The chapter explains how the model is built, requiring only minor extensions to the existing road infrastructure by adding vehicle collision points, a coordination unit that manages the reservation nodes, and the coordination protocol. The traffic flow model abstraction detailed with the mathematical model for vehicle dynamics and kinematics covering the underpinning vehicle Physics is presented in this chapter. Also captured in this chapter is the discussion, illustrating the similarities and differences between human drivers and autonomous vehicle's high-level behavioural, including how cars are created, the traffic routing and scheduling method used. Furthermore, the road system infrastructure design used for the evaluation purpose and the traffic flow model design with vehicle type contingencies details are described in the chapter.

Chapter four: This chapter presents a detailed description of how the prototype simulator was conceived and implemented based on the mathematical model and high-level abstractions. The chapter also introduces the proposed traffic simulator's architecture with a description of the simulator's essential components and the implementation of the simulator's mathematical abstraction with its numerical description. Also described in this chapter is the simulator visualisation and analysis component details include the drawing outlook and function or workings of the road system and intersections. The chapter also describes the actual implementation for the traffic scheduling and routing process describing test procedures and validation process for the simulator conducted using different traffic scenarios and a review of the output. Finally, the chapter describes some small experiments demonstrating that the mathematical model is well approximated and confirms that the resulting car behaviour matches our expectations.

Chapter Five: This chapter describes the model validation process with the simulator test procedure. This is implemented using different traffic scenarios.

Chapter Six: The details of the conducted experiments estimating the benefits and drawbacks of the research hypothesis with an overview of the different road intersection management scenarios and an introduction to traffic controls and road parameters are described in this chapter. A qualitative and quantitative assessment criteria to evaluate the alternative traffic management strategies are used as the model performance assessment benchmark. Also described in this chapter are the conducted experiments and results generated from different mixed-traffic management strategies. This follows an overarching conclusion drawn from all experimental results.

Chapter Seven: This chapter presents an all-embracing conclusion of the thesis and some encountered challenges with suggestions for future research work on mix-traffic integration. The proposed work builds on the existing traffic management approach driven from reviewing related pieces of literature in Chapter 2.

Chapter 2

Related Works

This chapter presents an introductory background in the road traffic system with a review of state-of-the-art mix-traffic management. First, a theoretical introduction to traffic management, traffic rules, and regulation is presented in Section 2.1; also covered in this section is an introduction to the relevant traffic terms and concepts. Section 2.2 introduces traffic intersection management, covering the different types and means used in managing road traffic intersection. The traffic flow parameters are presented in Section 2.3. Section 2.4 covers the traffic flow theories and their fundamentals impact in defining traffic behaviour using traffic flow parameters. Section 2.5, deals with introducing intelligent transportation systems, covering the history of intelligent transportation and autonomous intersections. The transition from human-driven to autonomous vehicle technology is covered in Section 2.6, with details of the differences involved in the vehicle autonomy process stages. Also covered in this section is the intersection capacity analysis. The traffic intersection management strategies, which involve the planning, arrangement, guidance, and traffic control, are covered in Section 2.1. Traffic models and simulation are covered in Section 2.7, detailing the different modelling approaches of microscopic, macroscopic, and mesoscopic traffic modelling. Also captured in this section are the car-following models and cellular automation modelling. The introduction to mix traffic intersection management is covered in Section 2.1 with the impact of drivers' behaviour in mix-traffic modelling. The state-of-the-art in mix-traffic management is presented in Section 2.1 involving the different mix-traffic system types. The classification matrix of related work is presented in Section 2.9 with communication and mix-traffic management approaches. Also covered in Section 2.9 are some key intersection performance indicators like efficiency, fairness in traffic scheduling, safety, and scalability features of each of the approaches. A summary of the pros and cons of the approaches is also captured in this section. The research gap is discussed in Section 2.10, while the summary was covered in Section 2.11

2.1 A Review of Traffic Management

Traffic management aims to improve the traffic community life. The earliest global traffic signals were established outside the Houses of Parliament in Britain on 10 December 1868[Mue70]. The system is operated manually with semaphores to control traffic by alternating the right to traffics at a fixed time interval. The aim was to prevent traffic collisions/accidents and create a seamless flow of traffic. The increase in population and road traffic with this system's attendant advancement lead to the current traffic control status. Road traffic management involves using predefined rules to organise, arrange, guide, and manage stopped and moving road users, including traffics of different types, pedestrians, bicyclists, and all types of vehicles. By default, the traffic management system is guided by protocols that are mostly executed by traffic signal lights. The conventional traffic control system uses lights, signals, pedestrian crossings, and signalling equipment located at the intersection zone to control traffic flow. Traditional traffic management system uses time-based scheduling for traffic management at road intersections. The modern traffic scheduling system tends to improve on the idle time associated with time-based management by involving a set of applications, management, or command-control and signalling system to improve the overall traffic performance and safety of a road intersection. The traffic management applications gather complex real-time traffic information related to traffic (vehicle type, vehicle speeds, in-road, and roadside sensors), analyse it, and use it to provide safe and efficient traffic control services for all vehicles using the road facility in real-time. Besides, traffic risk is predominantly high at road intersection because of the multi road and users which converge from different routes to diverge differently after crossing the intersection.

Traffic Rules and Regulations There is a universal traffic rule: vehicle and cyclist drivers are anticipated to circumvent collision with other public road users (vehicle or pedestrians), notwithstanding the applicability of the road, traffic rules permit them to be where they occurred. There are right-of-way rules applicable at every road intersection without a traffic light, which states that vehicles necessarily give way to vehicles moving in the intersection on their right-hand side. Traffic incidence involving the above situation is usually analysed using the approved speed limit of the incidence area. There is an international treaty traffic rules described by the authority of the United Nations, 1968, though there are peculiarities in the rule to countries depending on their vehicle driving style. The traffic rule is the general practice and procedure that traffic are expected to obey. The traffic rules govern interactions between all road users, from pedestrians to vehicles. In the United Kingdom, traffic rules as enshrined in the Highway Code are a legal requirement with an attached punishment for breaking the rules.

Traffic light Traffic lights system which was developed in 1912 according to [GECK16], are light signalling devices that control the traffic flows at road intersections, the light coordinate safe access of the road system by all categories of road users: vehicle, cyclist, pedestrian, rail trains, and others as the case may be. The road traffic lights consist of three all inclusive coloured signal lights that alternate the traffic right of way, following road users with a order of shining lamps or LEDs. Traffic light uses three quality colours: the green light permit traffic to get going in the indicated direction, the yellow light is a transition light from the move to stop, and vis vasa, while the red signal interdict any traffic from going through. This approach could involve a time-based scheduling system or any other compatible approach. Vehicles stop at the red traffic lights and yield right-of-way, as appropriate, before entering the intersections space. The traffic light process controller must cycle through from a green light phase to a yellow light phase and red phase for a specified time before switching the right-of-way to another route or lane as the case may be. The switching time depends on the scheduling mechanism in use, which is driven by the number of vehicles available in real-time. The controller combines traffic data from both AV and HV to avoid conflict at the cross-collision points. Therefore, the AVHV control traffic light control strategy is not physically realisable because it ignores all other road users except vehicles, but it does provide a baseline of best-possible performance to which other mixed-traffic control strategies can be compared. Besides, it is not easy to control human-driven vehicles' speed to prevent them from coming to a complete stop before the right-of-way is assigned.

Traffic yield and rule of priority: For a vehicle to yield at the road intersection means stopping and allowing other road users to go first. Certain road intersections are designed with a priority rule; a particular road segment has a yield sign that automatically assigns the right-of-way to traffic to another road segment. The implication of this rule means that the priority is assigned to a segment that always has the right of way at an intersection. However, when a driver observes a yield sign ahead in an intersection, it is expected that the drivers decelerate to give other vehicles the right-of-way.

Traffic Management Strategies Traffic control strategies are employed to ensure the safety of life, efficient flow of traffic, increase road capacity, reduction of delay/congestion, and a general effort to ameliorate problems resulting from traffics. A good traffic management strategy represents the most visible end-results to manage the long-awaited mixed traffic scenario involving human-driven and autonomous vehicles. Traffic management strategies are concerned with planning, arrangement, guidance, and control of traffic services needed to efficiently move vehicles within a road system. It aims at the safe and seamless traffic movement and preserving and improving quality of life and the local environment. Algorithms of traffic management have helped in defining an efficient and safe traffic flow. Generally, routing forecasting data are used to estimate the effect of traffic performance. Traffic routes help in managing collisions and improve the safety of the traffic flow scheme. Among all the human-driven vehicle traffic controlling methods, the traffic light signalling method, a visual signal that controls traffic flow at intersections, is the most effective and secure approach. However, this traditional traffic light signalling method is what one would find on the street, but it increases the amount of delay time due to stops and lane schedule then; for this reason, various automated vehicles and semi-automated vehicles will be faced with various delay problems [WKGM19]. While the regression method involves the statistical experience, it considers that roads are associated with varying traffic densities at different periods and times. This fluctuation in traffic densities is likely to bring about random fluctuations in traffic within the different hours of the day.

This research deals with the flow aspect of real-time traffic, which involves controlling and routing strategies. This research area is directed towards preventing congestion and increasing flow efficiency in the existing traffic intersections. There is currently extensive research going on in the area of mix-traffic control methods. However, this underpinned the integration of autonomous vehicles. [MJ17], provided an overall research direction in the mix-traffic control system, covering a mix-traffic flow control, intelligent transportation system, and traffic coordination scheme in urban areas motorway networks. Currently, there exists a wide gap between hypothesis and practicability in this area of mixed traffic. The attempt by [HLS16] focused on addressing safety assistance and the integration process. Research in a mix-traffic flow environment has been investigated, though with its challenges because of car behaviours. In microscopic traffic modelling, the conduct among individual vehicles and the road intersections are modelled independently.

2-Seconds Rule The 2-second rule states that a driver shall preferably maintain a minimum of two seconds apart from any vehicle ahead of the reference vehicle. It is planned for vehicles, while this underpinning concept applies to every other vehicle type. In driving, it is general knowledge that a driver shall maintain must keep an adequate distance between vehicles to avoid a collision whenever the leading vehicle decelerate.. There is no standard internationally accepted safe distance; somewhat, it varies from country to country. In the UK, for instance, there is no distinct law for closely following a car. Highway Code Rules for safe distances procedure contain the 2-second rule. However, many of the Highway Code Rules are requirements by law but, the safe distance is not part of it. Besides, disregarding safe distance could be regarded as hazardous driving 'driving without due care and attention, which one could be prosecuted for in line with the law. Drivers in an ideal situation keep a minimum safe distance from the leading vehicle approximately equal to the distance the vehicle covered in two seconds. This value should be twice for heavy vehicles. This safe distance is the actual distance (represented in meters) between the front bumper and the back bumper and the following and leading vehicles, respectively. However, it can be demanding to practically maintain the 2-seconds rule in a city with heavily slow-moving traffic. This is because of the limited road space available. [COD93], states that keeping a distance of at least 2 seconds from the lead vehicle will yield a distance of one car length every 5 mph per second (equivalent to $2.2352m/s^2$), at whichever speed you drive. Figure 2.5 illustrates the 2-second rule analysis. The safe distance complements distance headway, as it defines the same distance in another way. However, distance apart in a traffic stream is the product of speed and distance headway. In this era of COVID-19 and observing social distancing, a safe distance, which is the "physical distancing apart," means observing a safe space between individuals to curtail the virus's spread.

More often than not, traffic ideally observes enough distance urban and suburban roads network for safety reasons. When driving on a good dry road, one can keep approximately 1 metre (1 yard) for every one mile per hour of your speed. The 2-second rule applies irrespective of the vehicle's speed since the distance between the following and the leading vehicle will naturally extend the faster travel. However, a car moving at 30 mph, will be 30 metres away from the vehicle in its front, sufficient to encompass the propose comprehensive stopping distance published in the UK transport authority [ta20]. The 2-seconds rule is a technique used by drivers to calculate their safe following distance, enabling them to control or stop their vehicle any time the vehicle directly ahead of it stop for an emergency. Besides, this 2-seconds rule is not a guide to the safe stopping distance of the vehicle; instead, it is a more useful guide to drivers' reaction times. These 2-seconds rule is calculated by a driver taking cognisance of a fixed position of an object/sign along the road part, and start timing once the car ahead gets to the observation spot, then the driver checks the time it takes his/her car to get to that same spot. However, the speed limits requirement of different city roads guides the rate of vehicle motion. This limit is usually indicated on the traffic signs with the permitted speed range for each route. The UK High way code specifies a maximum of 30mph for city roads, 60mph on main single-carriageway roads, and 70mph on dual carriageways and motorways. Besides, the general UK traffic rules state that at road intersections, all traffic slows down at road junctions and wait until it is convinced of a clear through fair. Vehicle drivers keep to the left on a two-way road to permit vehicles from the opposite direction to pass and on a one-way road to permit following vehicles to overtake from right. In a scenario where the vehicle is turning left, the driver keeps to the left of the destination roads' source and right. While the vehicle is turning right, moving from the centre of the source road, and the destination road is the left side.

Mixed Traffic Management The scenario of mixing traffic behaviours in a single flow model brings a mountain of complex variables into consideration, lies the elements of human and machine co-existence: in mixed traffic flow at a road intersection, each vehicle type are expected to behave in line with its default design/operation, have a very minimal behavioural deviation and maintain the essential objectives of traffics, which is to safely reach its target destination or goal in the shortest possible time. With traffic flow parameters, the behavioural pattern of vehicles could be evaluated reasonably to suggest that the co-existence of human and autonomous vehicles is possible. In doing this, developing a mix-traffic flow model is the first step towards shaping a more sophisticated traffic management strategy to midwife the transition period seamlessly.

Mix-traffic flow management creates room for vehicle co-existing by negotiating with other vehicle types and traffic participants who have a different behavioural pattern based on agreed set down rule to avoid a collision. The platooning model of traffic management strategy is used to optimise the traffic flow. Besides, the method of varying the safe distance between autonomous and human-driven vehicles is also deployed to enhance the optimal efficiency of the traffic. [ZNS+18] proposed a real-time co-operative eco-driving scheme for AV and HV mixed-vehicles using platoon. According to [ZNS+18], the lead vehicle receives timing and phase signal information through (V2I) communication, while the preceding vehicle on the reference platoon communicates via V2V. Generally, mixed traffic is mainly comprised of road users, which include vehicles, pedestrians, and cyclists. However, the vehicles involved in [ZNS+18] generally were termed "homogeneous" traffic, but the vehicles have a wide variation in their static and dynamic characteristics. The vehicle type for the purpose of this thesis is human-driven (HV) and autonomous vehicles (AV). The vehicles share the same right-of-way, resulting in a jumbled traffic flow. The main distinguishing characteristic of this mixed vehicle is based on their driving behaviour and the means of communication among vehicles and road infrastructure. These driving characteristics resulted in a wide variation in behaviours of the vehicles, which makes the mix-traffic management more complicated.

The emergence of autonomous vehicles has witnessed a growing demand for mixed traffic research for the autonomous vehicle integration process. The design concepts of managing human and autonomous vehicles are because of the difficulties and problematic areas of human-machine interaction and the theoretical context of mental modelling. In contrast, the traffic-mix model seeks to use existing homogeneous traffic management techniques to manage a heterogeneous traffic system. The approach first made use of the traffic flow models presented in Figure 3.2, while the second approach used relative distance in a car-following model and compared it with the proposed strategy. The core problem in mix-traffic modelling, is the case of modelling the driver's behaviour.

State of the Art Mix Traffic Management: The emergence of the autonomous vehicle has moved the role of human drivers from active control operation to a passive supervising role [BAJ19]. A closer look at the modern road vehicles, one will observe that there is a high-level advancement in the automation of most vehicle devices, like the adaptive cruise control, obstacle sensor, and automated brake system [VBOGN18, PVGA^{+}21]. [ZNS^{+}18], proposed a receding horizon model predictive control (MPC) with dynamic platoon splitting and integration rules for AVs and HVs, which mostly ease out the trajectory and prevent any shock-wave but does not concurrently optimise the trajectory and signal to time of the road intersection. Currently, there is a large diversity of research going on in mixed traffic generally and the co-existence of human-driven and autonomous vehicles. However, most of these applications are directed towards different types of human-driven vehicles (car, bus, truck), motorcycles, bicycles, and pedestrians, which exposes very few design details. Generally, the state-of-the-art in traffic management was implemented with the event-driven traffic control system. However, there are drawbacks concerning throughput and safety when these methods are implemented in a mixed scenario. There are some traffic management techniques, [Fri16, MP20, DTRW20, Lia20, BPN12] who investigated the impact of integrating AV's on the existing roads to co-exist with the HV's; how will the mix work concerning traffic efficiency? The researcher looked critically at a high-way road system using the following three traffic parameters: Traffic flow characteristics (vehicle, driver behaviour and road intersection, Merging entry, and Exit at intersections). This work appears interesting, but it was only restricted at the microscopic level. However, Tesla, Incorporation based in Palo Alto, California, developed electric cars with high tech features like autonomous vehicles and has been chaining the growing impact of autonomous car integration.

In a mix-traffic system, microscopic models are used to model each vehicle as a kind of particle. The interactions among cars are modelled with simulations with each component of the proposed framework verified. Each car type model with the cars and road interaction protocol system is being implemented in the proposed mix-traffic framework. This framework was verified through simulations involving 3-way and 4-way intersection environments with a full detailed assessment of the impact of each vehicle type. The critical challenge in agent-based traffic simulation is re-creating practical traffic flow at both the macro and micro levels. By seeing traffic flows as emergent phenomena, [BESA10] proposed a multi-agent-based traffic simulator. According to [FUY17], car agent's behaviours are often implemented by applying car-following theories using a continuous one-dimensional road model. [HKGK17] proposed a multilevel agent composed of agents models involving micro-meso, micro-macro, meso-macro simulation framework to address a large scale road traffic mix system using an organisational modelling approach. The multiple-leader car-following model involves a heterogeneous mixture of vehicle types that lack lane discipline. According to [MNHF^{+}20, BM17, MMB15], these traffic conditions lead to a complex driving maneuver that combines vehicle motion in a lateral and longitudinal direction that is needed to address multiple-leader following.

[MNHF+20] sought to simplify mixed traffic modelling by developing a technique based on the concept of virtual lane shifts, which centred on identifying major lateral changes as a signal of a lane-changing situation.

2.2 Traffic Control Methods

This review of related literature looked at traffic flow model methods, traffic management categorisation, and mix-traffic methods. Due to the challenge of the availability of existing data in a traffic-mix involving AV and HV, it is only feasible for researchers to resort to model-based approaches in solving the challenge. Before going into the traffic controlling method, presented below are the traffic control terminologies:

- Cycle: This is a full distinct period of traffic signal light such as green, amber, and red. After a cycle, the control could restart another cycle subject to the traffic control method in use.
- Cycle time: This implies to means the time it takes to complete a single period of traffic signal control. This time is usually a constant for the fixed-time base traffic scheduling system.
- Transition time: This is when it takes to switch in-between the traffic signal light control, for instance, transiting from red to green. This transition period is usually assigned to the amber light, and it is time taken for one car to pass through the intersection.
- Phase: This is assigned to a specific traffic movement allowed in the traffic scheduling at a given period.
- Phase sequence: This is the approved order of the phase movement. It deals with a particular order in which traffic light moves.
- Travel time: This is the total time spent transiting a specified range of distance.
- Signal time: this is when it takes each traffic signal light to be on before going down for another light to come on.
- Traffic detectors: These can be devices that monitor vehicle arrival at the intersection and communicate with the roadside infrastructures.
- Capacity: The maximum volume of vehicles the road system or intersection can contain at a given time.
- Queues: Sum of the vehicles that arrive at the intersection on a particular road lane.
- Approach: This refers to a group of vehicle streams from the same direction.

There exist three main traffic control methods, which includes:

- **Time-based traffic control:** This involves traffic signal control with a fixed time for each scheduling light. This could be designed using historical data-set; which is appropriate and works efficiently for a traffic intersection with a consistent traffic flow pattern. This method cannot respond dynamically to traffic real-time traffic events because each signal time has a calculated fixed time. Consequently, the scheme do not respond spontaneous to traffic demand and emergencies. The fixed-time-based traffic control is suitable for executing permanent strategies, like restricting traffic volume at certain intersections. Because of its static nature, it is sometimes associated with delays and idle time, this is one of its major shortcomings, but it is cheap to design, implement and manage.

- **Adaptive traffic signal control:** This is an intelligent traffic control method based on the real-time traffic demand; it is event-driven. Each traffic light is a kind of cyber-physical system in each road direction is expected to have a complete control strategy of itself without the orthogonal requirement. It is suitable for an extensive, changing pattern or unpredictable traffic flow intersection. This method uses the traffic detectors to monitor the arrival vehicles counts at the intersection (queue length) with arrival time and uses the detail to control traffic. Its significant advantage over the time-based system is that it reduces the delay time to its lowest and increases the utility of the intersection. The disadvantage of this method is that it is expensive to deploy and manage. In the year 2010, Kesting et al, [KTH10] developed an enhanced intelligent driver model with a controlled acceleration and deceleration strategy to prevent a vehicle from stopping to a zero velocity while crossing the road intersection. The Adaptive Cruise Control (ACC) system is designed to automatically adjust a vehicle's speed without the help of the driver, thereby helping road vehicles maintain a safe following distance and stay within the specified speed limit. The ACC features of autonomous vehicles are relevant in the collective dynamics of mixed traffic flow, mainly when the AV follows an HV. [KTH10] proposed an intelligent driver model (IDM) of car-following using adaptive cruise control with desired velocity, acceleration, comfortable deceleration, and expected minimum time headway traffic behavioural parameters. This method eliminates the unrealistic behaviour of the IDM in a high-density traffic scenario by maintaining small gaps that are caused by lane changes. In investigating the influence of different ACC strategies on the intersection capacity, with a sensitivity of the order of 0.3, i.e. 1 per cent more ACC vehicles leading to an increase in the capacities by about 0.3 percent.

- **The semi-adaptive traffic signal control method:** This method partially applies the above two methods by combining parts of each method into a single control strategy. A typical example of it is the green light extension to allow bus to pass through, the early termination of red light signal to reduce bus waiting time, and changing the traffic light signals in real-time following the speed of vehicles. [BBEG14] proposed the Green Light Optimized Speed Advisory (GLOSA) systems, which optimised the vehicle speed to pass a traffic light just after it turned green, reducing CO 2 emissions, reduce fuel consumption, and also reduce the number of unnecessary stops at an intersection. By integrating transit signal priority within an adaptive traffic signal control system as proposed by [DRZ05] increased the on of vehicles at signalized intersections adaptive traffic signal control system. This traffic light control strategy could efficiently maximise the number of cars passing the intersection and prioritise vehicle type and lanes in assigning the right of way. This approach aims to minimise congestion and pollution being more event-driven in controlling vehicles. Its main advantage is that it reduces traffic delay and the traffic detectors' failure does not break down the traffic controlling process.

Traffic intersection is a road region where two or more road segments converge, diverge, meet or cross. Intersection management involves designing and implementing control strategies for smooth traffic flow: vehicles, cyclists, and pedestrians at road intersections. Intersections could be categorised subject to the number of the road system joining together, traffic controlling pattern, and road lane design. We have a three-way intersection or T-junction (involving a 3-road system), a four-way intersection or crossroads (involving a 4-road system), five or more ways intersections based on the number of road systems involved. Besides, the intersection is categorised based on the traffic controlling pattern into signalised and signalised intersections. Traffics are managed via communication channels between road users and road infrastructure. Human drivers' communication process uses the standard traffic light signals for indicating plan for turning signals, the horn, and headlight flashing hazard lights, brake lights. In addition to this list of traffic signal communications, some road users communicate through "informal" communication medium: gestures, body movement, facial expression, voice, tone of speech, and eye contact. Besides, there are some particular vehicle anticipatory behaviours and actions that predictable for other road users the intention of another road user by using gestures. This scenario occurs when a pedestrian approaching a crosswalk and if a vehicle is approaching the left lane (without using the turn signal), this shows an plan to swap lanes. All these psychological behaviours of the vehicle might be challenging to model in sustaining mix-traffic management. Traffic management is carried out via traffic signal lights.

Signalised intersection This is a signal control intersection with operational conditions to support traffic access within the intersection space. The signal control could be made of traffic lights or other vehicle communication devices. This is usually associated with intersections with heavy traffic or fast traffic, which are usually controlled by stoplights.

Unsignalised intersection These are uncontrolled intersection that has no traffic lights or traffic signs commonly found in rural areas. This type of intersection is usually controlled by traffic law does not specify who has the right to proceed first, but the law specifies who must give up or yield the left to another. The law is written in such a way to help prevent accidents. In traffic management, the right of way refers to a driver or a person who has the right to proceed first, while the law specifies who must give.

Fixed Time-Based Traffic Scheduling System Based on general knowledge, it has been established that a fixed time-based scheduling process is inefficient because of the idle time associated with it. In most cases, the intersection zone will be idle, while there are waiting vehicles from other lanes. An improvement on the fixed time traffic light schedule led to the adaptive scheduling which is based on the number of cars in the queues of each road segment. This number of cars in the queue is unpredictable, making the schedule impossible to match the proper time for a lane to the number of cars in the queue; this problem leads to associated traffic management delays. Because of this problem, there is idle time and delay associated with the time-based traffic scheduling system, and the event-driven traffic light management system allocates time-based on the vehicles count were introduced to address the problem

2.3 Traffic Flow Parameters

The traffic flow parameters are those numerical or measurable factors forming a set that defines a traffic flow system. The motion of independent vehicles and drivers, the interaction between them and the road infrastructure could be effectively analysed or represented using the traffic flow parameters. In dealing with this research, some basic traffic flow data analysis approach are used for representing and analysing the parameters performance of the model. The microscopic traffic flow parameter considered are as follows:

- Flow/Volume q(veh/h)
- Density k(veh/km)
- Speed v(km/h)

(where q = volume, v = speed and k = density). The above parameters could be measured for a section of the road over time by observing path interval (the distance against time).

Speed (denoted by 'v') This is the rate at which a vehicle moves per unit of time 't'. The vehicle speed is recorded instantly along the roadway, which could analyse other parameters like traffic performance. Speed variation (expressed as two or more separate speed variables of the standard deviations of vehicle speeds within the same road represented as the inconsistency of vehicle speed along a road segment) exist naturally among vehicles travelling simultaneously; this scenario can be represented by calculating the vehicles' average speed. [CIVC18] applied the variable speed Limits (VSL) or cooperative systems designed to provide speed harmonisation anticipating a smooth flow of traffic. This will give one a picture of the time mean speed (the arithmetic average speed of all vehicles travelling in a given road segment during a specified period or time) of the vehicle group. The vehicle mean speed v^m describes the average travelling speed of a vehicle at a time interval 'T'; this could be evaluated as Equation (2.1)

$$v^m = \frac{[\int_0^t \delta x]}{\delta t} \tag{2.1}$$

Distance (denoted by x) The distance covered in a traffic flow represents the space's length between two positions of a vehicle.

Distance Headway (denoted by s) 'S' is the distance in meters, between the leading vehicle front bumper and the following vehicle bumper in a vehicle platoon. S is reflected in Figure 2.1, the distance between the front bumper of CarB1 and the front bumper of CarB2. The safe distance complements distance headway, as it describes the lowest inter-vehicle gap that is needed to be maintained to avoid a collision.

Time Headway (designated by h) This is the estimate of the temporal gap between two vehicles, which inadvertently defines the interval of time when two following vehicles proceed along with the same position of inspection. From Figure 2.1,

$$h = t_2 - t_1 \tag{2.2}$$

From Figure 2.1, X represents the point of observation, N represents number of cars, while $t_i and t_f$ represents the initial vehicle and final vehicle time. Then we have $N(t_1, t_2, X)$ represent the total count of cars proceed with inspection point 'X'. For analysis purposes, the traffic distance headway is the time pressed on all following vehicles because of road safety, which is represented as the time that elapses between the leading vehicle's arrival and the following vehicle at the designated test point. However, distance apart in a traffic stream is the product of speed and distance headway. One can measure the vehicle distance headway by marking a point on the road and recording the time between when the first vehicle bumper passes across the point of observation and in addition documenting the time of at the same instance the second vehicle's bumper.

Traffic Count 'N': This is the number of vehicles that cross-over a given observation point along the road in a defined period. From the scenario in Figure 2.1, the traffic count is calculated by Equation (2.3) at a time instance t:

$$N(X_1, X_2, t) = 3 \tag{2.3}$$

Besides, traffic volume is usually converted directly to traffic flow (q), which takes the number of the vehicle that passes a specific observation point at a set out period.

Traffic Flow/Volume (denoted by q): This parameter could be quantified by the number of vehicle 'N' that pass or the average 'q^m' traffic flow over an observation point 'X' or time interval $[t_1, t_2]$. The traffic flow variable represents the vehicle distribution over time, typically given in terms of vehicles per hour. Equation (2.4) represent the traffic flow equation.

$$q^m(t_1, t_2, X) = \frac{N(t_1, t_2, X)}{t_2 - t_1} \tag{2.4}$$

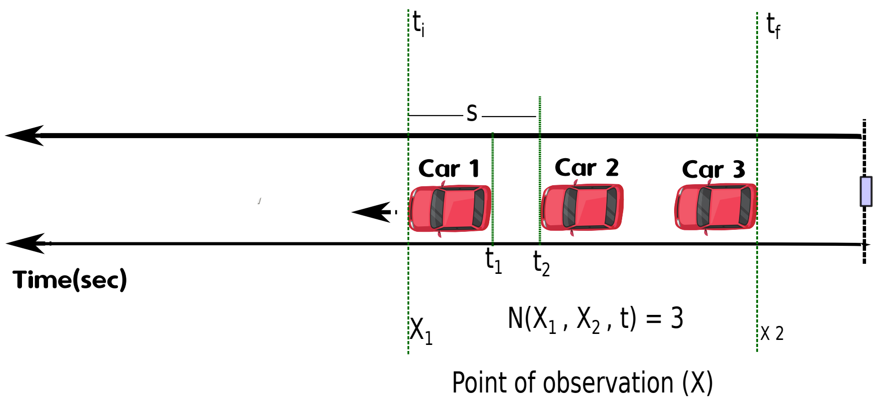


Figure 2.1: Traffic parameters

Where $N(t_1, t_2, X)$ the count of vehicles passing through 'X' during the observation interval $[t_1, t_2]$.

Traffic Density (denoted by k): This is the spatial distribution of the vehicles k^m or the traffic count occupying a given length of roadway. Typically, density is estimated in terms of an region covered by points of monitoring (X_1, X_2) vehicles per mile or vehicles per kilometre at a time 't' as represented in Equation (2.5).

$$k^m(X_1, X_2, t) = \frac{N(X_1, X_2, t)}{X_2 - X_1} \tag{2.5}$$

Where $N(X_1, X_2)$ is the number of vehicles between the observation point (X_1, X_2) at a time t. A scenario where the different vehicles observe a minimum gap between them is termed 'High Density.'

2.3.1 Traffic Flow Description Using Scenarios

The values for the traffic parameters in a city traffic system according to [CBC78] were analysed, and consideration was purely based on the real-life city traffic system involving a low and high-end traffic scenario. To provide better control on the mechanics of the experiments given the dimensions of the city road (outlined in the section, Mathematical Models) in the experiment, maximum speed and maximum acceleration/deceleration for cars were instituted:

- V_{max} = 10m/s (maximum velocity)
- $A_{max} = 10m/s^2$ (maximum acceleration)
- $D_{max} = -10m/s^2$ (maximum declaration)
- M_{Car} = 1200kg (mass of car)
- F_m = 2200N (moving force)
- F_b = 1200N (braking force)

The traffic state:

$$q = v.k \tag{2.6}$$

(where q = volume, v = speed and k = density)

$$v_k = v_f - \frac{v_f}{k_{max}} \cdot k = v_f(1 - \frac{k}{k_{max}}) \tag{2.7}$$

where:
v_f = Free traffic-flow speed
k_{max} = Maximum traffic density
from the 2 equations above, we have :

$$q_k = v_f \cdot (\frac{k - k^2}{k_{max}}) \tag{2.8}$$

However, traffic efficiency depends on the capacity of an intersection, while the traffic signal defines the traffic system's performance.

Intersection Capacity In analysing the intersection capacity in a mix traffic scenario, the following factors are considered:

1. The inter-vehicle space or distance observed by a vehicle in following another vehicle at a given speed is calculated based on the Section 2.1. The relationship between the intersection capacity (the number of the vehicle that passes through the intersection at a specified time), the speed of the vehicle (measured in metre per seconds) and the inter-vehicle space (in metres) can be represented thus:
$$c = \frac{v}{s} \tag{2.9}$$
2. Shortening of distance headway between AV
3. Platoon speed. In this scenario, the traffic volume increases with an increase in speed at a constant density.

A simple explanation of road capacity means the maximum traffic volume Equation (2.6)
Density
$$k = \frac{1}{vT_h + L} \tag{2.10}$$
Where T_h = time gap(temporal distance)
L = length of vehicle

HV capacity:
$$C_h = q_{max} = \frac{v}{vT_h + L} \tag{2.11}$$
Where q_{max} = maximum volume
v = speed
vT_h =total speed of HV
L = length of the intersection

AV capacity:
$$C_a = \frac{v}{vT_a + L} \tag{2.12}$$
Where the same variable definition as above applies.

Combined HV and AV: From this, one will be able o generate the expected impact of AV on HV when implemented on a graph with varying parameters.
$$\frac{C_a}{C_h} = \frac{vT_h + L}{vT_a + L} \tag{2.13}$$
For a traffic mix, the mix capacity C_{mix} could be represented as:
$$C_{mix} = \frac{v}{nvTa + (1-n)vT_h + Lk} \tag{2.14}$$
Where n represents the ratio of AV and HV mix.

An algorithm for traffic flow rule at a road intersection represented in 6. It calculates each car's position and distance to the intersection and, using their current speeds, calculates the time it would take to get to the reservation node and communicate them to the central collision control system.

2.4 Traffic Flow Theories

Traffic flow theories are the baseline foundation of Traffic Science and modelling, which provides the understanding of phenomena relating to individual vehicles' movement along the road with their interaction with neighbouring vehicles. The formulation of Greenshields' traffic theory in 1933 [GTDS34] gave rise to large-scale investigation in traffic modelling. Greenshields looked at the correlation between vehicle velocity and the mean/average gap between two successive vehicles. With the emergence of microscopic, macroscopic, and mesoscopic traffic flow modelling, Greenshield model was expanded to integrate other traffic parameters in the year 1950s. The measurement of traffic flow characteristics parameter considered are:

- q-v(volume/speed)
- q-k(volume/density)
- k-v(density/speed)

Below is a list of traffic flow parameters with a description of what they are doing in a traffic flow phenomenon. The expected impact of each parameter on traffic flow is explained using the diagram in Figure 2.1. These terms are used for describing or expressing traffic parameters in the concept of traffic flow. The traffic behaviour and the impact of the traffic parameters were their primary objectives. This model looked at three main underpinning traffic parameters of velocity, density, and volume (flow rate) of the vehicle. The correlations between velocity, density, and volume (flow rate) q is Equation (2.15):

$$q = k \cdot v \tag{2.15}$$

Then the traffic flow equation of cars conservation (assuming cars are not generated nor destroyed) and obeying the 0 initial conditions is given by Equation (2.16)

$$\frac{\Delta k}{\Delta t} + \frac{\Delta q}{\Delta k} . \frac{\Delta k}{\Delta x} = 0 \tag{2.16}$$

The fundamental characteristics of vehicle behaviour along the road are the basis for determining traffic performance concerning road vehicle volume and sustainability of different amount of traffic volume. The traffic flow theories define traffic and describe the relationship between drivers and their vehicles with the road infrastructures (made up of traffic signs, control devices) and intersection design. According to [AR18, LCD$^+$15] traffic modelling helps to acknowledge the advancement in the traffic system, formulate and calibrate models to precisely predict the traffic state and behaviour for efficient traffic control and management. [PBAB$^+$07, Pip53, Gip81], presents an overview of varying traffic modelling approaches based on the nature of the traffic: microscopic, macroscopic, and mesoscopic modelling methods. Most advanced investigation in traffic management combines different traffic type to form a hybrid model.

In macroscopic models, [MP90, Dag94], the traffic's characteristics behaviour represents traffic state, usually related to the average density and average speed for a specified period. Mesoscopic models engage both microscopic and macroscopic modelling approaches by using varying levels/degrees of detail to model traffic behaviour. This is realised by modelling vehicle mix with an accumulated estimation as macroscopic, and the driver's behaviour is modelled with specifics attributes of individual vehicles as obtains in the microscopic modelling procedure. Most real-time traffic optimisation controls assume a discrete event system for traffic arrivals and because it is assumed that the traffic flow will not change or vary with the trend of data of previous ones in a short time. It appears very difficult for traffic controllers to come up with a safe and efficient road traffic movement that will serve the test of time. The interconnection of different road paths makes intersections, where the decision and possibilities of vehicle collisions are critical without suitable traffic control measures [FTF$^+$15, FHKZ15].

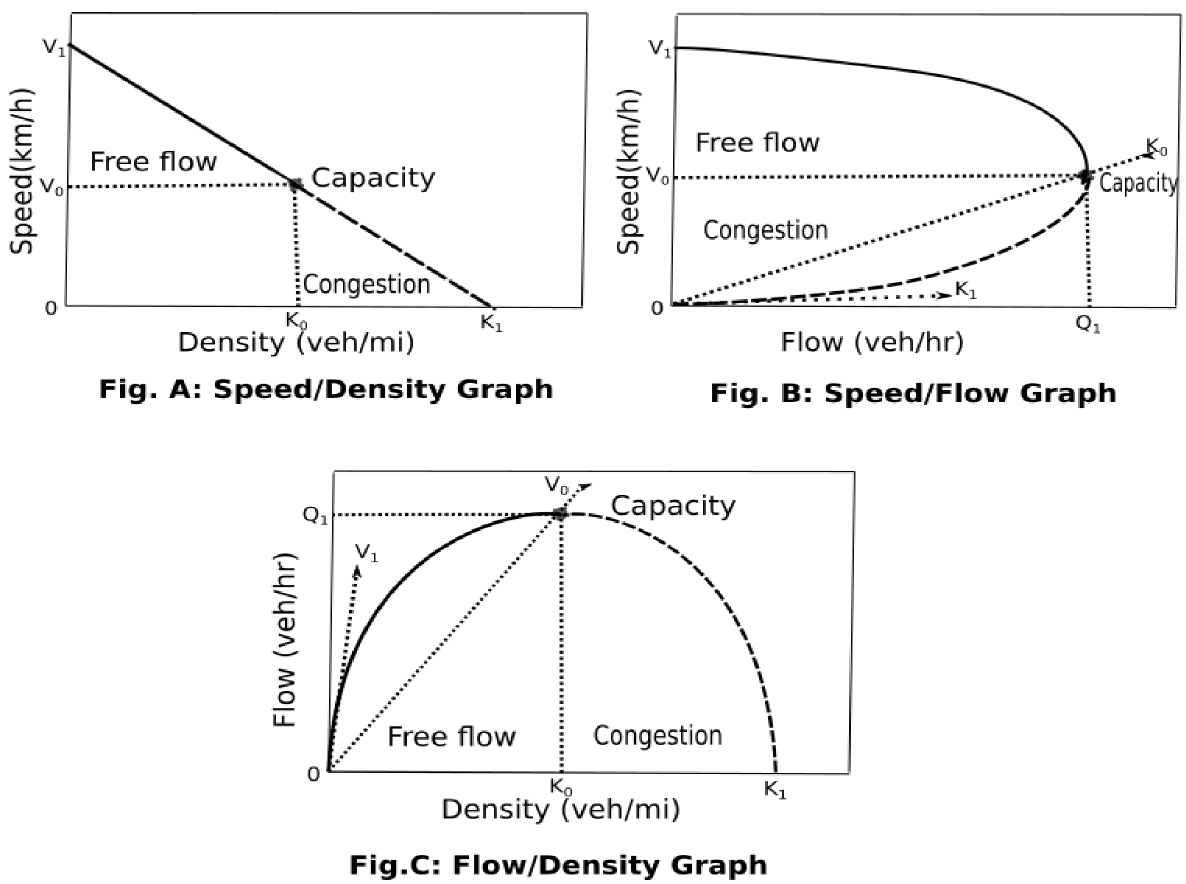


Figure 2.2: Fundamental traffic flow diagrams

Table 2.1: Traffic flow variables

Variable	Description	Unit
q	flow	vehicles per hour
p	No of vehicle	vehicles
q_m	optimal traffic flow	vehicle per hour
k_0	Optimal Traffic density	vehicles per mile
k_j	Critical density	Vehicles per kilometer

2.4.1 Traffic Flow Characteristics Fundamental Diagram

This is derived from the relationship between traffic flow's fundamental parameters (volume and density, speed and density, and speed and volume relationship curve). According to Greenshields' in [GBCM35, Ker13] large-scale investigation in traffic modelling started in 1933 with the conceptualisation of the renowned traffic theory of Figure 2.2 using the underpinning traffic parameters as reflected in the fundamental traffic flow diagram. The study deals with the correlation between the vehicle velocity 'v' and the average safe distance 'x' between two consecutive vehicles. The Greenshield model was later broadened to integrate other traffic variables such as density 'p', and flow 'q'. The traffic floe characteristics fundamental diagram can now be demonstrated in terms of a plot of flow-density, Figure 2.2 A, speed–density Figure 2.2 B and speed-flow Figure 2.2 C. Relationship in traffic variables could be described graphically resulting in the traffic characteristics fundamental diagrams Figure 2.2.

Traffic flow theory fundamental diagram guides in modelling an continuous traffic flow that estimates and describe the observed pattern in real traffic flow scenario.

Speed vs. Density: Under continuous traffic flow conditions, speed and density are linearly related and expressed mathematically and graphically in Figure 2.2.

$$q = v \cdot k, \ therefore, \ v = \frac{q}{k} \tag{2.17}$$

Where:
v = speed (mi/hr)
q = flow (veh/hr)
k = density (veh/mi)

Flow vs. Density The traffic flow is 0 at 0 density because there are no vehicles on the roadway, but the flow increases to some maximum flow conditions when density increases. At maximum density (traffic jam), traffic flow must be zero as the vehicles tend to line up end to end.

Flow vs. Speed Figure 2.2 is an illustration of the fundamental traffic flow curve, which describes the traffic behaviour using the traffic theory. where Table 2.1 defines the curve parameters:
From Figure 2.2, "A" represents the flow-density curve, the speed-density curve stand for "B" and "C" represents the speed-flow curve, respectively. Figure 2.2 describes the relationship between the traffic parameter using the essential traffic theory

In Figure 2.2, p_c, p_j, and p_m represent the optimum, congested and topmost density respectively, v_f and v_m speak for the free-flow and speed max respectively, while q_m represents the max traffic flow. However, the traffic density increases with a rise in traffic flow rate but drops with max road capacity (optimum density).

A reduction in the traffic flow and speed Figure 2.2 C, lead to an increase in density after jam density, until the flow and speed, = '0' at jam density p_j. Following this scenario is the development of other traffic flow models such as microscopic, macroscopic, and mesoscopic in the 1950s. The traffic flow modelling are designed as strategies for managing, controlling and predict the state of traffic in a road intersection. This review is performed under the following sections, traffic flow models, mix-traffic management strategies, and traffic performance estimation, and prediction methods.

The work of [Fri16] presented the relationship between traffic density (count of vehicles / distance) and the mean speed in investigation data and detailing the initial traffic flow modelling efforts, which is a guide for all modelling traffic and traffic networks. In Figure 2.2, listed below is the definition of the variables used:
q = the traffic volume (count of vehicles that passes a point of reference or observation at a specified time),
u = the space- mean velocity at the reference point
k = Traffic density at the reference point (caount of vehicles / lenght).
From Figure 2.2, an equation that represents the relationship between traffic density, and speeds equation could be represented as:

$$q = u \cdot k \tag{2.18}$$

eq. (2.18) represents the effect of the number of vehicles on traffic flow and traffic management strategies. Looking at the graph, one will observe that the traffic flow pattern changes as the number of participating vehicles increases. Based on existing research, whether theoretically or experimentally derived, microscopic, or macroscopic traffic flow fundamentals Section 2.4.1 corresponds to the above diagram in Figure 2.2. Figure 2.2 explains the traffic flow theory concerning the traffic flow parameters of speed, flow, and congestion. It presents the standard spatiotemporal experimental attributes of traffic behaviour that vary qualitatively for different traffic scenarios, measured during traffic observations. From Figure 2.2 "A", traffic congestion decreases with a decrease in the count of vehicles or road capacity. While in "B," the optimum traffic capacity is maintained when the density and speed are at equilibrium. Moreover, "C" the speed increases with a decrease in capacity.

Flow-density curve: This deals with the correlation between traffic density and the associated flow, which varies with location and time. The flow-density relation has the following characteristics:

- When the traffic density is zero, there is no vehicle on the road, and therefore the traffic flow rate will also be zero.
- The number of the vehicle is directly proportional to the density rate and flow rate. An increases in density and flow rate, increases vehicles count .
- At maximum density (traffic jam stage), the traffic flow is zero, as vehicles are cant move.

Speed-density curve The speed will be maximum at a free-flow traffic condition (zero density), but the speed will be zero while the density is maximum. From fig. 2.2 as vehicles are expected to flow at their desired speed, the traffic density 'B' is linear curve.The vehicle speed is '0' at maximum density.

Speed flow curve The relationship between traffic speed and flow could be explained using traffic conditions thus; traffic density is zero for non-vehicles flow or at maximum traffic density (jam), so no vehicle can move. The traffic speed is '0' and free-flow being maintain at a maximum traffic flow.

Optimal velocity The optimal velocity model is applied to control each velocity with the average velocity of the vehicle platoon. According to the work of Bando et al in [BHN+95], the optimal velocity model of 1995 came about from supposition that each vehicle driver maintains an optimal velocity in accordance with the distance headway and the variance in velocity between a reference vehicle and the preceding vehicle. Besides, the acceleration rate / vehicle deceleration rate is the mathematical representation of the following variables: the distance headway, the speed of the preceding vehicle, and an aggressive factor which represents the driver's behaviour or style of driving.

2.5 Introduction to Intelligent Transportation System

An Intelligent Traffic System (ITS) applications which are classified into three categories: mobility, safety and environmental, combines traffic control strategies with communication technologies for a safe, seamless and optimal traffic flow movement. Considering only vehicles in Figure 2.3, for an intelligent transportation system where all the traffic participants (vehicles, road infrastructure, traffic control signs like the stop lines, traffic light, and vehicle trajectories) are smart/intelligent and can communicate seamlessly with one another. The ITS feature provides a communication platform for all the road users, ranging from communication among traffics, communications between traffic and road infrastructure, travellers information, and improved traffic safety. The driving experience, congestion reduction, improvement in traffic efficiency, and reduction of accident to pollution reduction are the primary measurement parameters for efficient traffic models. An early approach to automation in vehicles started with the Automated Highway System (AHS) [HV00, HV00, LTSH04, VDEG16, AGS16]. Focus is on intersection capacity enhancement and safety of road traffic system. The advent of automated vehicles led to the birth of vehicle-to-vehicle and vehicle-to-infrastructure communication, which inadvertently led to road intersection settings without traffic lights but has smooth and efficient flows of traffic with reasonable safety measures. Automated vehicles (AVs) have shown the capacity to improve safety and efficiency with its environmental awareness by reducing and mitigating traffic accidents in real-time with a seamless flow of traffic and the right safety measures [SEL12, RTM17, LH19, ADLB19].

An intelligent transportation system is an economically optimised solution to general traffic problems. ITS employs technologies to reduce congestion by monitoring traffic flows performance using sensors, cameras, or analysing mobile phone data and rerouting traffic through navigation devices as the need arises. The advent of Intelligent Transportation Systems (ITS) in the last decades has resulted in a dramatic change in traffic management. ITS has changed the approach to traffic planning, monitoring, managing/control, and throughput enhancement. Intelligent transport systems (ITS) are compatible with modern vehicles as it makes use of state of the art communications device (electronics, navigation), and data analysis technologies to enhance the throughput of the existing road traffic system. The ITS aims to improve traffic in the following aspect: safety, throughput, comfort, fuel reduction, and decrease other unfavourable environmental effects. Some of the ITS examples are Advanced Traveller Information Systems (ATIS), which provide travelers with real-time information, and Advanced Traffic Management Systems (ATMS) collects real-time traffic information like the one used in SAVAV. The ITS will drive the integration process of AVs and HVs. The ITS applications include start city traffic systems, advanced traffic management systems, vehicle navigation equipment(satnav), advanced traveler information systems, vehicle cruise control systems, and platooning. The popularity of autonomous vehicles is increasing, and this increase is being driven by intelligent transport systems, which will benefit HVs in a mixed-traffic environment by better throughput and safety of the traffic system. City traffic congestion has been overgrowing, the universal mobility pressure and enhanced safety are on the rise while constructing new roads is constrained by meagre public funds and deep environmental concerns. To improve the quality of service in a mixed-vehicle environment without constructing additional

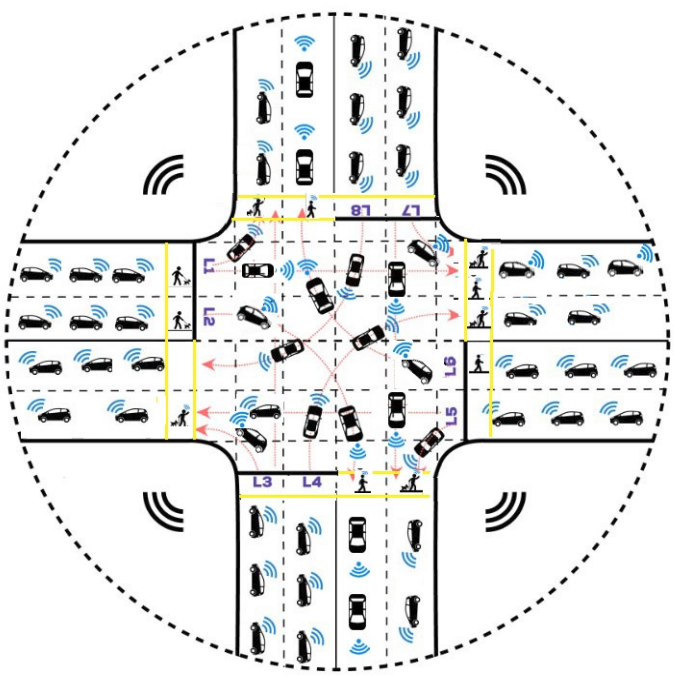


Figure 2.3: Intelligent Transportation Involving Traffics, Pedestrians and animals

capacity separately for AV and HV, respectively, robust traffic control and traveller services are essential to enhance the efficiency of the existing road system.

Intelligent Transportation System (ITS) requires specific traffic situation and behaviour for productive traffic observation and management. Traffic conditions are usually evaluated from traffic characteristics assessment utilising several methods, which can typically be cleaved into data-driven methods, model-based methods, or both. A summary of the distinct traffic flow modelling methodologies includes microscopic, macroscopic, and mesoscopic. Microscopic traffic models give a detailed, high-level account of each vehicle's motion. Condition of traffic are represented using and aggregated behaviour for macroscopic traffic models, generally concerning mean speed and mean density over a specified period. Mesoscopic models employ microscopic and macroscopic approaches by utilising varying levels/degrees of detail to model traffic behaviour. Some locations are modelled with aggregated measurements as macroscopic, and the remaining locations are modelled down to the details of individual vehicles as is done in the case of microscopic. In most cases, modelling traffics at the macroscopic levels is adequate to generate a sustainable mix-traffic model; they proffered the alternatives for most experimental purposes such as traffic control/management, road intersection nodes reservation, and road infrastructure alternatives.

2.5.1 Autonomous Vehicles vs Human-driven Vehicles

An autonomous vehicle is a vehicle that can sense and observe its surrounding environment, takes an informed decision based on its target/destination and the surrounding environment for its safety [LVZP15]. An autonomous vehicle does not need direct human intervention to achieve its movement objectives when in motion. Autonomous cars are intelligent vehicles [PCD14, LHW12] that control themselves with electronics used to combine four kinds of ultrasonic sensors, lidar, sensors-video cameras, and radars. Some of the advantages of autonomous vehicles are the significant increase in road safety, which reduces traffic deaths, harmful emissions, reduces travel time, and fuel economy. Besides, autonomous vehicles eliminate stop-and-go waves of traffic and an increase in lane capacity. The autonomous vehicle communication features create a platform for seamless and highly safe traffic management approaches. The actual reality of autonomous vehicles is yet to appear after years of confidence from the information technology and car technology industries. In 2015, BMW launched a self-driving prototype car along the autobahn, with the promise that by 2020, entirely unaided self-driving vehicles would come to stay in real-life but, unfortunately, in the last month of 2020, this dream has not come to reality because of the challenges associated with the AV integration.

In 2019, Musk claimed a one million global fleet of Teslas self-driving cars 2020 would be in place. These robotics taxies like cars will earn their owner money while they slept or were on holiday. This projection by Musk has not been realised as at today. Beside, Waymo in 2018, assert that its fleet of 20,000 Jaguar I-Pace electric cars would utter up to one million autonomous per day soon. However, it did not felt very confident that December 2021 is feasible for full fleets of autonomous vehicles which can take us to the shops or workplace from home and extended the self-drive to cover everyday activities. This full emergence of a fully autonomous vehicle on the road is hindered by the following challenges: useful sensors for seeing the environment around them and detecting objects such as pedestrians, other vehicles, and road signs. The problem surrounding the current human-driven vehicle road system and its co-existence with autonomous vehicles could be solved with machine learning applications for its safety behaviour. Besides the above challenges, we still have the challenges associated with autonomous vehicles' regulation and social acceptability.

The human drivers' behaviour is unpredictable and associated with a delay in making a driving decision. Autonomous vehicles' behavior is in the sink with intelligent transportation systems where vehicles sense the environment via sensors and take the best decision in real-time to avoid a collision. However, according to [AA14], the road's capacity can be increased with the increase of the cooperation level between vehicles when their behaviours are homogeneous, but this feature could be extended to a heterogeneous traffic system. This makes the study of traffic mix more complex considering the underlining difference in the behaviour of the two cars category of vehicles. Moreover, the simulation results from the study by [HR99] show that from mixing automated (AVs) and human-driven (or manually-controlled vehicles), the road capacity can be increased by 2.5 times when the percentage of automated vehicles is more than 70 percent.

2.5.2 Autonomous Vehicle Communication System

There exist communication among autonomous vehicles (vehicle-2-vehicle) and between autonomous vehicles and the road infrastructure (vehicle-2-infrastructure). The autonomous vehicle accurately ascertains its position and plans and follows a route using global positioning system (GPS) facilities. GPS technology is a real-time navigation device that helps minimise the count of random crossovers on the road intersection; it makes excellent decisive steps in improving road safety at the cross collision point of the road intersection. The GPS helps manage the unpredictable driving behaviours of human-driven vehicles during emergencies, besides improving the road intersection capacity. GPS enhances the performance of the intelligent transportation system in the following ways

- Automated Vehicle Node Reservation (AVR): Uses the real-time traffic information to assign reservation nodes dynamically to vehicles based on traffic demand. This technique also serves as a safety and high utilisation approach to intersection management when vehicles are dynamically assigned to transit the intersection simultaneously without conflict. The GPS updates the vehicle's position at any time step, route, and speed, which is used in taking appropriate policy control measures.
- Real-time Vehicle Position (RVP): The RVP records all the vehicle's position at every time step and updates the intersection control unit. With the GPS accuracy of centimeters, the GPS device effectively updates the real-time vehicle status: vehicle position (X and Y coordinates) procured from GPS receiver installed in the autonomous vehicles.
- Platoon monitoring: These features help the GPD device take the vehicle group's average parameter in the control process. This approach enhances the control process and increases the intersection capacity.

Wireless Access in Vehicular Environment (WAVE) In wireless communication, information transfer between vehicles and infrastructures occurs on a wireless platform using the free IEEE 802.11p protocol which is a Dedicated Short Range Communications (DSRC). Though the GPS protocol is free but is different from other mobile network which are primarily designed to replace cables. Examples of other free frequencies that powers GSM, Bluetooth and WiFi which operates at frequency of 900Mhz, 2.4Ghz and the latest 5Ghz. For safety reasons, most countries have allocated different frequencies solely used for vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communications. The interaction between vehicles and infrastructure supports a wide range of mobility and safety measures. In this scenario, the only autonomous vehicle can effectively on its communicate with the road infrastructure.

Autonomous Intersection Management The emergence of an autonomous vehicle and driving system lead to the advent of autonomous road intersections system. An autonomous intersection is a "node-based" traffic intersection system that assigns specific nodes to traffic. The node reservation and assignment are the systems of operations associated with the air traffic control systems at airports used to coordinate aircraft landing. For an intersection to be autonomous, it must be equipped with sensors, road-side communication units, and other intelligent transportation system devices.

The systematic use of the existing road infrastructure by novel intersection control and management is a feasible solution for the cities where road expansion and additional construction are deemed challenging. Conventional vehicles used a traffic light signal system, while autonomous vehicles access road facilities via wireless communication platforms: vehicle-vehicle and vehicle-infrastructure communication. Human-driven vehicles only involve driver-to-road infrastructure communication (one-way communication). The deployment of new technologies is not usually automatic. New ones will gradually replace the current technology; integrating autonomous vehicle movement parameters with that of the human-driven vehicle to midwife the smooth transition to a fully automated or smart city is necessary.

Literature [HHM+17, PSB18, BNP19] suggests that autonomous vehicles have a very high prospect to increase efficiency of traffic by reducing traffic congestion through the reduction in the vehicle time headway of traffic, improving the efficiency of intersection capacity, enhancing the safety margins in a car-following/platoon model, and improving the road users welfare as a whole. Currently, research in autonomous vehicles and their integration process has been in researchers' eye for a while because of the increasing population with already existing traffic congestion challenges, urbanisation, and the enormous advantages of autonomous vehicles. The theoretical background of intelligent transportation systems and the analysis of state of art in related works are presented with a brief overview of intelligent transportation systems and traffic management strategies. Traffic flow theories followed this as it relates to different traffic modelling approaches, namely: microscopic, macroscopic, and mesoscopic traffic flow models. These followed a matrix of categorisation of the different traffic management schemes with their pros and cons; this can be seen in Tables 2.3 and 2.4. The traffic management parameters shown in Figure 2.2 involve a set of applications and management tools to enhance the road transportation systems' all-inclusive traffic control effectiveness and security.

2.5.3 History of Intelligent Transportation

From general knowledge, errors from human drivers are the prime source of road accidents. The primary idea of an intelligent transportation system suggests enhancing error-prone humans drivers with technology-driven-vehicles. In the years (2001–2004), the European Union (EU) funded the development of ITS project KAREN (Keystone Architecture Required for European Networks) [PHJOZ15], which was supported by the Cooperative Systems based on the V2X communications framework. There exist distinct ITS architectures designed in the UK, covering Scottish transport, while FRAME Architecture was developed for transport for London with future integration ITS deployment attributes.

The successful emergence of intelligent transport is supported by critical factors like road infrastructure and vehicle design. The European Union 2010/40/EU [B+17], on July 7, 2010, adopted putting together all the transport networks within the EU countries to clearly show that it is time for transportation systems to rely less on material things and more on intelligence transport. This resolution focuses on the addition of traffic safety intelligence in managing speed and the interconnection of different ITS types from all the E.U. This approach confirms intelligent transportation as a means of increasing road capacity and a reduction in traveling time. ITS is designed to improve the transportation system, and by so doing, the improvement will have a drastic positive impact on the economy. The ITS will also affect the quality of life alongside reducing environmental problems like pollution to a reasonable level. The trend in implementing Intelligent Transport Systems in most parts of the world is being affected by the lack of infrastructure, leading to the unequal development of the transportation systems.

Smart Traffic Management: This involves a traffic management system that is centrally supervised with traffic signals and sensors controlling traffic flow in response to a request through the city. A smart traffic system is an event-driven traffic manager that prioritises traffic in response to request or queue length in real-time.

Vehicle Platooning: A platoon involves a group of vehicles that can move close to one another, one behind the other, and safely, maintaining a safe distance and communicates with each other safely at maximum speed. For platoon scenario, all following vehicles respond to the leading vehicle, which controls the speed and direction of the platoon's vehicle movement. A lead vehicle is followed by several other vehicles that closely match their speed and manoeuvres to the lead vehicle. Fundamentally, the ideas for vehicle platoons started with some mechanical coupling, just like in train coaches. The vehicles speed and steering are automatically controlled with the aid of computer. All vehicles in the platoon are linked to each other by an electronic "drawbar". This electronic coupling of vehicles makes vehicles organise themselves into platoons and self-driven a meter apart to minimise air resistance. The platoon distance headway usually act as the effective braking distance. Automated convoy driving (Platooning) helps control vehicles more efficiently with performance improvement, increases roads' capacity, provides a more steady-state traffic flow, and saves fuel consumption. The reverse concertina effect is another advantage associated with the vehicle platoon where each driver waits to see the vehicle in the front move before accelerating.

Each participating vehicle in traffic flow has a goal of moving from its start to destination. There exist conflicts in the direction of movement of traffic at the road intersection. For an efficient and safe flow of traffic exist, the traffic management system must be fair enough to assign all participating vehicles right of way. As a reason for the application or rationally put in traffic control strategies, it is imperative to understand each traffic participant's behaviour. Besides, effective traffic management starts at the microscopic level, which involves analysing a sole vehicle-driver unit. The dynamic parameters of the traffic models constitute resources like the vehicle position and velocity. With a good understanding of microscopic traffic behaviour, one can quickly develop a macroscopic traffic flow model involving stream vehicle flow. Vehicle Platoon has many advantages ranging from reduction in fuel consumption, does not need drivers, reduction in accidents, an increase in road capacity, and deliver increased stability in traffic flow[PVDWN13, KC11]. The traffic intersection reference model in Table 2.2 involves a conceptual structure comprising clearly defined concepts and set links for communication between players in the road traffic management system in the form of a platoon.

2.6 Transition from Human-Driven to Autonomous Vehicle Technology

The autonomous vehicles' emergence rate appears to increase with a glaring impact on human drivers-vehicle interaction. Modern vehicles are already designed with some autonomous attributes such as adaptive cruise and electronic stability control systems. Vehicle autonomy is a stagewise process with a baseline from the human-driving system and subsequent enhancement to address the human-driving system's challenges. According to [TK17, SM17],the vehicle automation process has been divided into five levels based on their autonomy features. The levels of vehicle autonomy are a product of a gradual enhancement in the human-driving system's automation to a fully autonomous vehicle driving system. The vehicle autonomy stages are as follows:

Level 0 – No Automation: This stage is the traditional driving system where a human being is responsible for the absolute vehicle control. At this level, there is 100 % human control for the vehicle. Human drivers handle the vehicle's motion, steering control, and safety intervention systems.

Level 1 – Driver Assistance: Here, the human driver is being assisted with the task of controlling the speed of each one of the vehicle's via cruise control, position, and through lane guidance. The driver must be active and observe roads and vehicles every instance of time and take control when the need arises. The driver controls the vehicle steering wheel and the brake/throttle pedals. At this level of automation, the steering and pedals control of the vehicle is done by the computer. For example, the vehicle adaptive cruise control and parking assistant system belong to this level of automation.

Level 2 – partial self-driving: The computer is designed to control the vehicle's speed and lane position in some defined or secluded environment at this automation level. The driver may disengage off the steering control and pedals at this level but is expected to observe navigation to assist in the control if the need arises. The control of the vehicle at this level is fully automated in a particular environment. This level provides the driver with options to intervene if necessary in controlling both pedals and the steering wheel at the same time automatically.

Level 3 – Limited Self-Driving: This level is the beginning of the complete disengagement to complete control and fully independent control of vehicles in some secluded environment, it involves the full monitoring of the traffics and road and triggers for drivers assistance, and the need arise. When a vehicle is in self-control mode, the driver does not need to monitor vehicle road and traffic navigation but must be ready to take control when required. This stage is associated with the risk of safety liability for incidence. At this critical automation level, the vehicle has a specific model that can take driving charge in certain conditions, but the driver must take the control back when the system requests it. The driver's attention is highly needed as the vehicle on its own can take lane changes and event response decisions, and it uses the human driver as a backup in a high-risk environment.

Level 4 – Full Self-Driving under certain conditions: This level involves full vehicle control with or without a human driver in certain conditions or environments. An example of this condition is urban ride-sharing. The driver's role, if the presence is to provide the destination of the vehicle. This level is safer than level 3 as the vehicle has full control of itself under a suitable environment without any request for driver's intervention. The vehicle takes care of its safety challenges at this level.

Level 5 – Full Self-Driving Under All Conditions: This is the destination of vehicle automation where vehicles operates absolutely on its own. At this level, human intervention is not needed as the vehicle drives its self. This is a full automation stage without any human intervention. The level of full vehicle autonomy goes with the state of the art environment control protocols, advanced detection device, vision and uses real-time obstacle position measurements for guidance and safety purposes.

2.6.1 Intersection Capacity Analysis

According to [AA16] Intersection capacity is mostly analysed either by the regression or gap-acceptance technique. The regression approach involves a comparison of two distinct states: prior to and after study. Regression investigation design a stable external scenario incorporating the facts with the effect of the object in analysing the dependent and independent variables. [ZB13]. It is most challenging to design a scenario to reflect the fundamental dynamic traffic system characteristics. The gap-acceptance method appears to be the commonly used strategy intersection capacity manual in most countries. Nevertheless, in preliminary research in traffic mix-traffic management, the gap-acceptance approach has a few drawbacks because it is not compatible with a heterogeneous pattern behavioural traffic system. The gap-acceptance theory fails when a mixed behaviour of aggressive and gentle cars co-exist.

Table 2.2: Traffic intersection reference model

Platform	Infrastructure	Participant behaviour
Road space	Flow Model	Physical movement rules
Intersection space	Control strategy/rule of engagement	Routing rule

With the emergence of autonomous vehicles, quantifying and describing traffic flow at a different level and perspective emerges. This support the wide range of investigation in the field of mixed-traffic behaviour. This area includes the safety of mixed traffic [Lit17], the impact of mixed traffic on the motorway[TBM08].

Traffic dynamics modelling has two main components:

- Road infrastructure modelling with vehicle occupancy: This involves the modelling of the road intersection dimension based on the vehicle's number that could access the intersection at a given time. In this case, the parameter needed in calculating the intersection capacity is the size of the vehicle and the road size.
- Vehicle behaviour modelling involves how vehicle moves and its relationships with other vehicles sharing the road. The consideration for the behaviour is based on the parameters that are being driven by vehicle behaviour. Such a parameter includes: the sopping distance, distance headway, safe distance.

Intersection capacity could be analysed by grouping the model parameters into a domain of (infrastructure vs. behaviour) and by the spatial degree of abstraction (available usable space vs intersection type). Table 2.2 describes the different levels involved in traffic management and the parameters involved in managing each level.

2.7 Traffic Models and Simulations

Primarily, the two broad divisions of traffic modelling types are macroscopic and macroscopic traffic models. While the microscopic model describes an individual vehicle's characteristics, the macroscopic describes the characteristics of a group of traffic in a traffic flow system. Both modelling approaches are in research for traffic phenomena. Modelling of traffic flow describes, simulates, predicts, and show the relationship between traffics and traffic flow parameters. Traffic simulation tools are used to plan and forecast or predict traffic behaviour based on simulated or real traffic data. Traffic simulation and mathematical modelling address the real-world traffic system for road users and infrastructures. Traffic modelling fundamentally is based on the theoretical foundations of physics theories like the kinematic and dynamic of car physics. Besides, traffic modelling involves applying computer software to simulate a traffic system to better help plan, design, and operate a transportation system for efficiency and safety reasons.

An survey of various traffic flow modelling procedures are given in [HB01, PBAB+07]. These modelling approaches comprised of microscopic, macroscopic, and mesoscopic methods. Microscopic traffic models [HB01, PBAB+07, Pip53, Gip81] describe the vehicle's navigational behavioural characteristics with a high level of detail. There exist generic traffic simulation software that was considered in this project for the validation process. Traffic modelling involves three significant stages based on vehicle count and level of details. They include:

SUMO (Simulation of Urban Mobility) SUMO [PCS16, KPM18, LBBW+18] was developed in 2000 as an open-source tool to support the traffic research community with the design, implementation, testing, and evaluation of new traffic control algorithms. SUMO is a free and purely microscopic, space-time discrete, and continuous road traffic simulation software with each vehicle modelled explicitly with defined routes and goals or destination. It is a suite plan to drive heavy road traffic networks, creating platforms for the modelling of inter-modal traffic systems for all road users, including vehicles of different types, road systems, and pedestrians. SUMO comes with preloaded applications used to import/prepare road networks scenario and traffic demand data for its use. SUMO platform may require some input variables such as road network, vehicle demands with routes, traffic infrastructures like a traffic light, stop points, vehicle speed, and any other variable that may be deemed necessary. The simulation of vehicle activity is implemented using the queue method, with one vehicle moving between those queues. Besides, SUMO is built with robust supporting tools that control traffic visualisation, route finding, emission calculation, and network import. In addition, SUMO supports a custom model integrated model and provides an application programming interface (APIs) to control the simulation remotely.

SimTram This is time-discrete traffic simulation software extension of SUMO, which is an open-source. Transportation Lab developed SUMO by adopting a SUMO version (version 0.12) to underpin less lane disciplined movement of traffic [PCS16]. SimTram divides lane width into multiple strips and assigns road space to vehicles in terms of a number of strips, thereby permitting multiple small vehicles to share the lane width. The SiMTraM is compatible with both homogeneous and heterogeneous behavioural models of traffic. The traffic behaviour model includes hybrid vehicle type, non-lane-based movement, and a discrete gradual lane changing behaviour. The SimTram used the traditional car-following model to access vehicle trajectory. [PCS16] state developed a one-lane based longitudinal movement model of car used to access left and right lane changing behaviours of a vehicle. Besides, SiMTraM defines and uses its road network description (road, route, and lane), converted from an existing data set into a SUMO-format.

2.7.1 Microscopic Traffic Models

Microscopic traffic flow models simulate vehicular traffic dynamics regarding a single vehicle and its driver's behaviour. The microscopic model primarily looks at the physical abilities of a vehicle's movement, and the driver is controlling behaviour. Microscopic models represent the vehicle properties of position and velocity, which analyses traffic flow by modelling the driver road interactions interaction, driver to driver interaction all within a traffic stream. According to [TBAD+04, CLRZ04], the microscopic model approach helps in analysing the interaction between a drivers on the shared road and can also be applied to analyse a single driver on the different features of a road.

At the microscopic level, traffic models are grouped into two broad categories: Cellular-automata and Car-following models. The Car-following model is designed to ensure that vehicles will maintain the lowest intervehicle gaps between the leading and the following vehicle. The first approach to the car following the model proposed by [Pip53] presumed that the speed of vehicles would change for it to maintain a minimum safe distance to the ones preceding it. The proposal by [Pip53] is improved by Gipps in [Gip81] with the introduction of acceleration and deceleration process, which models the driver ability to maintain a safe distance from the leading vehicle. Newell(2002) investigation direction in car-following modelling introduced a velocity model based on time gaps and acceleration based on the relative speed of the two reference cars (leading and following vehicles). The speed difference of the vehicles proportional to his deviation from an equilibrium curve with relaxation time. [SZ14] proposed a comprehensive review of the car-following model, which integrates and enhanced human driver's performance.

2.7.2 Macroscopic Traffic Models

The macroscopic traffic models present the traffic systems' aggregated or mean attributes rather than vehicle's specific properties. It uses the mean value of traffic flow parameters such as mean speed and average density within an observation point to access traffic behaviour. From first-order 'kinematic wave theory' (KWT), the macroscopic model applies partial differential equations to represent traffic flow subject to vehicle occupancy. In this case of the macroscopic traffic system, traffic may be viewed as a continuous flow system, and its characteristics demonstrate the corresponding behaviour and the physical characteristics of the imaging fluid. The macroscopic traffic models involve combining microscopic models of traffic with characteristics of single-entity level to be used in comparing the system-level behaviour [Dag95b, Leb05, Pap98]. The macroscopic traffic flow model formulates traffic relationships using high-level variables:volume, density, and mean speed of a traffic group. In analysing this scenario, traffic flow is observed at two or more fixed points in the road system, with estimation recorded at the time of traffic occurrence as defined earlier. For instance, is the vehicle arrival and departure time at a fixed point. This observation is made at a different time interval with different vehicle positions to analyse the traffic behaviour and then correctly predict the behaiour. The macroscopic traffic flow modelling is based on the assumption of comparing traffic flow streams with flood movements in long rivers [Dag95b]. Macroscopic modelling is categorised based on the kind of traffic: homogeneous or heterogeneous, and more much concerning the sequence of the mathematical model, which deals with the model parameters.

Macroscopic traffic models use traffic flow mean speed and mean density (aggregated data) of observation points to represent traffic behaviour. Lighthill and Whitham in [LW55] in 1955 independently proposed the first macroscopic model, which was named after him, whose effort was followed by Richards[Ric56] in the following year. The Lighthill-Whitham-Richards (LWR) model is developed from first-order kinematic wave theory and used partial differential equations in describing traffic flow dynamics. In 1971, Payne proposed a macroscopic model that addressed infinite deceleration and acceleration caused by instant speed after a change in density assumption.

$$\frac{\delta k}{\delta t} + \frac{\delta q}{\delta s} = 0 \tag{2.19}$$

Where;
k = density (veh/km),
q = volume (veh/hr),
s = distance (in km),
t = time (in hrs)

A drawback associated with this Peyne is the inability to model the driver's behaviour, speed choice, and distance headway accurately. Besides, for accurate modelling of the intersection reservation node and the combination of different control parameters, the macroscopic model is ideal for mixed traffic management.

The Node Transmission and Stochastic Compositional models(CTM and SCM) are the most adapted macroscopic models. The CTM is proposed by Daganzo in [Dag94, Dag95a] which divides roads into nodes with 3-distinct states:

1. $N_i(t)$, = Highest vehicle count permitted in node i at time t,
2. $Q_i(t)$, = Available vehicle count that can flow into a node i at time t, and
3. $n_i(t)$, = Actual number of vehicles in node i at time t.

The inflow for the first node and outflow for the last node. Traffic are generated $y_i(t)$ from node $i-1$ to i within a discrete-time step. δt is the lowest of three traffic variables, $n_i - 1(t)$, the vehicle counts in the previous node $i-1$ at time t, $Q_i(t)$ the highest vehicle counts that can flow into a node i at time t, and the available space in node i at time t denoted by $N_i(t) - n_i(t)$. according to the CTM car-following model [BM99].

The stochastic compositional model [BM06] involves traffic intersection with road lanes corresponding to road segment, all sharing the intersection space, which is made up of connected short segments (nodes). Each segment of the compositional model is a discrete-time stochastic system with a set of node reservation protocols for the vehicle. The SCM model increased the Daganzo node transmission model [Dag94] by describing random sending and receiving function variables and setting out the mean speed dynamics in each node. It formulates a stochastic traffic equation that describes the macroscopic traffic attributes of each node and its relationship with the closest nodes. Its edge over the CTM is its ability to simulate an extensive road network by composing many links.

2.7.3 Mesoscopic Traffic Models

The mesoscopic traffic flow models came about to bridge the gap between the microscopic macroscopic traffic models. The microscopic model describes individual vehicles' behaviour, while the macroscopic traffic models describe the flow of traffics. The mesoscopic model describes the individual vehicle entities with a detail of its high-level attributes, but not their interactions, and is most suitable for modelling traffic networks. Mesoscopic vehicle models simulate queue methods, while a queue is a summation of individual vehicles. However, when the vehicle is transiting an intersection, traffic flow results in a safe velocity is given by:

$$v_s = \frac{d_s}{t_s} \tag{2.20}$$

Where
d_s = Safe distance
t_s = Safe time headway.

The mesoscopic traffic flow models method uses a likelihood distribution basis to represent vehicles' behaviour in aggregated expression akin to macroscopic models and describe the individual traffic behaviour rule using microscopic properties. The kinetic gas model [HB01, PA60] is an excellent example of a mesoscopic flow model which is most. The mesoscopic model is the most compliment applications that need capturing group interaction details like the microscopic. The Federal Highway Administration (FHWA) has adopted are the DynaMIT [BABB$^+$01] and DYNASMART [JMH94] as a good mesoscopic traffic models.

The traffic flow model is derived from the traffic flow equations of microscopic, macroscopic and mesoscopic traffic flow. Besides, extending the microscopic traffic flow in Equations (2.19) to (2.21) using scenarios to a macroscopic traffic flow model will mathematically describes the characteristics of traffic flow parameters of: Speed, volume, density, and time in relation to the above parameters. For analysis of the AVHV control model, traffic flow is not uniform but predicted over time and distance. For this experiment, consideration is based on the following three types of traffic flow:

- Free flow of traffic at high speed and low traffic volume of 50% intersection caoacity.
- Fully constricted traffic flow with high density, low traffic volume, and speed of 100% capacity.

For AVs, the uninformed flow of traffic can easily be implemented but not for HVs where we can only take a random sampling of the variable of interest to model the traffic flow rate. The traffic flow rate expressed as:

$$Rate_{flow}\, q = \frac{N_v}{t} \tag{2.21}$$

Where N_v is the number of vehicles at each instance of time(t)

The speed is a measure of distance covered over time, which involves monitoring over time and space. In this model, the radar defines the instantaneous velocity of each vehicle.

$$Speed = \frac{\delta x}{\delta t} \tag{2.22}$$

Assuming that the distance travelled is in km and time is in hours, then the speed is km/hr. Therefore the absolute speed travelled by the vehicle in relation to its direction is equivalent to

$$\sqrt{(v_x \cdot v_x + v_y \cdot v_y)} \tag{2.23}$$

The relationship between the characteristics of traffic flow parameters could be described using the traffic flow model. However, there are two main types of inputs that apply to the traffic flow control system [WYHZ13], these include:

- Static or fixed-time control approach: This is the statistic data based on historical observations of traffic volume and off-line calculations. This input is insufficient to obtain the variation of traffic flow in this situation.
- Dynamic, actuated and adaptive control: This input on the event-driven traffic flow with volume accumulated from loop detectors as we have on this model.

The above traffic input definition is derived from the three primary traffic flow modelling approaches: microscopic, macroscopic, and mesoscopic.

Relationship between the microscopic model of individual vehicle motion and the Macroscopic traffic flow theories and parameters

The modelling approach employed for this research describe the relationship between the microscopic models of individual vehicle motion and the macroscopic traffic flow theories and parameters. While microscopic models consider the interaction of individual vehicle motion, the macroscopic models consider the full road-traffic flow or the aggregated behaviour of the traffic flow prototype. The macroscopic approaches model approach considers the general traffic density, vehicles distributions, different constraints (as crossroads, traffic lights, control strategy). Also, the microscopic traffic parameters include driver behaviour, vehicle locations, distance head-ways, time head-ways, and the velocity and acceleration of the individual vehicle. [SJKH20] used a two-step clustering to develop a multi-regime microscopic and macroscopic model parameter relationship concerning velocity–density and can forecast traffic using Gipps car-following models. The simple first-order traffic flow model developed by [SJKH20], described the relationship between the macroscopic variables of (k, v, q), as represented in Equation (2.24)

$$k_t + (kv)_x = 0 \tag{2.24}$$

Equation (2.24) is incomplete, and need to be supplemented by the underpinning traffic flow Equation (2.6), with the empirical relation between the mean velocity and traffic density under the condition of equilibrium to form a complete description of traffic flow dynamics.

$$v = V_e(k)(= equilibriumvelocityasafunctionofdensityk) \tag{2.25}$$

The integration of macroscopic and microscopic-level models for the investigation of a mix-traffic is proposed. A baseline consideration that the macroscopic model manages a network of traffic, while the top-quality detail for the individual vehicle can is achieved at the microscopic model. The Micro-and macro-simulation models for different types of vehicles on a lone lane turn out relatively the identical traffic condition with variation in behaviour, reflecting in the empirical traffic observations [WVAHH95, SC05]. The macro and micro model parameters are believed to be the same and easily calibrated for performance analysis.

Agent-based system

The agent-based system provides both concepts for describing complex structure involving process and agents for the co-existence of the independent agents' behaviour's. A mixed-traffic involves multiple heterogeneous agent-based systems of different driving behaviour based on defined traffic rules and signs. The traffic light signal operation synchronises with autonomous vehicle sensing ability for crossing the intersection. The intersection cross collision points (CCP) serve as a safety buffer to compensate for human-driven cars' irregular movement. The vehicles are treated as agents in agent-to-agent communications that execute a behaviour and timing strategy to improves traffic flow as shown in Figure 2.4. Simultaneously, the intersection manager observes and analyses the respective vehicles on each lane and defines the scheduling plan based on two conditions: vehicle of the first arrival and the queue length(no of vehicles). The agents negotiate and collaborate to ensure that the traffic flow will be optimised throughout the intersections regarding the cross collision point. The agent-based system approach is an essential feature of AVHV control system used in controlling the mix-traffic flow and enhancing safety through the CCP. The architecture we propose for the mix-traffic system consists of several independent agents where vehicles are treated individually. Each agent uses the intersection control algorithm to manage the CCP from experiencing an accident.

Car Following

The basic concept of all car-following models theory originates in 1953 with Herrey and Pipes in [Spy07] who suggested that drivers keep a "minimum safe distance" from the preceding vehicles. The Pipes theory was discussed further by Kometani and Sasaki in [New02], Chandler et al. in [RNK05], Gazis et al. in [BCM12] and Newell in [CLZA12], amongst others. The car-following model concept uses a speed control technique to maintain the minimum safe distance between the leading vehicle and the next vehicle. (restricting traffic flow to the case of a single lane with no overtaking). Newell's car-following model in [CLZA12] determined how vehicles follow one another on a roadway where the speed of the leading car will accordingly influence the speed of the following car point in time-space along with the traffic wave speed. The existing methods applied to car-following model is divides into three main broad techniques:

- The first method applied the technique of vehicle speed changing to maintain a minimum safe distance towards the leading vehicle. The drawback of this approach is that vehicle maintains the legal maximum speed limit and vehicle's capability without consideration to the safety issues.
- Gipps improved on this model by introducing the acceleration and deceleration process to the model. The Gipp's microscopic collision avoidance method indicates that vehicle maintains a safe inter-distance by slowing down on the leading vehicle [HB01, PBAB+07, Pip53, Gip81]. From Gipp's model, vehicles adjust its speed depending on the position and speed of the vehicle in front. The drawback of this car-following models method is its inability to effectively describe mixed traffic behavioural dynamics involving both longitudinal and lateral movement. Gipps' model initially investigated the simulation of high way, but with the introduction of speed reduction rules was later applied to urban traffic signal with the concept of stop and platooning.

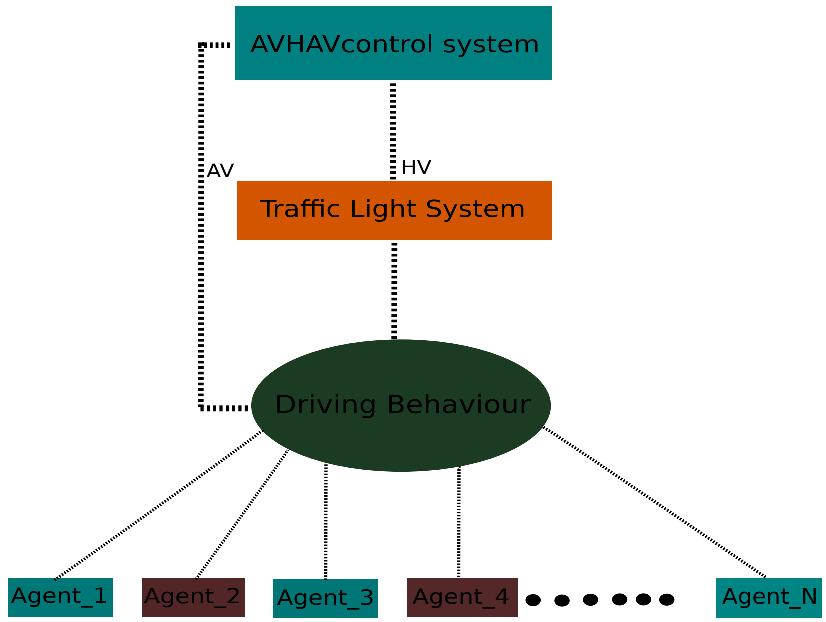


Figure 2.4: Agent-based traffic control

- Newell suggested that the following vehicle driver chooses its velocity based on the time-space method of acceleration. The time-space strategy driven from the vehicles relative speed that corresponds to the equilibrium curve of the deviation of the relaxation time.

The proposed model mirrors down the car-following models behavioural dynamics. The leading and the following vehicle have to co-exist and share behavioural characteristics which are used to model and predict traffic flow. The behaviour of each vehicle and traffic flow are model using the following baseline traffic parameters:

- Vehicle position 'x'
- Vehicle velocity 'v'
- vehicle acceleration 'a'

$$v = \frac{\delta x}{\delta t} \tag{2.26}$$

and ,

$$a = \frac{\delta v}{\delta t} \tag{2.27}$$

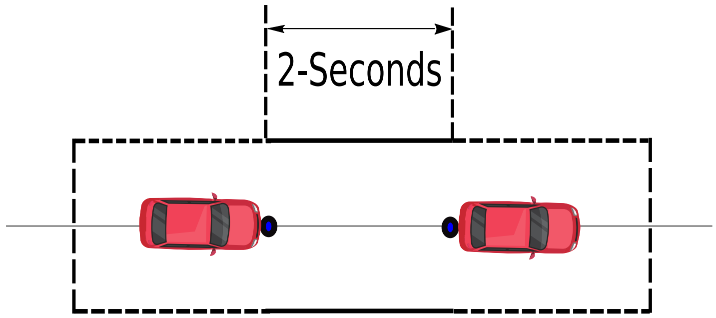


Figure 2.5: Car-following model using 2-second rule

This approach assumes that car 'n' responds to the car in front of it 'n + 1' according to their velocities difference. Assuming a deceleration factor of λ, therefore $v_n > V_{n+1}$. Where v_n and v_{n+1} are the velocities of the following and leading cars respectively.
However,

$$a_n = \frac{-\lambda(v_n - v_{n+1})}{\delta t} \tag{2.28}$$

where a_n is the acceleration as defined earlier.

In terms of position's position, we have:

$$\frac{\delta^2 x_n}{\delta t^2}(t) = -\lambda(\frac{\delta x_n}{\delta t}(t) - \frac{\delta x_n + 1}{\delta t}(t)) \tag{2.29}$$

Mathematically, the 2 seconds rule Figure 2.5 is a product of the thinking distance (the time it takes to perceive the danger and react to it) and the braking distance (distance it takes the car to stop once you apply the brake). This rule is mathematically described in Figure 4.10. Let us assume that a car is travelling at speed v(m/s); the braking distance is somewhat the velocity squared multiply by a constant (this constant is made up of factors like how good your brake, road, and vehicle are, in the UK a constant of $\frac{1}{13}$ is used). Thus, the safe distance "D" in between two vehicles:

$$D = Thinking\ distance\ + \frac{1}{13} \cdot (velocity)^2 \tag{2.30}$$

The car-following (CF) theory only considered the similar vehicle longitudinal interactions with strict lane behaviour and cannot describe in detail the lateral interaction. Hence, a detailed study that will combine lateral and longitudinal vehicle motions required to estimate the driver's behaviour in mix-traffic settings. Currently, there is no generic traffic flow theory that addresses a complex 2-D mix-traffic flow. [KLC17] proposed a conditional gap-threshold and reaction-time distribution acceleration model of a car-following behaviour that corresponds with relative speed. This model is associated with an insufficient accuracy reaction time due to the absence of individual reaction time from previous cars. [DR14]investigated divergent car-following models for both homogeneous and heterogeneous traffic systems, but the lack of a generic model best describes all types of complicated traffic conditions. Traffic research in Fuzzy logic [ZM05, CK99, MWB97]contribute towards setting some rules that guide vehicles in a car-following model. but, the results appear unrealistic because the model fails to capture the human driving behaviour pattern and the heterogeneous nature of the car-following model. The application of Fuzzy-based intersection management to mixed traffic under a secured test-bed shows HV with significant speed fluctuations, while AV could not stop at the intersection area. [MPOG10, FTF+15, HBF+08, BBS07, Lit17].

2.7.4 The Gipps Car-following Model

Gipps in [Hid02] developed his theory further to include lane-changing behaviour in his model. Resent traffic-flow simulation software like SIGSIM, SISTM, AIMSUN, and SITRAS [Spy07] are more easily characterised through advanced computation technology, but Gipps' car-following model has formed the basis for simulation fundamentals. The drive to develop a good car-following model for a hybrid traffic arises from the need to analyse the effect of mix-behaviour on traffic flow using Gipps' model. Most car-following model in use are variations of the Gipp model Equation (2.31) for a homogeneous traffic flow.

$$v_n(t+T) = min\ \{v_n(t) + 2.5a_nT(1-\frac{v_n(t)}{V_n})(0.025+\frac{v_n(t)}{V_n})^{\frac{1}{2}}, \\ b_nT + \sqrt{b_n^2T^2 - b_n[2[x_{n-1}(t) - s_{n-1} - x_n(t)] - v_n(t)T - (\frac{v_{n-1}(t)^2}{b}]}\} \quad (2.31)$$

Where n-i is the immediately followed by vehicle n
$v_n(t)$ = Speed of vehicle n at time t
$a_n(t+T)$ = Acceleration of vehicle n at time t + T
b_n= Most severe braking undertaken by driver ($b_n < 0$)
T = reaction time
s_n = Effective size of vehicle n (physical length plus margin)
V_n = speed at which the driver of vehicle n wishes to travel
$x_n(t)$= vehicle 'n' location at time 't'
$l_n,\ k\ and\ m$ are estimated parameters.
The understanding of the theory behind the application of Gipp's model is of great importance because they form the foundation for all the theories, techniques, and procedures that are being applied in the design, operation, and development of advanced transportation systems. The chosen Gipp's model [Gip81] which has an underpinning built-in collision avoidance mechanism, is a kinematics-based car-following model developed based on the theory of classical physics, which can be classified into optimal velocity, and safe distance model while taking the reactions times as an input. Unlike the machine learning-based car-following models strategy, which has no physical meaning of parameters, and the model outputs are complicated to control in practice, "Black box-like," the Gipps model uses real vehicle trajectory data sets. Also, the machine learning strategy effectively replicates the car-following behavior of human drivers and makes the AVs learn both the good and bad human driving skills in the car-following model [YZL+18]. Ironically, the Gipps collision avoidance car-following models only try to replicate human driver behavior [Gui11, Che13], which is not enough to effectively mimic the autonomous vehicle behaviour safely. It will not be easy to filter the good driving skills in the learning process of a machine learning approach. AVHV applies the real vehicle trajectory data sets to calibrate and validate the proposed models, and simulations are conducted to evaluate the model performances using city traffic settings, unlike the machine learning approach, which is data-driven. AVHV control model describes the kinematic mechanisms of car-following maneuvers, such as the safe distance models [Gip81], and the Intelligent Driver Model (IDM) [THH00]. One of the major drawbacks of Gipps' model is that vehicle often does not have zero speed when they slow down [Spy07],

which is not a realistic behaviour of vehicle on roads. Another weakness of using Gipps' model to simulate traffic is the amount of traffic that passes through an intersection is not specified as a parameter. This thesis looks at developing a mixed car-following model with vehicle type specific feature:

- The model should effectively mimic the behaviour of AV and HV.
- The model parameters should consist of basic characteristics of hum drivers and driver-less cars which can easily assigned values without resorting to calibrations procedure.

Car-following theory and dynamics have been investigated, and updated models that produce better results, including the full velocity difference model [JWZ01] and optimal velocity model [NSH01], have been suggested. However, little work has been performed on interpreting Gipps' model in a mixed-traffic setting. Still, the simple properties of the model (speed, acceleration, deceleration, reaction time) and their dynamics need to be investigated. The AVHV model has an explicit mathematical form, with most model parameters having obvious physical meanings and the model outputs can be easily controlled by adjusting the model parameters. The inter-vehicle distance adjustment is introduced to the calculated Gipps safe speed, which is naturally a safe-driving model to harmonise the vehicle speed in a mixed traffic environment. Though the machine learning-based models have higher accuracy than the kinematic approach in mimicking human drivers, the kinematics-based car-following models easily ensure safety by giving appropriate model parameters, even in uncommon situations. The reason for using and improving the Gipps model rather than other vehicle group models is that it is a collision-avoidance car-following model. However, combining it with machine learning-based car-following models can enhance the safety level of the automated vehicles. In the Gipps model, it is assumed that when the preceding vehicle "n" makes an emergency braking, the following vehicle "n + 1" can adopt an appropriate velocity after a reaction time to avoid rear-crash with the preceding vehicle n [Gip81].

2.7.5 Cellular Automata

Cellular Automata (CA) is a discrete model of computation investigation that uses automata theory in modelling discrete variables of time and space in a large-scale traffic dynamic model. CA describes the dynamical properties of the traffic flow system using integer variables. In this case, the road is sub-divided into nodes of a certain length $\Delta x$and the time is discretized to steps of Δt, each node is active when being occupied by a vehicle and inactive when it is empty. The CA logic could be represented as:

$$v_i^t + 1 = f(s_i^t, v_i, v_{i-1}), ... \tag{2.32}$$

$$x_i^t + 1 = x_i + v_i^t + 1 \tag{2.33}$$

Where t is time,v_i is velocity and x_i is the position According to [Dag06], CA shown that aggressive drivers' behaviour can enhance the traffic flow and improve the mixed traffic flow efficiency in the intermediate density range. The road region is subdivided into nodes containing single vehicles (typically 7.5 m long) for discrete traffic flow management in CA, [NWWS98, LCS03]. The model, at every instance, updates the road nodes their traffic parameters: speed, acceleration/deceleration, safe distance, and reaction time. The CA model was not considered for use in the proposed model because of its major drawback: the requirement of a high computational time, which restricts the implementation of the driving protocol. Besides, the node size negatively impacts the evaluation of the vehicle velocity. [LCS03] developed a particle-hopping model of a mix of motorcycle and car addressing their driving behaviours. [LH$^+$05] extended the CA model to involve different vehicle behavioural types with consideration of the traffic volume, efficiency, and capacity to effectively evaluate a group of vehicles, but this model was unable to address the ongoing harmonising of lateral and longitudinal relationship between AV and HV.

The cellular automata (CA) proposed by [CL86] and later adapted for real life applications by [SSNI95, NS92, Nag96, RNSL96] to address the limitations of mix-traffic behaviours. The evolution of CA model can effectively model a stochastic or deterministic system of single or multi-lane traffic with a set of discrete traffic relationship rules. The CA effectively modeled retarded (noisy) acceleration, overreactions drivers behaviour with deceleration, and maximum speed fluctuations in a randomised manner [Nag96]. The CA divides road lane into nodes i of length δx, time t with a j intervals of 1s duration, at any time instance, node i is either occupied by a car with speed v_jj given by or empty

$$v_j = \lambda j \frac{\delta x}{\delta t} \tag{2.34}$$

where:
$\lambda j = (0, 1, 2, ..., v - max)$ is a quantity which takes a discrete value between zero and the maximum velocity, v_{max}.
The discrete-time and space updates the vehicle positions using rules (i) to (iv) [Nag96, Hel01]:

1. Motion: Move individual vehicle by v_j nodes and update the maximum velocity v_{max}
2. Acceleration: check $v < v_{max}$ and increase velocity to $v = v + 1$, if there is enough space ahead. Else:
3. Slow down (Deceleration): for fast vehicles
4. Harmonisation of speed: If above the steps yield $v > 0$, decelerate velocity by one with tendency p.
5. Traffic spread: extend the flow ahead.

In addressing the mix-traffic problem, two distinct models were identified and considered: the driving behaviour model and the car-following model. However, the first driver's behaviour model addresses drivers' response to obstacles or changes in the relative positions of the leading vehicle or obstacle. The Optimal velocity, Pipes, Forbes, and General Motors model solved the address drivers behaviour concern using the Hidden Markov Model (HMM), which is a randomly changing system statistical model [ZL06]. The modelled mechanism is thought to be a method of unmeasurable states. The HMM makes the assumption that there is another mechanism on which the behaviour "depends." The HMM's aim is to learn about the current case by analysing it. The second, car-following model was identified and modelled using gap acceptance models which describe how a driver decides to execute its movement based on the vehicle ahead and in lane merging to ensure the safety of road users. A state-of-the-art review of driver behaviour and car-following models is in [ZQL17].

The enhanced car-following model, which is single lane dependent, is based on the full velocity difference (FVD) model does not consider the acceleration of leading vehicles and mixed vehicle driving behaviour. To overcome the above limitations of car-following, the cellular automata model was used. The cellular automata could effectively describe both single-lane and multi-lane road system. In the evolution and interactions of vehicles, it follows a series of laws, one of which is known as randomisation. These rule models describe three common human driving behaviour: delayed (noisy) acceleration, overreactions at braking, and variations at maximum speed. The street is divided into nodes in this model, and the time is divided into intervals of time. The lane-changing model is concerned with the driver's decision to switch lanes, either mandatory or optional. Raravi et al.[RSRB07] proposed an automated merge control system for intelligent vehicles that ensures secure vehicle manoeuvrings at road intersections in a cooperative vehicle-infrastructure context. The optimal manoeuvres for merging vehicles were obtained by minimising the driving time inside an intersection for each vehicle coming from two directions using an optimisation problem with constraints to ensure protection on conflicting approaches. A successful contribution was a merge control application based on V2V communication under the principle of virtual vehicles that are used to map vehicles on one lane into the other lane for maintaining safe distance requirements, but it was not appropriate for mixed traffic intersections because complex movements of vehicles to and from different roads are involved. [UST99]. According to [MDF+18, Shl09] communication systems are used by connected automated vehicles to increase efficiency and, as a result, transportation by allowing cooperative features, such as cooperative sensing and cooperative manoeuvring.

Dresner and Stone in [DS08] suggest that autonomous intersection management (AIM) is a term proposed as an alternative to traditional traffic signal control mechanisms. In Goal, vehicles and intersections are viewed as autonomous agents in a multiagent scheme. The road intersection is divided into several parts, and the software schedules reservations for temporal node nodes use from each vehicle and provides right-of-way to each vehicle to ensure a stable and protected crossing. The method's main flaw is its inability to achieve optimum global alignment, which ensures that stop delays are likely to occur in most cases. However, since this system does not coordinate the vehicles globally for optimum flow, stop delays are unavoidable. The problem with this approach is that it lacks global coordination, making it impossible to prevent stop delays. According to the work of [AZS15] intersection is divided into a grid of reservation nodes by the intersection control policy, which can be applied to rectangular and irregularly shaped intersections. When a vehicle reaches the intersection, the intersection manager simulates the expected path through the intersection using the information in the vehicle's reservation request, such as arrival time and velocity, vehicle size, and other parameters. The policy specifies the reservation nodes the vehicle will occupy at each simulated time point. It implemented the Semi-Autonomous Intersection Management protocol, which allows vehicles equipped with partially autonomous features like adaptive cruise control to approach an intersection from several directions at the same time. With the aid of advanced sensing systems, autonomous vehicles can be safer and more efficient than human drivers by eliminating human factors from intersection control loops. As compared to traffic signals, the AIM protocol takes advantage of autonomous vehicles' fine control to allow more vehicles to cross an intersection at the same time, effectively reducing vehicle delays by orders of magnitude [DS08, FAW+11].

A cooperative vehicle intersection control (CVIC) system has recently been proposed, allowing automated vehicles and infrastructure to work together for successful intersection operations [LP12]. The CVIC algorithm works by reducing the overlap of opposing vehicle trajectories at the intersection. This device attempts to avoid having any two different vehicles at the same time in the intersection area. Since each vehicle's trajectory is created by fixing an acceleration rate from its current location to the end of the intersection, the prediction horizon ignores the vehicle's natural dynamic behaviour. Furthermore, CVIC simplifies the optimization problem by omitting any cross-collision avoidance constraints, and minimization of overlapping trajectories does not guarantee a feasible collision-free solution. As a result, an additional algorithm in the form of priority rules for specific lanes is needed to address system failure caused by infeasible solutions. [KIO+13].

During the red-light cycle, the queue length of the vehicle is used to monitor the green cycle during the same period for effective intersection utilization [CZW10, ASS08, WL06]. The texture difference is used to distinguish vehicles from the pavement, and edge detection was proposed to detect length. This method was interesting, but it does not function in real-time, which inadvertently affected efficiency. Scott et al.[LVKLP16] looked into the consequences for intersection capability and level of service of giving passengers of automated and autonomously running cars a ride standard comparable to rail systems (in terms of optimal longitudinal and lateral acceleration). According to the findings, car passengers begin to feel uncomfortable

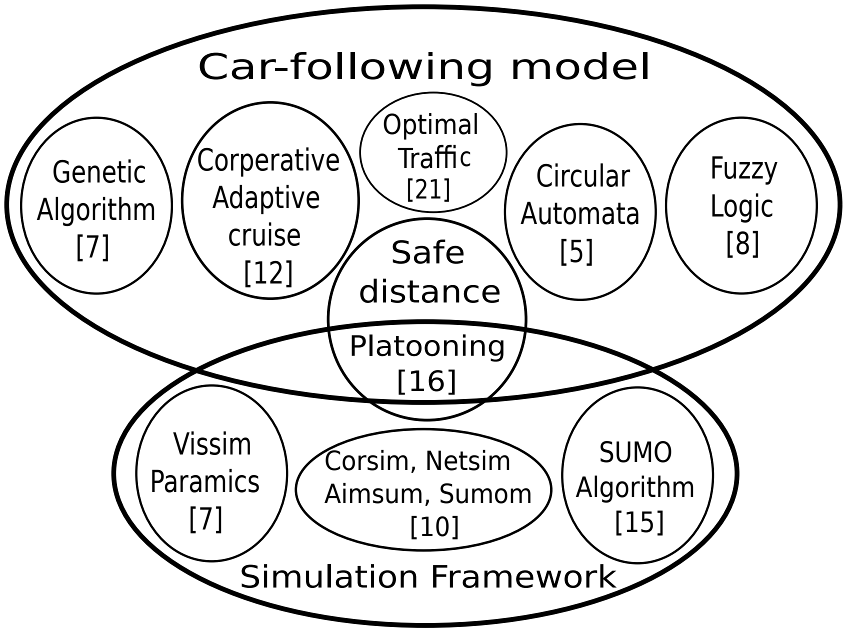


Figure 2.6: Venn diagram of a list of reviewed literature

at lower acceleration rates than car drivers [LVZP15, Reg14, BNG14, JO14]. As a result, occupants of autonomous vehicles may wish to order their vehicles to perform manoeuvres that provide them with greater ride comfort than if the vehicle control algorithm mimicked human-driving-operation. The graphically depicted list is the literature considered in this study from 1970 to 2020. in Figure 2.6, the diagram also explains all the modelling methods that combine other approaches together. This figure includes the total number of literary works taken into account for micro and macro traffic simulation frameworks.
According to Uno et al.[UST99] a combined control application based on V2V communication is used to map other vehicles from one lane to another to ensure safe distance requirements. However, since complex movements of vehicles to and from different lanes are involved, these merge control systems are not appropriate for intersections.

2.8 Driver Behaviour

The driving behaviour model predicts drivers intent, vehicle and drivers state, and environmental influence, to enhance efficiency in driving experience [AAz16]. [YBS11], define "a driving behaviour is aggressive if it is deliberate, likely to increase the risk of collision and is motivated by impatience, annoyance, hostility and an attempt to save time." non-observance to successfully model drivers' behaviour is a critical difficulty in modelling microscopic traffic flows. Most drivers' behaviour model currently use estimates. Modelling drivers' behaviours predict human driver's psychological behaviour, ranging from driver state, driver intention, vehicle and environmental influence, to enhance traffic safety and societal well being as a whole. It involves the design and analysis of drivers's psychological and behavioural characteristics, so as to predict their capabilities in traffic and make effort to acknowledge and emphatically increase traffic throughput. This provides an informed understand of traffic and has the prospect to improve driving behaviour, supporting a safer and efficient driving. Driver's behaviour model is capable of generating a classification that characterises the different profile level of drivers aggressiveness. According to [FCF+17], drivers behaviour impacts traffic security, safety and efficiency, better understand and potentially improve driver behaviour. Attaining a driving task is a mobility goals while avoiding obstacles and collisions on the roadway. Aside from the mobility target, there are several secondary goals, one of which has sparked a long-running debate about drivers' psychological behaviour when driving to their destination. For a vehicle to get to its destination, there is a lot of decision-making process based on feedback. [Ful05] considered driving behaviour with regards to the difficulty of the driving task, and the risk of collision. The work of [Ful05] classified driving risk into three main components: risk is measured in three ways: quantitative risk, subjective risk assessment, and risk perception. The most important aspects of the driving role were avoiding potential adverse effects of risky driving and maintaining a high level of safety. Also, the work of [LO07, Sal06] proposed drivers maintain safety margins to change their speed to cope more efficiently with any danger or possible difficulty along the lane..

Road fatalities, injuries, and accidents generally are caused by driver inattention and unintended manoeuvres. Modelling driver behaviour is a complex task because of the unavailability of instruments for measuring self-reported driving behaviours. Some mistaken drivers blame road deaths, but they are also to blame for the neutralisation of road infrastructure and other economic factors like high fuel consumption and wear & tear on the vehicle. According to [Shl09, MDF+19], wrong driving styles notable have a negative impact on emission pollution and about 3–5 L per 100 km increase in fuel consumption. The report from [MDF+19], shows that just 11% of the road lane length on highways is taken up by cars. At the same time, the remaining 89 percent reflects the distances between vehicles that drivers must maintain to feel comfortable when travelling at high speeds. It has been shown that older drivers have more trouble driving than younger drivers. According to [KGM17], older females are not the only ones that have trouble driving. Older drivers had more trouble driving on foggy days than younger drivers ((25.3% *compared to* 16.8%, $p = 0.01$), and females had more difficulty than males ((29.3% *compared to* 14.8% , $p = 0.001$).

[Smi16], state that it is general knowledge that human mistake is the principal source of most traffic mishap. The effect of alcohol and drugs are some of the risk factors that contribute to a road traffic accident. Perceived driving skill includes some inappropriate driving behaviour (divided attention, over-speeding, tailgating, fatigue, and aggression), loaded on independent factors, risk-taking,long hours of driving, late night driving, stress driving and driving with a cold and road driving with fog and traffic accidents. Besides, a risk taken is assumed to be a general type of behaviour because it is associated with safety-critical circumstance such as driving. According to [PSS+04]demographic factors in many cases constituted a great chunk of risk-takers, it states that "young men are known to be at a greater risk of having an accident". Besides, young men's way of life factors such as driving heavy alcohol are proven risk factors for impaired driving. Working at night or working long hours, and psychological personality are some other factors that can cause impaired driving are characteristics such as . [Smi16] identified four types of driving behavioural problem to include

- Speeding
- Driving calculation errors,
- Inattentive
- Aggressive driving

According to [FCF+17], drivers' behaviour impacts traffic security, safety, and efficiency. The driver behaviour model deals with the analysis of the drivers' psychological and behavioural characteristics which helps to analyse and predict drivers' capabilities in traffic and tries to understand and positively impact driver behaviour. The decision-making process is the driver's perception of the driving environment or situation in real-time. Modelling the drivers' behaviour model helps to predicts human psychological behaviour, ranging from driver state, driver intention, vehicle, and environmental influence, to improve traffic safety and efficiency. Modelling Advanced Driver Assistance System (ADAS) in modern vehicles has the driver's behaviour model integrated into it to improve traffic safety and, efficiency and the society well being as a whole. For instance, by modelling the psychology of an aggressive driver with an accurate car-following and platooning forecasting models, an ADAS can check tailgating issues by maintaining a minimum safe distance [FCF+17]. The effectiveness of ADASs can be determined by determining the drivers' conditions, such as their concentration level and driving competence. Besides, in modelling the vehicle behaviour, determining the drivers' age, sex, and state of mind will reasonably play an critical role in the success of the mixed-traffic model. [KGM17] claims that older drivers have fatigue and trouble driving than younger drivers because, but not exclusively, and older females have difficulty driving.

In modelling drivers behaviour, two class of observatory data are needed to be able to address the peculiar driving features of each vehicle type:

- Drivers details: This involves data like the driver's age, experience, concentration level, vehicle type, and size.
- Calibrated data: This involves the spatial-temporal traffic state of the vehicle, like the relative velocity, safe distance, time headway.

[MNHF+20] states that analysing such a volume of data from the above two data classes could be difficult because of the large number of parameters that are involved. A realistic driver's behavioural model of a mix-traffic will be able to fully analyse the parameters of relative speed and velocity, longitudinal and lateral gaps, as well as front and rear vehicles on the adjacent route and leading and trailing vehicles to gain a better understanding of the behaviour. Besides, the vehicle trajectories detailing the path from start to the goal or destination of each vehicle at any time instance will help in the analysis of the above parameters and modelling of 2-dimensional traffic behaviour.

Driver behaviour profiling This involves the use of simulation process to automatically collect driving data (safe distance, reaction time, speed, acceleration, deceleration/breaking ,position) and analysing them with a model in order to generate a safety and efficient driving throughput The analysis and classification of human behaviour for implementation in autonomous vehicle driving tasks can be identified by analysing the human-drivers behavioural characteristics. A detailed driving behaviour model could be implemented using different traffic scenarios for driver characteristics. Driving models are integrated into an Advanced Driver Assistance System (ADAS) in the vehicles with accurate vehicle platooning estimation models to maintain a minimum safe distance. In addition to modelling vehicle behaviour, deciding the drivers' age, gender, and mental state will be critical to the mixed-traffic model's success. The effectiveness of ADASs depends on determining the drivers' state, such as their concentration level and driving competence. Understanding the drivers' goals, such as their preferred destination and route, opens the door to new travel assistance systems and facilities. This section introduces a general structure for categorising the various models used to capture psychological driver behaviour, emphasizing human cognitive and traffic decision-making dimensions. The study looked at the microscopic and the macroscopic vehicle level and integrate the developed model to two core driving assistance technologies: vehicle platoon and lane-merging systems. According to the basic assumption in this driver model, the following vehicle's behaviour is directly related to a stimulus observed/perceived by the driver, identified relative to the lead vehicle, according to the basic assumption in this driver model. In which case, the lead vehicle determines the following car's driver behaviour.

With the emergence of the autonomous vehicle, research in drivers behaviour modelling is currently receiving increasing interest because to several present-day issues, ranging from the concern of a mix-vehicle co-existence to the level of road accidents recorded annually. However, the modern vehicle is supported with Advanced Drivers' Assistance System which guides vehicles in sensing information with accurate safety response and prevent accidents by alerting the driver to possible dangers ahead of time. Besides, gaining insight into the driver's goal such as vehicle destination will help in modelling drivers' behaviour. Due to variability in driver behaviour among driver, modelling drivers behaviour may be complex and require some key input, which includes:

- Vehicle parameters such as pedal positions, steering wheel angle, RPM acceleration, and turn signal lights are updated and correct in real-time.
- Radars, lane location sensors, the Global Positioning System (GPS), accelerometers, and gyroscopes are examples of vehicle sensors will be needed for the gathering of real-time accurate information.
- Though cameras are a good example of the sensor it could predict the driver's mental and physical condition, as well as his or her level of exhaustion. They may also be used to enhance the recognition of manoeuvres.

Driver motive, state, and vehicle dynamics are all variables to consider when modelling driver behaviour. Since managing the correlation between these factors might be risky and difficult, a driving simulator is ideal. Several variables, such as driver motive, obstacles, traffic conditions, and vehicle speed limit, can be precisely monitored with a driving simulator without jeopardising safety. As suggested by [MHBM+13] who proposed applying different driving behaviour scenarios to effectively model different driver behaviour. Driving fatigue contributor to 15–30% of all crashes [CNA+02, WLF+11, AIF+16]

Connected Vehicle Communication: Vehicle-to-vehicle ($V2V$) and vehicle-to-infrastructure ($V2I$) communications are both possible in a connected vehicle system [KIO+13]. CACC systems can safely drive vehicles with very short distance headways by forming platoons to increase road traffic flow capability using $V2V$ communication. [VAVDV06, PSH11, OOHU10]. CAVs' advanced technologies open up a world of possibilities for developing novel traffic flow management approaches, such as cooperative adaptive cruise control (CACC), speed harmonisation, and signal control, to name a few. With much room for improvement in terms of traffic safety, quality, and environmental sustainability, the intersection coordination scheme has obtained broad research interests. [GD18, CGJ+12, ZACN17, SHCI94]. [KK15, FHKZ15, KDAM14, WDHvA14]. For several years, the idea of following a vehicle with a short gap in CACC has been generalised to provide a new intersection control model, in which nearly conflicting vehicles approaching from different directions will cross the intersection with marginal gaps without using a traffic signal. This will enable automated vehicles to reach their maximum potential to reduce traffic congestion, reduce travel time, and increase intersection capability. However, Omae et al.[OOHU10] suggested a virtual platooning system for automated vehicle control at an intersection that allows vehicles to pass through without pausing. Vehicles in both lanes are deemed to be in a virtual lane situation, and their intersection interference is taken into account. They are separately managed so that they can safely follow the platoon's previous vehicle. The system, which was tested using four electric vehicles fitted with automated driving and V2V communication technologies at a one-way intersection, resulted in a significant reduction in traffic congestion.

Traffic Filtering: This is a method of traffic management that allows the traffic manager to define specific traffic to grant access while excluding all other traffic (pass by criteria). This technique was first applied in computer network traffic technologies and are commonly divided into traffic stream filtering/platoon and lane combination filtering method. The traffic stream filtering functionality is built into the AVHV control with a traffic routing feature.

Tilgating: This is a risky driving habit in which a driver follows too closely behind the car in front of them, making it impossible that they would be able to prevent a collision if they brake suddenly. In tailgating, drivers do not keep a safe distance to the leading vehicle and, as a result, increasing the chance of a collision should the other driver break suddenly. This is against the UK Highway Code.

2.9 Classification of Related Works

We have two principal methods of managing traffic flow within an intersection, based on existing state-of-the-art in-vehicle technology and road traffic management systems as it applies to human-driven and autonomous vehicles:

- **Traffic Signal Light:** These signal scheduling systems are classified into time-based Scheduling systems in terms of control flexibility and coordination capability, event-driven scheduling systems, centralised signal control systems. Furthermore, an efficient traffic light signal system should regularly maximise available intersection power by regularly adjusting traffic control and coordinating traffic parameters. This consists of the installation of signal lights that control traffic streams by using different light indicators. Its primary aim is to prevent simultaneous movement of two or more incompatible traffic schedule of phases by assigning and cancelling the right-of-way to a set of traffic schedules [OOHU10, VAVDV06, KIO+12, THH00, PDD+03].

- **V2V and V2I Communication:** This involves a traffic intersection control schedule without lights, in this case, autonomous or semi-autonomous vehicle accesses an intersection using vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) communication means [KIH+15, FAW+11, AZS15, MDF+18, UST99].

- **Centralized Approach:** This approach is similar to that of traffic lights, but it incorporates Vehicle-to-Infrastructure (V2I) communication. In some instances, an intersection agent (IA) receives requests from vehicles to cross the intersection, schedules them, and determines the best crossing sequence. [DS06]. This method of traffic strategy's as reflected in Table 2.3, there is at least one factor in the traffic scheduling characteristics or features that are centrally decided for all vehicles in the scheme through a coordination unit. When a central decision is made for at least one of the factors, it is called a centralized approach [MPOG10, Lit17, ANS+14, SSS16]

- **Decentralized Approach** Instead of using traffic lights or a manager, the decentralised solution relies on vehicle-to-vehicle (V2V) contact synchronisation, enabling vehicles to cross an intersection without anticipating their potential trajectory. In this category Table 2.4, all the vehicles are handled as autonomous agents but use the interaction between (vehicle-to-vehicle and vehicle-to-infrastructure) to maximise efficiency in communication and control. In this case, however, the individual agents (vehicle) receive information from other vehicles and or road-side infrastructure to enhance performance criteria like safety, efficiency, and travel time before accessing the intersection [CHW11, DS08, ZWPL15, EK07, FTF+15, KDAM14]. The correlation used in intersection control with the underpinning technologies with the evaluation of its performance matrix is as shown in Table 2.4.

However, we categorize the above two methods of implementing a traffic schedule into two distinct strategies based on the two-underpinning factor: centralized and decentralized strategies.
Each matrix node defines the performance index of various methods and identifies which characteristics are to balance. This matrix presents a detailed picture for consideration in the development of a robust hybrid-based system with some degree of safety, performance, costing, and adaptability.
The classification categories are based on the below column headers:

- **Method**: This involves the traffic management procedure consisting of systematic planning, designing, control, implementing, observation, measurement, and the formulation, testing, and modification of the traffic management system to solve a traffic problem. Most traffic control methods involve direct communication between traffics and road infrastructures, such as signs, signals, and pavement markings. The primary objective of any traffic control system is to guarantee safety and optimised traffic flow. The control or strategy to orchestrate the traffic flow, such as the rules deciding which car may drive or wait?

- **Vehicle Type**: Vehicle type means the category of vehicle driving system characteristics of human and machine driven vehicles. This model approaches the vehicle classification system into two distinct class of autonomous vehicle (AV) and or human-driven vehicle. Besides, the vehicle classification is done based on the communication capability with the intersection control unit, while assumption is made for all the vehicle to be of the same dimension.

- **Performance Index (PI)**: This is a measure of intersection efficiency: where $+$, $++$ means good and best performance respectively. Every traffic intersection control model has a Performance Index (PI) that indicates the overall efficiency of the vehicle's control method. The traffic control performance measurement and monitoring significantly impact the design, implementation, and management of traffic control models and to a large extent contribute to the identification, comparison, and assessment of alternative traffic management methods.

- **Means of Communication** This is the channels within a medium that vehicle and roadside devices use in sending signal or message across to each other at the road intersection. Traffic signal, and vehicle to vehicle (V2V) or vehicle to infrastructure (V2I) communication is what the model needs. This represents the means of intercommunication where signal from traffic light, V2V, and V2I wireless transmission of data between motor vehicles are the means of communication for AV and HVs on the road. Road intersection-vehicular communication systems involve networks in which vehicles and roadside units communicate with each other for a free and safe flow of traffic. The communicating devices (vehicles/drivers and road roadside devices) are providing each other with traffic information which are effective in avoiding accidents and traffic congestion.

- **Fairness**: Fairness in intersection management contest is the impartial and just treatment or behaviour without favouritism or discrimination to traffics. Fairness metrics are used in traffic network engineering to determine whether participants are treated fairly with consideration of traffic efficiency The measure of fairness to traffics requests at the intersection is based on a classification algorithm using the vehicle of the first arrival and queue lengths. This feature takes care of the waiting time among vehicles in which case, the principle of "FIFO" is obeyed at the point of intersection less there is a priority request from an emergency vehicle.

- **Safety**: The road traffic safety matrix refers to the approaches and strategies applied in preventing traffic collisions and road accidents at the intersection. Every traffic management solution usually defines the potential collision areas before making optimal decisions about which countermeasures to use and when they should be used to fix intersection safety issues. This deal with the percentage efficiency of the safety of the control system in avoiding conflict of the vehicle or accident is very paramount. Though, there is no ideal system considering human error, but health and safety issues is paramount in a traffic management methods.

- **Scalability**: "Scaling a road intersection" means to "increase or grow a number of roads that join together in an intersection" or "increase the size of a road network generally" This is the estimate of a system's potentials to vary the number of roads infrastructure like roads size, and lane. Besides, scalability is related to both efficiency and cost in response to changes in application and device processing demands. For a new system to serve the test of time, the system must poses the capability or potentials to be expanded to be able to address more complex traffic control scenarios with a different type of road network and size .
- **Cost**: This cost parameter could be quantified with a variable. In analysing the intersection cost of different traffic control methods, the comparison process could be based on any of the following cost matrices:
  - The initial project capital cost: This is the total cost of preliminary design and analysis of the method, right-of-way, utilities, and construction.
  - Operation and maintenance cost: This is the ongoing costs associated with the intersection throughout the design life. According to [SLE12], the annual cost of lighting an intersection includes maintenance and power supply is $750 .
  - Delay cost: According to the Texas Transportation Institute's 2012 Urban Mobility Report [SLE12], the cost of an hour of delay of vehicles at road intersection is $16.79. This report quantifies the amount of congestion in cities across the US, and provides a number of cost related impacts of congestion.
  - Safety cost: This is the computation of the expected number of crashes and that may be associated with the control method.
- **Complexity**: The design and implementation of a road traffic intersection range from a simple road network joining two roads to a complicated convergence of several high-volume multi-lane road networks. The management of intersection is directly proportional to its complexity. Besides, complexity described how complex and intersection is and the amount of time it takes to execute a traffic scheduling algorithm. Therefore, the time has to do with how complex the control can be implemented in real-time and how complex the errors could be resolved.

Tables 2.3 and 2.4 show a matrix of classification used to quantify the quality of each feature concerning traffic management strategy, it shows the statistical impact of the on the column header item. The signs: 0, +, -, ++, and - - are used in this order to show statistical impact levels of non-impact, adverse impact, positive impact, major negative impact, and significant positive impact respectively. A detailed Pros and cons matrix of each reviewed traffic management method was analysed in Table 2.5

Table 2.3: Categorisation based on centralised intersection control

Method	Vehicle Type	Communication	Performance	Fairness	Safety	Scalability	Cost	Complexity
Cooperative eco-driving model	AV and HV	V2I and V2V	++	++	+	+	+	-
Fuzzy-based	AV	V2V	++	++	++	++	+	-
Automatic merge control	AV	V2V and V2I	+	++	++	+	−	+
Vehicle platooning	A	V2V and V2I	+	+	+	++	+	−
	H	Signal	+	++	+	++	-	+
Cooperative adaptive cruise control	AV	V2V	+	+	+	++	++	+
Game theory-based intersection control	AV	Signal	+	++	++	+	+	-
Genetic Algorithm	AV	Signal	+	++	++	+	++	+
Optimisation approach	AV (CVIC)	V2V and V2I	+	++	+	++	++	-
	HV (MPC)	V2V and V2I	++	++	++	+	++	-
	AV (Multi-agents)	signal	+	++	+	+	-	-
Safe velocity and acceleration	HV and AV	V2V	+	++	++	++	++	++
Buffer-assignment based coordinated	AV	V2V and V2I	+	++	++	++	++	++

Table 2.4: Categorisation based on decentralised intersection control

Method	Vehicle Type	Communication	Performance	Fairness	Safety	Scalability	Cost	Complexity
Job scheduling	AV	Signal	+	+	++	+	−	−
Optimisation of Connected vehicle environment	AV and HV	Signal	++	++	++	++	++	++
Marginal gap intersection crossing	AV	V2V and V2I	++	++	++	++	++	++
Merge control using virtual vehicles to map lanes	AV	signal, V2V and V2I	++	++	++	+	++	++
Autonomous agent-based scheduling	AV	V2V and V2I	++	+	+	++	+	+
Virtual platooning	AV	V2V	++	++	++	+	+	−
Our Approach: Space-time node with HV and AV	AV and HV	Signal,V2I and V2V	−−					
Virtual platooning	AV	V2V	++	++	++	+	+	−
Space-time node reservation	AV and HV	Signal,V2I and V2V	**	**	++	**	**	+

The state-of-the-art in mixed traffic intersection management scheme, emphasise on its significance in addressing the following: efficiency, improve safety, reduces emissions, and fuel consumption. According to Phil Blythe, in [NHHB13] an Intelligent Transport Systems Professor at the University of Newcastle, there is currently ongoing work to connects traffic signals to cars which give personalised information directly to help drivers make their way around town. The proposed technology will linked vehicle communication devices direct to the city's Urban Traffic Management Control (UTMC). It uses Infrastructure to Vehicle (I2V) communications to create an enhanced and safe junctions, diffuse and optimise traffic, and respond directly to drivers at car priority at junctions. When the traffic light is red, drivers will know how long they must wait and will be told when to turn on and off the engine to minimise pollution. They will also be advised on the best speed to get through the next set of green lights, minimising the need for stopping, starting, and accelerating.

Given rising vehicle patterns and the long-term viability of the road transportation system, a breakthrough in the efficient use of existing road networks via creative intersection management and control is unavoidable, especially in cities where road expansion and development are deemed problematic. Unlike autonomous vehicles whose movements can be well manipulated or controlled seamlessly, human-driven vehicles naturally do not observe control protocol with unpredictable random and uncertain movements pattern because of the human attitude to driving (stochastic). Several simulation studies have indicated that human-driven vehicles degrade autonomous vehicle performance. at road intersections[CVDBvN11, MSS+14, VAVDV06, WLZL15].

Traffic flows at intersections are controlled by traffic light signals or signs in the conventional traffic control model of using lights, limiting the intersections' maximum traffic handling capacity and increasing the inconveniences of repeated stops and idle time [PDD+03, THH00, KIO+12]. If all approaches to the intersection are not similarly congested, traffic signal management solutions can only increase traffic flow to a limited extent, and they cannot wholly eliminate vehicle stop delays at intersections, regardless of traffic volume. Several factors may cause the deceleration process to begin, such as when a driver is required by traffic rules to slow down and ultimately stop at a signalised intersection. There may be two stages to the deceleration phase. [WDI+07, YP10, WZG+11];

- In the first point, drivers depressed the throttle pedal and, if further deceleration was needed, applied the brake pedal to slow down until the speed reached zero.
- Drivers waited a long time for the light to turn green.[WZO11].

The fuel consumption rates of drivers vary from driver to driver on the same journey and the same type of car due to their attitude to driving. The European Traffic union project was initiated in 1986 as part of a highest efficient and unprecedented safety research project whose output will be a common traffic technological platform to be used in turn by the participating countries once the product development phase begins, which was aimed at the following: improved driver information, proactive driver assistance, vehicle cooperation, and traffic management [BD14]. According to[VdVDvM01, WZO11] reducing the change in driver behaviour is an efficient way to minimise fuel consumption in the short term; thus, if drivers are willing to change their driving behaviours, they will complete the same journey in the same amount of time while using substantially less fuel.

There are studies on creative intersection management that seek to regulate vehicles without using traffic signals in the literature. The pros and cons of current methods of light-less intersection scheme for autonomous vehicles are categorized in Table 2.5. The systematic review of the automated vehicle intersection coordination scheme was based on the guideline from the below table of review summary.

Table 2.5: Pros and cons matrix

S/N0	METHOD	PRO'S	CONS.
1	Fuzzy-based intersection control	Reduce waiting time and improve fairness	Difficulty in determining the appropriate size of traffic groups at real-time traffic
2	Model predictive control (MPC)	Reduces the average queue length and waiting time	This method is only effective for a small road network
3	Connected vehicle environment	Global coordination of vehicles with safety and trajectory generation	High computation time
4	Cooperative adaptive cruise control	Traffic flow improves in conditions with high traffic volume	Vehicle communication is restricted to longitudinal control only
5	Genetic Algorithm	Optimises traffic flow to use alternative route with minimal computation time	Cannot be applied to an isolated intersection
6	Job scheduling	Isolated intersection is considered as a single machine	Not suitable for multiple intersection
7	Automatic merge control	Safe vehicle maneuverer at road intersections	Requires a large investment in road infrastructure, not suitable for intersection control because of complex movement involved
8	Multi-agents approach	Ensure the driver's safety and increasing the travel efficiency	Cannot handle multiple policy features simultaneously
9	Virtual platooning	Effective in a one-way intersection system	vehicle pass through intersection without stopping, and independent control of vehicles to follow the preceding vehicle in the platoon
10	Cooperative Vehicle Intersection Control	Avoid presence of any pair of conflicting vehicles at the same time and fix the acceleration rate for vehicles	High computational time required

2.10 Research Gap

The number of vehicle types present in traffic and the relationship between the lateral, longitudinal vehicle motion, and the vehicle's speed plays a significant role in managing such a heterogeneous mixed traffic behaviour [WPH19, MR11, GK05]. There appears to exist a wide range of adoptable microscopic simulation models for car-following homogeneous traffic systems based on the different version of Gipps model [Gip81], but they can only describe a unidirectional (longitudinal) interaction of vehicles. These existing homogeneous car-following models are not suitable for describing a two-dimensional heterogeneous mixed traffic model. To apply the existing car-following model in a mixed-traffic situation, the model should simultaneously describe the lateral and longitudinal behaviours involved in a mixed traffic system. There has been minimal real-time data from mix-traffic studies; the little available consists primarily of assumptions based on the traffic flow theories and simulation using realistic traffic parameter values. Besides, the recognition and integration of traffic parameters that control the complex 2-dimensional vehicle behavioural models of traffic participants are critical tasks towards a new research direction.

The current literature confirms that typical constraints in the car-following model are its rigidity to longitudinal vehicle dynamics: safe-distance, maximum speed, and acceleration/deceleration rate. Most existing traffic models are only suitable for the description of a homogeneous traffic environment using firm lane behaviour. According to [TK09], CAV can obtain neighbouring information via V2V and/or V2I, and adopt a suitable control law to maintain constant inter-vehicle spacing or smooth driving patterns. As a result, an in-depth analysis of vehicle lateral and longitudinal movements is needed to assess driver behaviour in this heterogeneous traffic flow. Currently, no widely used traffic theory could exhaustively simulate a 2-dimensional mix-traffic flow involving a lateral and longitudinal behavioural model because of the intricate human driving behavioural pattern involved. It is only a robust 2-dimensional traffic flow model that can perfectly describe the characteristics of vehicles with complex behaviour that can simulate a mix-traffic of AV and HV successfully. However, few studies attempted to model an integrated and robust driving behaviour phenomena like multiple-leader following, road tides (rise and fall of the road surface), tailgating (driving dangerously close to a leading vehicle, making it impossible that they would be able to avoid a crash if the driver braked quickly), filtering(Filtering involves moving past queues of stationary or slow-moving traffic), swerving in a dull mix-traffic setting (involves using operational data received to identify a potentially high-risk or unsafe driving behaviour by the first vehicle). Most existing mix-traffic models employed the basic principles of homogeneous traffic models development which deviate from the heterogeneous nature of a mix of Av and HV. [TSN99] proposed a Generate-Spatio-Temporal-Data (GSTD) algorithm for generating two-dimensional moving points over time as a line in three-dimensional space or rectangular data that follow an extended set of distributions. This work of [TSN99] was extended by [PT03, TVM02] with the introduction of new parameters to create more realistic object movements and permit the creation of trajectories originating from objects moving in an obstructed environment. However, the works of the above three authors did not consider a road intersection as the basis of its simulation. In contrast, other researchers like [Li13] considered their model as a network but not in a mixed traffic environment.

Traffic intersection is the major part of the road segment that experiences high traffic congestion and high-risk level. The regression approach or the gap-acceptance method are often used to analyse the intersection. In most countries' intersection capability manuals, the gap-acceptance approach is commonly used. However, previous research has found that the gap-acceptance approach has a few disadvantages: This approach cannot be used on traffic streams that do not follow a consistent pattern of car behaviour. The gap-acceptance theory fails when a mixed behaviour of aggressive and gentle cars co-exist. The basic model of car-following was designed for homogeneous traffic conditions whose traffic parameters utilisation cannot effectively address a for mix-traffic conditions. In a dynamic traffic behaviour scenario, the current research direction in mix-traffic is to apply the technique of the homogeneous car-following model to heterogeneous mix-traffic models. When combined with the intelligent driver model (IDM) proposed by Treiber in [KTH10] for a single-lane road with heterogeneous traffic behaviour, the Gazis–Herman–Rothery (GHR) model used in modelling complex 2-dimensional traffic could not effectively handle a mix-traffic scenario. This will go a long way to address the research gap of evaluation of 2-dimensional traffic using both a linear and IDM model of traffic flow. However, a modification of Gipps' model was used on a single-lane route to provide vehicle-type-based parameters for various combinations of cars, trucks, and buses.

Simulation of Mixed Traffic Mobility (SiMTraM) was used in one of the standard car-following model structure simulators to create a new approach to modelling heterogeneous traffic flow conditions (SUMO). SUMO is a multi-modal traffic simulation package that is open-source, compact, microscopic, and continuous. It is designed to manage massive traffic networks. However, SiMTraM and SUMO have a downside in that they cannot comprehend vehicle behaviour in a variety of traffic environments. In addition, to model a traffic mix flow scenario, assessing the effect on individual vehicle behaviour is needed. This model can account for the dynamic interactions between individual vehicles, road structures, and the need for model calibration and validation using real-time data. As proposed by [CA14, DASM+09], the multistep sensitivity analysis (SA) approach for model calibration is crucial for a compelling description of a complex traffic simulation like the mix of AV and HV. However, its main obstacle is the high number of model runs required for such sophisticated techniques.

Because drivers tend to maintain a safe gap with others to avoid a collision, the safe-distance modelling approach is reliable in simulating the longitudinal movements of different vehicles in a mixed traffic stream. Furthermore, compared to fuzzy logic models, cellular automata models appear to be more appropriate for modelling lateral interactions or lane-changing behaviour of vehicles. Incorporating vehicle-type-dependent behaviour in mixed traffic conditions of car-platooning models to precisely recognise driving behaviour. In the basic car-following model, a traffic collision is imminent when the leading vehicle's operation is uncertain, resulting in a decrease in relative spacing between the vehicles, jeopardising the safe following distance. Azevedo in [CA14], made an essential contribution to developing a safe distance model that successfully estimated actual vehicle behaviour in a variety of traffic conditions. However, the model's accuracy in estimating the safe distance remains undoubtedly because this critical aspect of the model was not captured.

2.11 Summary

In summary, this chapter presents the background of literature in traffic management, with fundamentals in describing traffic control systems and details of the impact of traffic control parameters. The related literature in conventional traffic management, intelligent transportation, and mix-traffic management system was captured in detail. The state of the art methods in managing both homogeneous and heterogeneous traffic systems is also presented with suggestions on addressing mixed traffic from the state of the art. From the above review of traffic modelling, mesoscopic models are often hard to discretise or represent traffic accurately and are therefore not often used in traffic simulation and modelling. Besides, microscopic and macroscopic traffic simulation models are often used because they can easily describe the full details of an individual vehicle and group of vehicles respectively. From the fundamental diagrams of traffic flow, the proposed AVHV control mixed-traffic flow could be realised by combining both microscopic and macroscopic traffic model parameters. However, microscopic models and simulation tools could perfectly forecast traffic in a more detailed way, therefore the microscopic model is proposed for use in effectively predicting the behaviour of individual vehicles in mix-traffic settings. The review of the state-of-the-art in mix-traffic modelling capabilities indicated that no single traffic model could address a mix-traffic of AV and HV effectively. Existing analytical models, such as car-following models, have demonstrated greater flexibility while requiring less computational workload than rule-based cellular automata models, which use complex rules to simulate vehicle dynamics. In modelling an efficient 2-D behavioural traffic flow model that can accurately replicate a mix of Av and HV behaviour environments, there is a need to incorporate more than one traffic flow model with varieties of parameters. The proposed model involve the integration of traffic simulation models with the required modification to meet the functionality involved in a mix-traffic setting. The proposed single lane-based model considers the left and right lane as agents for joining the vehicle platoon or the new lane. These behavioural features of the model are what will make vehicle co-existence possible. Based on the foregoing, two traffic models (car-following and gap acceptance model) were identified for integration and enhancements to support a mix of AVs and HVs model. There has been much improvement in mix-traffic management strategies over the years, but the state-of-the-art has not addressed the challenges attendant to mix-traffic using the 2-dimensional gap-acceptance method in a car-following model. From the review finding, the currently available mix-traffic models cannot be directly utilised to simulate a traffic-mix involving AV and HV without modification to the identified essential traffic parameters holistically in each vehicle type for the model. The proposed transition to the fully autonomous driving vehicle has generated various expectations ranging from an increase in traffic efficiency, decrease in traffic incidence, increase in road comfort, decrease in carbon emission, decrease in fuel consumption, and decrease in driver shortage. Within this envisaged transition and integration period of the co-existence, there is a need for a robust technology to be put in place to drive and support the transition process. This critical review of the state of the art in mix-traffic management and the definition of the research gap lead us to the development of our proposed model design Section 3.2

Chapter 3

Research Methodology

Chapter Overview

This chapter presents the framework for the research design methods and strategy for mixed-traffic management. Section 3.1 presents the research hypothesis involving the research background idea and explaining the problem investigated through experimentation. Presented in Section 3.2 are the research design procedure, methodology, and fundamental assumptions of the proposed model. The proposed mixed-traffic solution is presented in Section 3.4. The solution requires only minor extensions to the existing road infrastructure by adding vehicle collision points, a coordination unit that manages the reservation nodes, and the coordination protocol. An abstraction of the traffic flow model in Chapter 4 to better understand the assumptions used for the implementation is presented in Section 3.5. In Section 3.6, the mathematical model for vehicle dynamics and kinematics is described presenting the underpinning vehicle physics. In Section 3.7, the cars' high-level behavioural model is discussed, illustrating the similarities and differences between human drivers and autonomous systems. Also described in Section 3.7 is how cars are created, the traffic routing and scheduling method used. Section 3.8 describes the traffic flow model design with vehicle type contingencies detail. Section 3.9 presents the road system infrastructure design used for the evaluation purpose. Finally, Section 3.10 present a summary of the chapter.

3.1 Research Hypothesis

The hypothesis investigated as part of this thesis is: "reservation of intersection nodes for vehicles provides a seamless, safe, and efficient traffic flow". The co-existence of traffic with distinct characteristics (autonomous and human-driven vehicles) decreases the traffic flow efficiency and safety. High traffic flow performance at road intersections is a result of an optimum traffic management scheme. One could investigate the expected impact of autonomous vehicles on human-driven vehicles by integrating a varying proportion of the two-vehicle types in a scenario when they co-existence. It is anticipated that AVs presence in a mixed traffic scenario will improve the traffic flow efficiency of HVs through an optimised distance headway that exists between AVs and HVs. The HVs naturally is associated with inefficient traffic flow due to the unpredictable human drivers' behaviour. This envisaged inefficiency in mixed traffic coursed by HVs presence is due to the complexity in managing the variation in the vehicle behaviour and control parameters. Typical traffic signal control systems at a signalised intersection are designed to accommodate a range of target users, usually at the traffic detector instead of collision points. The detector level control is based on traffic cross-section characteristics at the intersection instead of individualised traffic characteristics. A detailed investigation of the different mix-traffic management strategies is carried out, and this forms the basis of this proposed method. The road intersection is the point of vehicle collision occurrence; hence this study is based on the road intersection area. According to [WN18], AVs benefits cannot be over-emphasised. Its emergence and the need for co-existence are inevitable. Thus, it was hypothesised that vehicle collision at the cross collision points (CCP) in an intersection space would increase drastically because of the barrier in communication between AVs and HVs. Besides, the traffic flow performance improves by assigning time steps at the CCP for multiple vehicles that share the same CCP on its trajectory. In a mixed traffic system, every participating vehicle is driven by human beings or autonomously driven by a computer system. It is required that the driving behavioural model must depict the real-life roads and vehicle system. The model should simulate actual human drivers' behaviour, such as acceleration, deceleration or braking, car-following, obstacle avoidance, observing traffic signal rules, and many others. The design establishes the relationship between the autonomous vehicle (AV's) and human-driven vehicle (HV's) with a performance impact on either vehicle type using different vehicle mix ratios. The proposed traffic simulator involves a causal design strategy where the observation of the gradual impact caused by the introduction of autonomous vehicle is made. For example, one monitors the influence of introducing a given ratio of AV's on an existing HV's traffic system.

The rationales for the research conducted in this thesis reflect the challenges faced in mix-traffic management, emphasising the driver behaviour problems in a car-following model . Previous researchers resorted to various traffic flow control methods and approaches such as car-following, vehicle platooning, and cellular automata models to address this challenge associated with drivers' behaviour. The drivers behavioural model's core problem is developing a strategy that describes a 2-dimensional lateral and longitudinal driving behaviour needed for a realistic mix traffic flow model. Factors such as lateral vehicle displacement, driver behaviour, and the environmental influence of surrounding vehicles control the vehicle interactions along the road. The idea behind cooperation among vehicles is to use information collected by employing vehicle-to-vehicle communication links to adjust the vehicle's motion, reduce idling time, and fuel consumption rate at a road intersection. Generally, it is assumed that autonomous vehicles communicate with the road infrastructure and receive information about the intersection environment and upcoming traffics approaching the intersection.

3.2 Research Design

The high-level design and framework of the proposed system works by assigning individualised nodes and time to each vehicle when they may enter an intersection space. When we reserve a node in the road intersection space, AVs and HVs can achieve maximum driving utilisation. The idea is conceived from the way aeroplane makes use of reservation node for landing purposes. Driving a vehicle across an intersection requires some precautions because other cars share the same space and will naturally become worst when AV and HV of different characteristics co-exist. The basic idea of the AVHV control mixed-traffic algorithm is to model a safe and efficient vehicle control scheme at a road intersection. The system's makeup is purely driven vehicles by a human being, without any vehicle to vehicle (V2V) or vehicle to infrastructure communication facilities on the one hand, and autonomous vehicles with fully vehicle-to-vehicle and vehicle-to-infrastructure communication facilities. The concern in modelling the mixed-driving of human and autonomous vehicles poses a danger due to the communication barrier between the two-vehicle category. The hardware installation is easy and cheap because it uses the existing traffic infrastructure for AVs and HVs. The AVs can ignore the traffic light signals, but AVs predict where HVs will be going and sequentially synchronises with their control operations. Human-driven cars take precedence over autonomous vehicles whenever they request to access a shared reservation node at the intersection as reflected in the research goal Section 1.3. The autonomous vehicles' behaviour control is seamless, environment aware and take decisions at real-time with the aid of its intelligent transport features. The intelligent transportation features benefit of autonomous vehicle drives the quest for its emergence, which begins with its integration with human-driven cars to co-exist, but the integration implementation details remain uncertain. The AVHV control method relies on applying available scientific theories on reservation nodes and is more efficient than the existing traffic control strategies.

The programming language tool chosen for the development of the system is Python 3.8 because it is easy to use, maintain and read code. With its large standard libraries, Python effectively manages an extensive application of this kind that supports multiple programming paradigms. Besides, Python simplifies the complexities of software development, and it is cost-effective. The implementation effort is toward a systematic mixed-traffic management strategy that will avoid potential vehicle collisions and guarantee an efficient traffic flow. The AVHV control model design allows for a choice in the research method of traffic management procedures, processes, or techniques utilised in the new system's design and analysis to uncover further information suitable for mix-traffic management.

3.2.1 Research Procedure

This section presents the related activities undertaken to achieve the investigation's objectives and offers possible solutions to the mixed-traffic integration problem. The proposed traffic intersection management's execution is based on Figure 3.1 - the road framework used in developing the proposed traffic model, where L_1 *to* L_8 represents the road lanes. The proposed scheme is centrally coordinated through the intersection control unit (ICU). The strategy efficiently utilises the intersection zone by assigning reservation nodes to pairs of conflicting vehicles from accessing a common cross collision point (CCP) at the same time instance. This approach improves the utilisation of the intersection space by assigning the nodes successively to vehicles sharing trajectories. The conventional traffic management system reserves the entire intersection zone for one of the conflicting vehicle trajectories. Furthermore, the introduction of appropriate constraints ensures the strategy is free from any crash and controls the vehicles' turning motion under a safe velocity limit mode. Turning vehicles at an intersection occasionally need specific control measures so that various traffics slowly and firmly cross the intersection. The autonomous vehicles use a traffic coordination scheme that directs vehicular traffic close to the intersection-priority conflict zone. This vehicle turning process involves autonomous vehicles communicating with the dynamic traffic control system located on-board its potential travel-priority conflict zone to prioritise human-driven vehicles to avoid a travel-priority conflict.

However, the main interest is implementing a traffic intersection strategy that will avoid potential vehicle collisions and guarantee an increased traffic flow efficiency at the road intersection space. The management of vehicle arrival requests and granting access to enter the intersection irrespective of its communication parameters is one of the primary objectives of this traffic scheduling scheme. Meanwhile, the proposed strategy concentrates primarily on intersection usage safety while reviewing other methods with our model to improve travel time, general traffic flow efficiency, and enhancement of safety. Another aspect of improvement on the mixed-traffic efficiency is speed control, which is being leveraged by human-driven vehicles. The improvement in traffic efficiency involves the automated management of autonomous vehicle velocity to avoid stopping at the intersection once all the cross collision points of its trajectory are accessible at the time instance.

Figure 3.1 represents the structure of the proposed 4-way road traffic intersection with distinct attributes. The mixed-traffic control environment synchronises both the traffic light signal of HV's and the wireless communication devices from the AV's atmosphere through a central intersection control unit. The intersection control unit computes and exchanges information with all the vehicle types and performs required computations simultaneously to harmonise all vehicles crossing the intersection safely. It also has two ad-

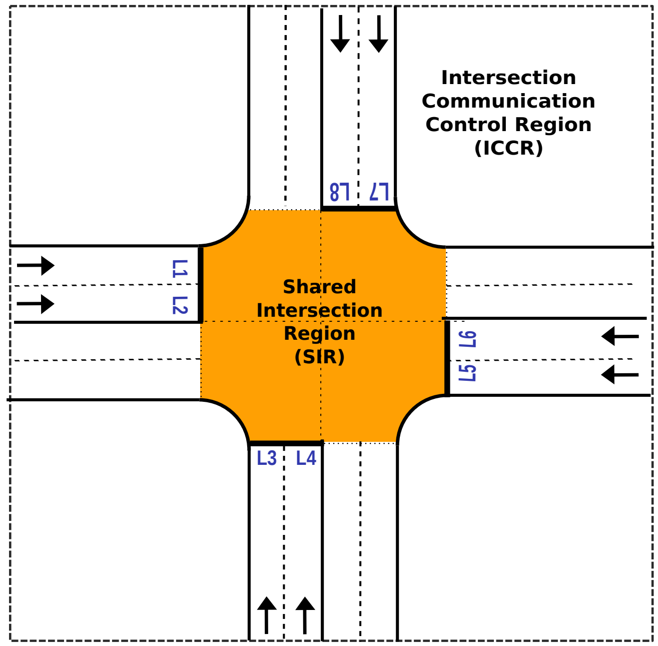


Figure 3.1: Road framework

jacent lanes of incompatible vehicles accessing the intersection facility simultaneously. In Figure 3.1, there are two critical regions for traffic monitoring and control:

1. The Intersection Communication Control Region (ICCR)- used for registering vehicle arrival.
2. Shared Intersection Region (SIR)- The traffic management strategy is applied here for seamless car usage from the different trajectories or lanes without collision.

The geometric road parameters are classified according to the vehicles' movement dynamics, whose objectives are to optimise safety and traffic efficiency while minimising environmental damage and cost. It is common knowledge that there is a potential cause of harm in safety-critical situations for an artificially intelligent system such as autonomous driving vehicles, which has been gaining research attention in recent times. For instance, the autonomous vehicle decision-making process at intersections is induced by the vehicles' arrival process in real-time. The model of the autonomous vehicle system detects and communicates with other vehicle approaching the intersection using the traffic parameters of Speed, flow, density and lane.

Intersection Communication Control Region: In this case, the intersection control uses both traffic lights signal to control human-driven cars, just like the conventional traffic system, and a wireless communication control environment. Both control media share the central intersection coordination model. The control unit can compute and share information with human drivers and performs required computations to harmonise all vehicles crossing the intersection safely. This event-driven traffic signal light control synchronises with the intersection control traffic system in AVHV control. An infrared device updates the real-time event with the lane on which a vehicle is approaching an intersection. Once a vehicle enters the communication zone, all these parameters act as an input to the control unit.

A vehicle detector at the ICCR senses vehicle presence from the infrared radar and feeds back to the control unit, whose responsibility is to classify the vehicle's type and grant permission to cars to cross the intersection space on a predefined rule basis. The installed intersection coordination unit (ICU) uses a two-way communication approach to receive necessary navigation information (such as current vehicle velocity, route, and position) from the next reservation node, all from the approaching vehicles. It sends real-time information on path advice to vehicles after evaluating their control parameters.

The combination of inter-vehicle communication features (IVC) and road-vehicle communication (RVC) produces a robust solution to the safe distance model and collision avoidance problem. The control of vehicle collision avoidance is by vehicles' relative distance in a car-following model. The inter-vehicle-space adjustment is only possible for AVs and not for HVs with a longer reaction time to mimic human behaviour. These high values are required with higher braking force to harmonises HVs' braking pattern with AVs. From our design, both AV and HV decelerate to 1 unit less the car's speed ahead in both cases. Speed is used to decide this effect because it is relatively easier to perform scalar operations and make comparisons with scalars than vectors. This technique ensures that the car behind has a lower velocity than car in front, and hence less likely to collide.

The lane detection scheme is critical in the road traffic study, especially regarding autonomous vehicles for essential sideways navigation processes. Some of the lateral movement processes are the lane departure warning system and the lane-keeping assistance system, which helps collision avoidance at the intersection. Furthermore, when lanes are detected, it could be considered as an indication of the vehicle's motion trajectory as it could be a crucial factor in deciding the extent to which an obstacle could be affected or not. Besides, longitudinal systems such as AV emergency braking systems could be agreed upon by lane detection. The adaptive cruise control and collision warning systems could indirectly affect the full spectrum of the automated driving system. This explanation defines the direction of the integration of the human-driven and autonomous vehicle process.

Shared Intersection Region (SIR) Figure 3.2, the shared intersection region represents the centre shared area where vehicles enter the intersection and connect to another lane. The area covers the 20 number cross collision points (CCP) s for a crossroad intersection. Wireless synchronisation between the traffic light, autonomous vehicle, and the input from the Intersection Control Region with a view of avoiding car collision at the CCP's defines the shared intersection region. Naturally, traffic congestion can be controlled by reducing the number of cars and increasing the shared intersection space or creating different schemes for each vehicle type contingencies in mixed traffic. However, this method might not be a feasible solution since increasing the shared intersection space will affect the road intersection design, and road reconstruction will face financial, economic, and environmental challenges. From Figure 3.2, L1 to L8 depicts the entering lane for the vehicle into the control region of the intersection while numbers 1 to 20 represent all the cross-collision points of vehicles within the intersection space.

The collision avoidance procedure uses the reservation node method as proposed to identify only the available portion of the intersection precisely. Besides, when two conflicting vehicles access the same CCP simultaneously, the risk function returns a high value to trigger the vehicle deceleration process. But, in a scenario when one vehicle is far from the CCP, the risk value returns a negligible value, allowing vehicle access to the intersection. The vehicle's state is considered based on its movement parameters and position, and distance to the cross collision point. The safe trajectories of vehicles are generated by reducing available time and space in the intersection area, which helps in risk minimization. This process accordingly increases the traffic-handling capacity of the intersection with an increase in traffic flows efficiency. Mitigating the risk factors associated with autonomous vehicle sensor failures is by using a single failure assumption method. This method states that one sensor can fail at any time in most cases. The component's failure rate is managed using a single failure rate approach to cover each operating condition instead of using an individual failure rate, which is not cost-effective. However, simple algorithms are used in the system's failure auto-detection mechanism, a feature in autonomous vehicle sensors systems. This process is generally carried out to develop a model-based fault-tolerant control scheme for vehicle lateral dynamic control. However, the single failure rate technique is effective in detecting and identifying sensor failures immediately upon occurrence. Then a mechanism of reconstructing the faulty sensor from the output of the healthy ones is applied. This process is called "Sensor data reconstruction using bidirectional recurrent neural network". Furthermore, it is intended that by increasing the proportion of AVs, the traffic delay will decrease because of the AVs level of intelligence and rapid response to control or instruction.

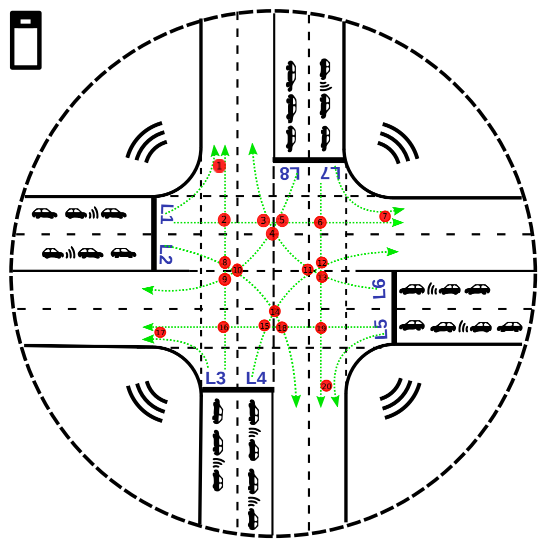


Figure 3.2: AVHV control region with 20-cross collision points

For a practical and safe co-existence, vehicles crossing at intersections must observe some lay-down crossing or joining protocol to guide the co-existing relationship. With these requirements in mind, the proposed model design is equipped with a specific autonomous and human driving system behaviour feature. The prototype traffic management system does not deviate from the baseline vehicle type characteristics, motion trajectory, and control. In achieving the above goal of maintaining the vehicle type movement characteristics, the AV and HV control parameters are combined in a single scheme. Meanwhile, this strategy concentrates primarily on the safety of intersection usage by traffics while we review other strategies with our model for improvement on the throughput of the intersection space. Other researchers [PDD^{+}03, THH00, KIO^{+}12], have applied the strategy of using speed to control autonomous car velocity and acceleration to avoid stopping at intersection points, but this strategy was only implemented for AVs usage alone and not in a traffic mixed environment

The traffic flow implementation process followed a systematic approach to creating traffic scenarios, testing, and validation of the proposed scheme. Table 3.1 demonstrates a matrix of car trajectories with 20 cross collision points (CCP) represented as "P" and $L_1 - L_8$ represents the road lane. These 20 collision points are where the possibility of conflicting vehicle collision is high if not well managed, and they are referred to as reservation nodes in the model design. "0" represents an incompatible or unavailable (unsafe) collision point , while "1" represents compatible and available for use collision (safe) points.

The vehicle control mechanism at the road intersection varies between autonomous vehicles (AVs) and human-driven vehicles (HVs), respectively, but the two control methods synchronise for safe and optimal performance. Like other mix-traffic models, HVs takes the default priority. This vehicle control rule followed a scheduling mechanism computed based on vehicle speed and in managing the cross collision points. The proposed model development combines two existing traffic models:

- Car-following model: This car-following model maintains a longitudinal trajectory for a particular route on the intersection, making it easy to predict potential conflict points.
- Gap-acceptance models: The use of gap-acceptance addresses vehicle conflicts at cross-collision points by assigning intersection reservation nodes as a sequential vehicle occupation of points.

Though the two models differ in their spatial representation of driving patterns, they form a safe and optimal mixed-traffic flow model. The optimization of this scheme allows conflicting vehicles to simultaneously move on an intersection as long as their trajectories do not simultaneously share one cross collision point.

Table 3.1: Lane Trajectory Matrix For a 4-Way Dual Lane Road Intersection (Key: P = collision point)

ID	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	P_{16}	P_{17}	P_{18}	P_{19}	P_{20}
L1	1	1	1	1	1	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0
L2	0	0	0	0	0	0	1	1	1	1	0	0	0	0	0	0	0	0	0	0
L3	1	1	0	0	0	0	1	0	0	0	1	1	0	0	0	0	0	0	0	1
L4	0	0	0	0	0	0	0	0	1	0	0	0	1	1	1	0	0	0	0	0
L5	0	0	0	0	0	0	0	0	0	1	1	1	1	0	0	1	1	0	0	0
L6	0	0	1	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0
L7	0	0	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1	1	0	0
L8	0	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0	1	1

Table 3.2: Path Relationship Table

Path ID	lead vehicle route an Lane	Option route1	Option route2	Option route3
West L1	(1,2,3,4,5,6)	L2(7,8,9,10)	L4(9,13,14,15)	L5(10,11,12,13,16,17)
West L2	(7,8,9,10)	L1(1,2,3,4,5,6)	L6(3,14,18,19)	L7(5,6,15,16,17,18)
South L3	(1,2,7,11,12,20)	L4(9,13,14,15)	L6(3,14,18,19)	L7(5,6,15,16,17,18)
South L4	(9,13,14,15)	L1(1,2,3,4,5,6)	L3(1,2,7,11,12,20)	L8(4,8,19,20)
East L5	(10,11,12,13,16,17)	L1(1,2,3,4,5,6)	L6(3,14,18,19)	L8(4,8,19,20)
East L6	(3,14,18,19)	L2(7,8,9,10)	L3(1,2,7,11,12,20)	L5(10,11,12,13,16,17
North L7	(5,6,15,16,17,18)	L2(7,8,9,10)	L3(1,2,7,11,12,20)	L8(4,8,19,20)
North L8	(4,8,19,20)	L4(9,13,14,15)	L5(10,11,12,13,16,17)	L7(5,6,15,16,17,18)

AVHV control Relationship Table

The AVHV control relationship table defines the road lanes (L_1 *to* L_8) with collision-free vehicle trajectories, which explains roads lanes whose vehicles can cross the intersection at the same time. The table contains details of vehicle route which can access the intersection simultaneously. Table 3.2 represents a trajectory relationship for a safe and seamless traffic flow. An efficient traffic scheduling scheme for a mixed vehicle is developed , the model will be compatible with any traffic intersection configuration. One can safely and adequately define the relationships among the lanes of trajectories that make up the intersection type. A lead lane is a lane that encounters the arrival of the first vehicle from the infrared detector at each instance, but in a situation where there is more than one lane experiencing vehicle simultaneously, the control unit grants access based on the priority of a human-driven vehicle.

However, looking at Table 3.2, the lead lane and its alternative lanes that can be combined simultaneously for vehicles to move simultaneously without any collisions to be encountered are explicitly defined. In a real-life model, there is still conflict among vehicle trajectories because of vehicles arriving simultaneously. In this scenario, the control system will handle this problem based on the lane with the first arrival or priority car or any rule choice. For instance, in L1 active lane, conflict occurs at point 9 between L2 and L4. Below is a description for the AVHV control collision algorithm for vehicle crossing the 4-way intersection.

Overview of the AVHV Algorithm The AVHV control algorithm for vehicle crossing the intersection observes a set of rules 1. The control process uses the vehicle's distance (represented in time(sec)) to the Reservation Node, priority vehicle and the right of way in assigning intersection space to vehicle. The control algorithm process applies the deceleration process to vehicles once their next node of arrival is the same node of arrival to the next car (more than one cars sharing the same RN at the same time).

Caveats and Special Cases for $4 - Way$ **AVHV control Algorithm with three Vehicle:**

- If a vehicle is aggressive, it ignores the rules and gives the right of way to that vehicle to ensure safety.
- Else, keep other cars yielding and allow the first car with the right of way to pass.

Under these mixed-traffic conditions, it will not be feasible for the human car drivers to predict an autonomous car's movements and vice versa. It is expected that traffic-mix involving human-driven vehicles (HV) and autonomous vehicles (AV) of varying behaviour: velocities, accelerations, reaction time, safe and distances, will give rise to more complex traffic behaviour. This mixed traffic behaviour causes vehicles to interact with other vehicles both in lateral and longitudinal directions at a road intersection. Consequently, a comprehensive analysis needs to be conducted to evaluate the heterogeneous traffic flow induced by mixed behaviours and propose a reliable strategy to handle such a scenario.

Based on the preceding, an alternative mixed-traffic management strategies of "Node reservation based intersection control management" Figure 3.6 is proposed. At the intersection, vehicles are allocated with reservation nodes at a time instance. At airports, air-plane are assigned landing nodes to avoid collisions. This proposal followed a review of traffic management strategy by avoidance of cross collision points. This involves using a centralised control of traffics by simultaneously preventing two vehicles from meeting at the cross collision points. Figure 3.2, describes the proposed intersection model whose strategies aim to prioritise the human-driven vehicle and control the speed of autonomous vehicles when they share the same cross collision points. Before the advent of vehicles with intelligent transportation features, traffic management strategies have focused on ensuring that road users comply with traffic rules by educating traffic users, implementing the engineering traffic management approach, and enforcing traffic rules to improve traffic performance. The objective of this approach is to implement a strategy to solve the following problems associated with mixed-traffic:

- Achieve a feasible, clear, consistent, and understandable co-existence of mixed traffic.
- Enhance the performance of traffic, pedestrians, and quality of life within the society
- Make the human-driven vehicles benefit from the efficient features of autonomous vehicle.

Table 3.3, presents a detailed schedule of how traffic moving from different lanes could be controlled simultaneously without conflict. Where' 0' and' 1' represent conflict and free flow lanes, respectively. The model could be optimised by assigning landing nodes to each collision point, defined as a reservation node.

3.2.2 Car Control Routine

This subsection deal with the underpinning sequence of methods that guide the full details of the car's behaviour. The design of the method involves creating objects with member variables and having behaviour associated with them concerning expressing the variables. These methods listed with a brief overview are in order of relevance, not necessarily in the way they are ordered in code, while those not consequential to the movement control of the car are neglected.

1. $Next_{Node}$: This method feeds the next route node that should be traversed by the Car. It produces the next point on the road for the Car to move to like a conveyor belt as long as the Car is not at the last node or minimum deceleration distance to the node.

2. $Reach_{Node}$: This method check the approximates position of Car to match node's position. This method copies the position of the next node on the list and assigns it to the Car's position. The reason for doing this is to ensure that the Car reaches the node otherwise, as there are infinite values between any 2 numbers, there is a high probability that the Car will never reaches the node.

3. $Move_{Car}$: This method moves the Car in a specified direction or manner, while checking for traffic control, intersections or obstacle. The X, Y, and Z coordinate axes contribute each component to a unit vector in the direction of Car movement.

4. $Set_{Environment}$: This method sets the running environment, using the Car's parent's method above. It Sets the Car's environment; copies route nodes into a "cache" variable.

5. $Behaviour_{Update}$: Updates properties of the Car; calls $Next_{Node}$, turning, $Move_{Car}$, and keeps updates the number of braked cars and cars in collision in the environment.

6. $Physics_{\,Update}$: This method updates the Car's properties using the parent's method physics, which is a method of physical forces properties (magnitude, direction,velocity, acceleration). It updates the physics of the Car, turning: keeps the right direction for the Car at all times.

7. $Apply_{\,Force}$: This method is responsible for applying engine force to move the Car. In addition this method requires another parameter called magnitude around curve ($around_{curve}$), which is used to curve the Car. It applies an engine force to accelerate and move the Car.

8. Decelerate: This method applies brake to the car to initiate the deceleration process. Speed brakes enable the car to carry out rapid deceleration reduction in speed or rate.

9. $Safety_{\,Control}$: This method prevents collisions of cars based on the reservation nodes system. This method is the collision avoidance protocol. It is a risk mitigation system designed to prevent any car collision

How the cars (AVs and HVs) are modelled The prototype model is built to represents a typical AV and HV, while approximating most of some salient features of the real-life system as closely as possible. Below are some of the essential attributes built-in on the model.

- AV observes a gentle driving style.
- AH observes an aggressive driving style.
- AV is environment self-aware with a gentle driving style features.
- Av is assigned a static reaction time value of 0.1 secs [LB16] for traffic stability to be maintained.
- HV is assigns randomised reaction time for HV's = 0.3 - 1.5 secs to reflect different driving psychology [MM08a].
- Priority is assigned to HV with aggressive behaviour for common space at any time instance.

3.2.3 Car Movement Control Process

Each car in the simulation checks at every instance of time "t" (0.1sec) and updates its current status. In real life, this translates to alert drivers paying full attention to the road and/or autonomous vehicles measuring distances between themselves and cars in front of them using LIDAR (or similar technology). A vehicle's distance to the car next in front of it is measured, and if this distance is less than the car's established safe distance, the car slows down or brakes as necessary otherwise, it maintains its velocity. The sequence of the logic involved in the vehicle movement control could be summarised as follows:

- Go through list of cars in the system:
- Get this current car's distance to the cars before it
- Repeat this process for all cars in the system
- Find the minimum distance in all these distances
- Check if the current car's distance to other car < it's safe distance:
- Car should brake and stop accelerating

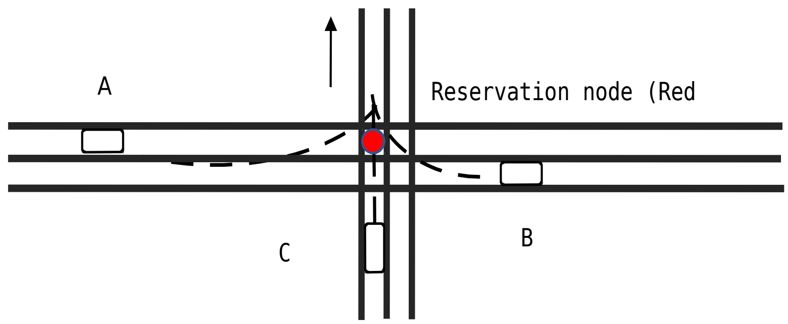


Figure 3.3: illustrating example

- Or, Car should keep going

The Vehicle Group Controller's (VGC), otherwise called the Reservation Node algorithm, coordinates the vehicle movement and prevents collisions by comparing and prioritising vehicle movements based on their nearness to a reservation node of reference. The VGC takes care of traffic coordination in the road intersection system on a broader scale. Each car in the system ensures that it does not collide with the vehicle in front of it through safe distance checking (See Movement Control above). In contrast, the VGC d several cars at once – directing them based on nearness to reservation nodes. The logic of this Reservation Node algorithm is represented in Figure 3.3

Explanation of the scenario in Figure 3.3 Assuming we have 3 cars; A, B, C and their routes have a common node (or meeting point, i.e. their paths will cross at some point). The steps involved in the Reservation Node process is represented in the RN scenario described in Figure 3.3.

Vehicle Movement Control Methods in the EnvironmentObject Class

The EnvironmentObject is responsible for driving all the physics of the car in guiding its movement process. Some key points to note:

- The car needs to remember its direction and the its polarity. It needs to recall if its velocity was negative or positive in the past. This influence the decision taking process of the car motion.

- To solve the Car Reversal Problem Section 3.3, we check for both components, x, and y of the Car's velocity with the $checked_{polarity_x}$ and $checked_{polarity_y}$ fields. Whenever a velocity component dips below zero, mark the polarity as negative (-) with the $polarity_x$ or $polarity_y$. Conversely, when it rises above zero, mark the polarity as (+), otherwise, the polarity is not set. When setting the polarity of that velocity component, make sure you don't reset it by setting $checked_{polarity_x}$ to True. Do the same for the $x_{component}$ but applied for the $y_{component}$.

- The road layout is easy enough that this polarity checking mechanism will suffice until the cars reach their destinations.
- Update the Car's velocity with its acceleration (or deceleration), scaling by the update time (0.1 secs).
- Check if the Car's polarity for the x- component of its velocity has been set, and the x component of the velocity goes below 0.0 even though it was positive at the previous time step (it was moving from left to right), set it to 0.0 to prevent the Car from reversing.
- Check if the y-component of the velocity goes below 0.0 and set it to 0.0 to prevent the Car from reversing.
- Check if the component of the car velocity rises above 0.0 even though it is negative (it was moving from down to up), set it to 0.0 to prevent the Car from reversing. Round the velocity components (x and y) to 2 decimal places.
- Update the Car's position with its velocity scaling by the update time (0.1 secs):

3.3 Car Reversal Problem

When a car moves from point A to point B in real life, the positive or negative coordinate values do not affect its acceleration or velocity. The car reversal problem only has to do with the movement direction and deceleration process of the car and has nothing to do with "car-following" and "gap-acceptance models". Figure 3.4 describe the car reversal problem highlighting the differences between road system representation in real life and on a computer screen (arrow directions are for demonstrative purposes). The X and Y coordinate values measures how far the car is from the origin (wherever that may be) along a particular axis. A 2-dimensional plane like the road system has 2-coordinate (X and Y) values that tell the position of any object from the centre. Because of the 2-dimensionality, the velocity and acceleration/deceleration must have 2 coordinate values for both the x and y-axis. The velocity starts from [0, 0] and increases as the car accelerates but decelerates back to [0, 0], bringing the vehicle to rest. The car can take a point of reference anywhere, and from any direction it happens to be facing while in the car, it is the positive direction.

In contrast, when a car is positioned on a computer screen, it is practical to have an origin at the centre of that screen [0, 0] that remains true regardless of scenario – the centre point of reference remains unchanged, and the screen can't be flipped to change the positive and negative direction. The axes polarities left and right from the centre is fixed. The following conditions will be true for a road system represented on a computer screen from Figure 3.4:

- Any location that sits on the left side of that centre will have a negative x property in its coordinate [-x, 0].
- Any location that sits on the right side of that centre will have a positive x property [+x, 0].
- Any location that sits above the centre will have a negative y property in its coordinate [-y, 0]
- Any location that sits below the centre will have a positive y property in its coordinates [+y, 0]

From the above conditions, the car velocity will have the same polarity (positive or negative) on a computer screen as the origin's side to displace the car to that side of the axis. When the car moves towards the left from the origin, it has a negative velocity to displace it to the new negative x coordinate. This is counter-intuitive to what happens in real life because velocity coordinates for a moving car are always positive no matter the direction you face.

Problems that arise with the Car reversal issues: The above limitation poses problems when:

- When the vehicle directions changes: When the vehicle directions change, the car will need to reverse its velocity's polarity as needed or keep moving the wrong way.
- When a car decelerate to rest: When decelerating to rest, the car will need to use the opposite polarities for its acceleration coordinate values to reduce the velocity until it reaches [0, 0], or it will continue moving.

A number line showing how positive and negative values needed to be 'reduced' or 'increased' to approach 0 is described in Figure 3.5. According to Gipp' in [Spy07], a vehicle could be braking harder than its desired deceleration. This scenario deviates from the set maximum acceleration/deceleration; hence it may need a constraint to be fixed.

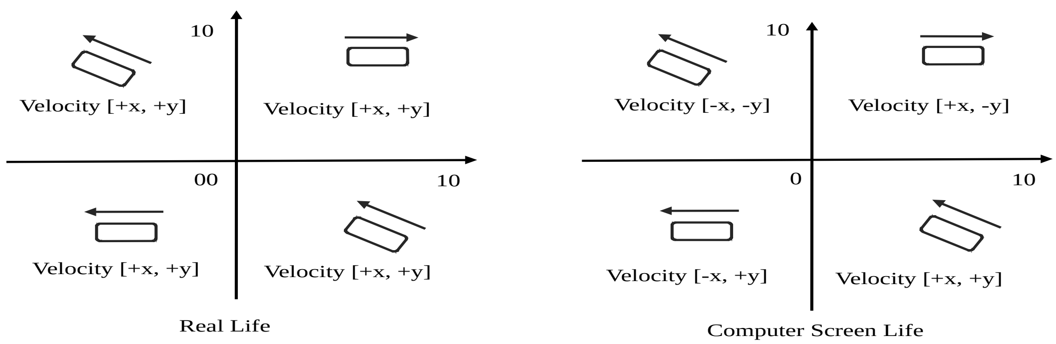


Figure 3.4: Car reversal problem

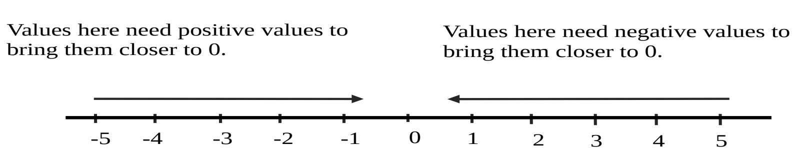


Figure 3.5: Positive and negative values of deceleration

3.3.1 Solution to the Car Reversal Problem:

To prevent the car reserval problem from occuring, each car would store its initial polarity as property and check against it when the direction changes or when coming to rest to know what polarity to assign to its acceleration coordinate values. This method works for the car direction changes, but for deceleration rest, it gets a little trickier because the acceleration and velocity increments can occur in fractions. There is a likelihood of overcompensating, causing the car to reverse or under compensating, leaving the car to keep moving in the direction it was beyond the destination point.

3.3.2 How the vehicle movement control methods relate to the proposed car-following and gap acceptance model

The vehicle movement control methods is dependent on three main factors when executing a car-following and gap-acceptance model:

- Reaction time
- Safe Distance (Minimum accepted gap)
- Aggressiveness

The relationship between the above factors brings us to the differences between an AV and a HV. The safe distance calculation for an AV used a default value of 0.1seconds. Conversely, HV need to add in some randomness to simulate the less preciseness and aggressiveness of a human drivers, as shown below:

$$Safe\ distance = speed * random\ factor * reaction\ time * acceleration * (reaction\ time)^2 \tag{3.1}$$

$$Reaction\ time = Pick\ a\ random\ number\ between(0.3 - 0.75) \tag{3.2}$$

$$Random\ factor = Pick\ a\ randomnumber\ between(1.0 - 3.0) \tag{3.3}$$

3.3.3 The working of the Vehicle Movement Control Procedures:

The process of this model could be subdivided into following broad categories

- Introducing cars into the roads:
  - Spawn car in each route
  - Wait for car to travel a safe distance is made
  - Spawn another car
  - Repeat until all the cars have been spawned
- Move the car on the road:
  - Go through list of cars in the system
  - Get this current car's distance to the cars before it
  - Repeat for all cars in the system
  - Find the minimum distance in all these distances

  - If the current car's distance to other car < it's safe distance
  - Car should brake and stop accelerating
  - Otherwise Car should keep going

- Human Driving Behaviour:
  - Humans are more aggressive drivers.
  - Humans are less precise drivers.

- Autonomous Driving Behaviour:
  - Autonomous systems drive cars more gently
  - Autonomous systems drive cars more precisely

Relationship with Human-Driver's Psychology:

  - if car acceleration is non-zero:
    - For AV: reaction time = 0.1
    - Random factor = 1.0 (same as having no randomness)
  - For car is a HV:
    - reaction time = Pick a random number between (0.3 - 0.75)
    - random factor = Pick a random number between (1.0 - 3.0)
  - $safe\ distance = speed * random\ factor * reaction\ time + \sqrt{(speed^2)/acceleration)} + reaction\ time$

How Reservation Node Algorithm is applied with the Safe Distance:

The Car Movement Control Methods is domiciled in the Environment Class with state variables whose values are calculated in the Car class at every time instance. This control measure could be summarised as follows:

- Prevent collisions of cars based on applicable reservation nodes of cars and distances between cars.
- Take inventory of all cars in the simulation.
- Create dictionary for time to node lookup.
- Loop through all the $active_{reservation\ nodes}$
- Check for each active $reserved_{node\ id}$, Loop through all cars.
- Check to see that this reservation node applies to this Car and find its time of arrival at the reservation, and then reserve a node. Then store results in lookup - dictionary.
- The above instruction goes through all the cars,
- Then calculate the distances from the Car of reference to other cars coming before it.
- Check to if they have not arrived their destination.

- Apply break if safety distance is met and decelerate the Car making sure it does not exceed the minimum safe distance. Or continue accelerating the car to maintain the maximum speed provided that the safe distance has not yet been met.
- Make sure that there is at least one time to look up in the system.
- Calculate the distances from the reference Car to other cars before it, that haven't reached their destination yet $other_{car\ is\ reaching\ destination}$..
- And if any of those distance lengths is below the safe distance, then signal this Car to either brake this Car and stop accelerating or not slow down and keep accelerating.
- Clear look-up dictionary for next iteration.
- Update time for the reservation node

The above $Safety_{Control}$ procedure, technique, practices, or policies are designed to mitigate risk.

3.3.4 Safe Distance in-between Vehicles

To avoid vehicle collision, we implemented a safe distance between vehicles. The safe distance is the minimum distance apart that exists between two vehicles in motion. A safe distance is a variable which one can set provided that crashing incidence can be prevented and controlled. In the model, the safe distance is defined to check for cars' safety against another car in a car-following model, but we considered different safe distance variables for the two types of cars (AV and HV) based on their behavioural pattern. A car must always be able to brake with the current velocity to prevent collision with another car. However, we set the car's safe distance as the distance between the car spawner and the car (about 30 meters). If the distance to the car is greater than the minimum safe distance, it is safe to spawn a car. This mechanism works efficiently for AVs because of its high precision.
However, a 'safe speed' [$v_{safe(s,v)}$] technique is introduced to avert accidents in the model. The safe speed depends on the distance ('s') to and speed ('v') of the leading vehicle and the braking factor (deceleration 'b'), which depends on the friction between the road, tyre and brakes of the car.

Conditions upon which safe distance is dependent on These conditions are established from the 2-seconds rule, stopping distance, deceleration rate and density [YWYJ20, ZKIC99].

1. Braking manoeuvre is implemented with constant deceleration b. Meanwhile, there is no clear path between comfortable and maximum deceleration.
2. There is a constant " Reaction-[time]" t_r of 0.1s for AVs and a randomised reaction time of between 0.3 to 1.5s for HVs.

Consideration was based on distinguishing between conservative driving and optimistic driving styles to help in the prediction of the car motion. A car must decelerate to a complete stop in conservative driving when the car in front stops suddenly, immediately, or entirely, like in a crash-like scenario. It is the worst-case scenario. In this case, for safety reasons, the distance gap to the leading vehicle should not become smaller than a minimum gap of 30m [Ler06], while in the optimistic driving style, we assume the car in front brakes as well, and the safe distance takes care of the situation.
During the reaction time, the car moves by:

$$s_r = v \cdot t_r \tag{3.4}$$

However, based on the above assumption, the safe distance between vehicles was set to be a constant for the two categories of cars. Condition 1 implies that the braking distance necessary for the leading vehicle to come to a complete stop is given by :

$$s = \frac{v_1^2}{2 \cdot a} \tag{3.5}$$

Condition 2 states that the driver of the reference vehicle needs the reaction distance $v\delta t$ travelled during the reaction time in addition to the braking distance $\frac{v^2}{2b}$. This is the condition that will bring the vehicle to a halt. (the time to decode and execute the braking instruction needed). Consequently, the stopping distance is given by

$$\delta x = v\delta t + \frac{v^2}{2 \cdot b} \tag{3.6}$$

When the gap 's' exceeds the minimum required value of '0' after considering the difference between the stopping distance, then, condition 3 will be satisfied.

$$\delta x = v\delta t + \frac{v^2}{2b} - \frac{v_1^2}{2 \cdot b} \tag{3.7}$$

The safe speed 'v' refers to the highest possible speed for which the equal sign holds:

$$v_{safe}(s, v_1) = b \cdot \delta t + \sqrt{b^2 \delta t^2 + 2 \cdot (s - s_0)} \tag{3.8}$$

What happens in a situation where the car in front applies an automatic brake? the driver must have time (reaction time) to apply an automatic brake, too, to avoid collision with the available space it comes to a stop. If v = 40 m/s on the motorway, then 20 m distance braking time is ideal. In general terms, it is recommended to Keep one pole distance (500 metres (550 yds)) when driving at a high speed on the motorway?

3.3.5 Basic Assumptions

This study we made the following carefully thought assumptions:

- Human drivers' behaviour pattern has some level of randomness and may not be precisely predicted, hence HVs assigned aggressive vehicles with high-priority access. In contrast, AVs are gentle vehicles that must stop and give way to HVs to avoid a collision.
- There are vehicle detectors located at the ICCR of the intersection Figure 3.1, which automatically detect and record vehicle arrival details and transmit them to the control unit.
- This research approach used the existing traffic theories, methods, and models suitable for managing homogeneous traffic systems in general and was improved to a suitable model for managing a mix-traffic involving AVs and HVs.
- The intersection control unit communicates with vehicles as an agent-based system within the intersection communication region.
- The design assumes a single lane road all through.
- With this protocol approach, vehicles traverse intersections as they do use traffic lights, otherwise treated as autonomous agents (individually), and in particular need not surrender control to any centralised decision-maker.

- A turn is not allowed, and all vehicles are travelling at the same speed. These simplifications make the analysis and implementation a lot easier but do not detract from the problem's fundamental challenges.
- Treads: The design is on rolled asphalt and uses car tyres and worn off tread, limiting its effectiveness in tractioning a braking process.
- The ICCR is assumed to be equipped with active sensors, defined by the ability for multiple lane operation or lane combination and, transmits multiple signals or beams for accurate measurement of vehicle, speed, and class. The infrared device updates the current event concerning the vehicle approaching an intersection, the detail of the lane, and the vehicle arrival at the communication region. All these parameters act as input to the control unit.
- Weather issues: Stable and friendly weather conditions without visual restrictions or influences on the vehicle and infrastructure is assumed. For example, the operation may be affected by fog or snow.

There are different types of traffic considerations for an exhaustive research performance validation. These include:

- Free flow of traffic at high speed and low traffic volume. The volume and speed rate are the key factors that determine the capacity of the intersection space. The free-flow speed describes the average speed at which a vehicle travels in a condition where there is no congestion or no other vehicle on the road or no adverse conditions (such as bad weather, bad road, to mention but a few). However, some of the factors that affect the vehicles' free-flow speed are road width, lateral clearance, the number of lanes, intersection density, geometric road design, visibility, and weather condition.
- Capacity traffic flow with the maximum volume and optimal speed and density: The capacity flow is the regime when the traffic volume is maximum. The traffic regime of a capacity flow cannot grow in either direction relative to the traffic stream. The capacity flow functions maintain the same location as an upstream boundary for congested flow and a downstream boundary for free flow. A bottlenecks (point of congestion) in a traffic flow will occur when the above traffic regime takes place.
- Constricted traffic with high density, low traffic volume, and speed occurs when the speed of traffic is less than the capacity speed of the road or where the density of the traffic is between the capacity density and the maximum traffic density. It is the regime in which traffic jams develop. The traffic flow propagation properties are inversely proportional to the direction of the vehicle stream.

However, traffic efficiency depends on the participating vehicle behaviour, intersection size, geometry, and traffic signal, which defines the performance of the traffic system.

3.4 Proposed AVHV-Node reservations system

Proposal for reservation of road intersection node-time for vehicles: According to [VG18, Nau11] Aeroplanes use landing nodes pricing to avoid landing conflict at the airports; what if mixed-traffic (AVs and VHs) does the same thing in a road intersection? This proposed traffic control strategy by intersection nodes reservation-based system communicates with oncoming traffic, calculates their arrival time at the designated collision points, and permits cars to pass at each instance. This method will require vehicles to request and receive node allocation at a time instance from the intersection manager, during which time they may pass through. This strategy will efficiently, safely manage, and ease off traffic congestion at the road intersections. However, most previous researchers focused primarily on HV or AV separately and not as a mix, which means that the mixed traffic was not investigated. Some research [RBS+14, HAKH20] simultaneously considered

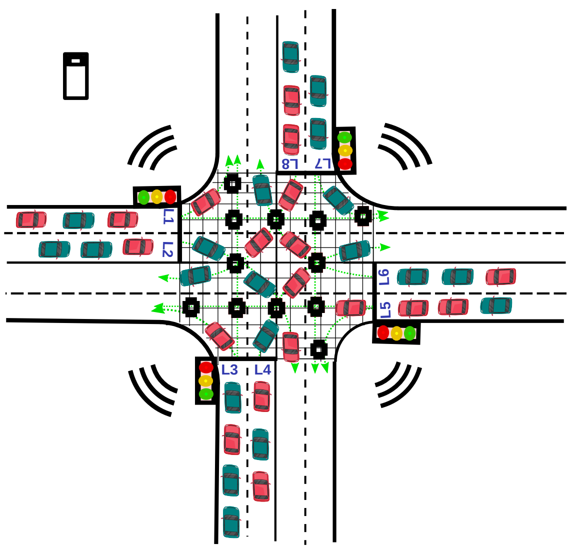


Figure 3.6: Intersection reservation node

the mix mode traffic using pathfinding, which is inefficient, while others worked on a mix of vehicles and pedestrians. From their work, the interference between different traffic flows was not considered holistically. However, lateral and longitudinal approach to vehicle behaviour has become apparent as an important method for managing complicated traffic problems of this nature. The programming approach involves two types of control (upper-level) variables that define the cross collision points along the traffic path and the lower level, which describes the traffic management actions. The management actions include traffic signal setting and congestion pricing by adding alternate routes to the lead lane.

3.4.1 Reservation nodes

Reservation nodes are specific points of the road intersection space registered by the central collision control system. They are of interest because areas around them usually have a high traffic flow from different routes per time with collision potentials. They are used as markers to tell the central collision control system were to establish priority based on the time it takes for vehicles to get to them. In a 4-way intersection, there are 12 reservation nodes. A reservation node is active if it lies in a route used in the simulation. At every instance in time, that is the time the control system updates the entire simulation (e.g., a time increment of 0.1 means each 1/10th of a second). Figure 3.6 presents the intersection area for the scheme and vehicle reservation nodes respectively,
In this strategy Figure 3.6, a vehicle accessing an intersection is assigned landing nodes just like an airplane to avoid conflict. The /slot is numbered 1 to 110, representing the intersection spaces where vehicles are expected to occupy during their trajectory. The traffic analysis strategies, techniques, theories, or models developed based on human-driven vehicles' operations were used widely in developed countries. This appears

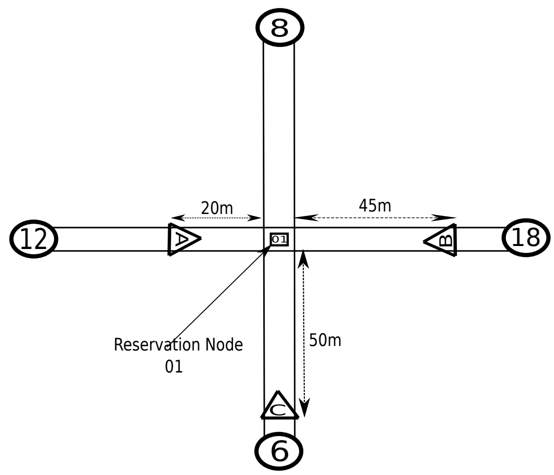


Figure 3.7: Schematic of the reservation node

to be inadequate to solve mixed-traffic problems. In a practice sense, both human-driven and autonomous vehicles behave differently, which results in a different traffic flow pattern in an intersection. So, their distinct characteristic is represented by interference between different AV and HV. The baseline assumption is that autonomous agents purely control vehicle navigation. By comparing the reservation node's performance and that of the cross-collision avoidance method, there is an observed improvement in throughput in managing a mixed-traffic system. The main advantage of this over the collision avoidance method from within the cars is that it broadcasts the relay message from each car quicker to the nodes than if they singularly told the node where they were going next.

The mix-traffic management strategy aims to use the distance headway to judge vehicle position and predict its movement. This strategy follows the safe distance model to keep each car safe from the other (the safe distance depends on car type). The cars also check for nodes (which is where the Road-Vehicle Communication comes into play) on the roads and how far away each car approaching is from its reference node position. In accessing the intersection, the control method uses a first-in-first-out policy approach. The right of way is assigned based on the vehicle type and the car nearest to a merging node. An analysis from the vehicle evolution and behavioural pattern indicates that vehicles driven by a human being are more aggressive in behaviour and has an associated delay in responding to the car-following

Figure 3.7 is a schematic showing a 4-way intersection with a reservation node and 3-cars approaching. A, B and, C are approaching cars with the same velocity 10m/s, and 18, 12, and 6 are the road nodes they left, respectively. 01 is a reservation node. Their distances from the reservation node are 20m, 45m, and 50m, respectively. Therefore we assume a constant speed; hence their times to the reservations node are 2 secs, 4.5 secs, and 5 secs respectively.

3.4.2 Coordination Protocol For Reservation Node

The reservation node system allows the driver agents to "call ahead" and reserve the spaces they need along their path. The SIR is subdivided into an n × n grid of reservation nodes Figure 3.6, where n is called the details of the reservation nodes system. Each reservation node RN can only be reserved by one car at each time step.
The request to use RN contains the following details.

- Vehicle type
- Vehicle arrival time
- Vehicle current velocity, though in the simulation, we maintain a maximum velocity of 10m/s for optimal performance.
- v_{max} *and* v_{min} represent the maximum and minimum respectively.
- a_{max} *and* a_{min}represent the maximum and minimum respectively.
- Vehicle trajectory with details of the requested RNs

A step by step summary of how a vehicle schedules a reservations node is as follow:

- Upon vehicle arrival, a request is sent to the CU for the vehicle request to be scheduled. The CU must ensure that the time duration for each RN along the vehicle trajectory on the SIR will not conflict with the current reservation.
- Let RN_k be the k-th RN in the SIR, where $1 < k < n$ and n is the number of RN's along the vehicle route. Let ta_k be the requested time of arrival to RN_k and td_k be the departure time from RN_k. At every time instance, the CU checks whether the requested RN is available for reservations.
- If the RN is available, the CU will check the next RN along the vehicle trajectory for availability at the next time step and continues this process until the vehicle exit the SIR.
- If the road camera senses the presence of HVs from the intersection, a reservation access is granted to HVs based on vehicle type-priority.
- If the request is unsuccessful or the requested RN_k is not available at time interval ta_k and td_k, the CU performs a search for the next available time for the first requested RN. The CU iterate this process for another RS request.

The reservation node framework that coordinates traffic flow at the intersection could be explained using Figure 3.7. This scenario only uses one RN to explain the background of the reservation node process. From Figure 3.7, it is assumed that car A has the minimum time to the reservation node, so it is allowed to keep moving. Car B and car C, which are farther than car A, are then inspected to see if their distance to another car is below minimum distance and, if that is true, are braked, but if false, allowed to keep moving. The above process is repeated for car B and car C. In this simple example, car C is the last car because car B is closer to the reservation node than car C. The process could be implemented over and over until there is only one car left to go across the reservation node.

Scenario of the Data Structure for the Reservation Node strategy involving the future time node reservation: The structure of the collection of data values, the relationships among them, and the

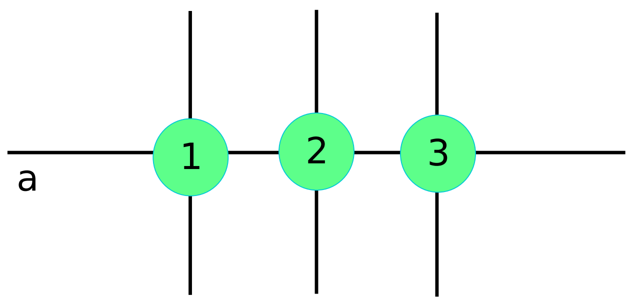


Figure 3.8: Scenario for managing conflicts in RN method

storage, functions, or operations that can be applied to the data in the algorithm are as described below: The control unit (CU) holds for each RN an array containing the next 100 timesteps (100ms intervals), so basically one can reserve 10s.

Algorithm 3: RN Process:

```
Data: CU, RNs,EAT
Result: RN Traffic Flow
for CN holds for each RN an array containing the next 100 timesteps (100ms intervals), so basically
 you can reserve 10s. do
    Car computes trajectory through RNs with ETA.;
    Car sends path request to CN;
    for CN checks the array for all RNs in the respective time node do
        A conflict arises if a RN is already reserved;
        for If there is a conflict do
            Calculate backwards deceleration needed, update path, then goto 3.;
        end
    end
end
```

Algorithm 4: RN Process Scenario using Figure 3.8:

Data: Reference from Figure 3.8
Result: RN Scenario
for *Car drives through RNs 1, 2, 3;*
Cars driving from top to bottom individually through 1, 2, 3;
At beginning of the scenario;
do
    RN1 : Reservation data structure = [0, . . . , 0] (100 0s);
    RN2 : Reservation data structure = [0, . . . , 0] (100 0s);
    RN3 : Reservation data structure = [0, . . . , 0] (100 0s);
    for *Car drives through 1, 2, 3,;*
    data structures will look like this: **do**
        RN1 : [0, 0, a, a, a, 0, 0, . . .] (it need 300 ms to pass through CN 1);
        RN2 : [0, 0, 0, 0, 0, 0, 0, 0, a, a, a, 0, 0, . . .] (it need 300 ms to pass the road between RN 1 and 2);
        RN3 : [0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, a, a, a, 0, 0, . . .] (it need 300 ms to pass the road between RN 1 and 2)
    end
    Now car “2” drives through RN 2:;
    for *When the car reaches the node, (when car “a” reaches RN1)* **do**
        RN2 : [0, 0, 2, 2, 2, 0, 0, 0, a, a, a, 0, 0, . . .]
    end
    Now another car “1” wants to drive through RN1 at timestep 4:;
    for *At timestep 4:* **do**
        RN1 however, has at timestep 4 and 5 already “a” saved, so car i need to get a delay of 200 ms, so need to adjust speed, after that the RN looks like:;
        RN1 : [0, 0, a, a, a, 1, 1, 1, 0, 0 . . .]
    end
end

Car computes trajectory through RNs with ETA. Car sends path request to CN, then the CN checks the array for all RNs in the respective time node. A conflict arises if RN is already reserved. If there is a conflict, calculate backwards deceleration needed, update path, then goto 3.

Algorithm 5: Reservation Node (RN) Method for AVs and HVs

Data: Environment:No of lanes $l_i - l_n$, Id of RNs, position, Route, Speed, Car , Car size, and Car type
Result: RNs to Vehicles

```
1  Get the time steps in the RN ts_1 − ts_n ;
2  for Car arriving the intersection make request for an RN on its path: do
3      if The Vehicle is HV then
           // (Checks for access request;
           The CU checks if any other request from route having HV and pattern match their route RNs
            EAT;
4          if The request in line 2 is a lone request from an HV route for that expected arrival time (EAT)
            then
               RN for the vehicle with the green traffic light indicator;
5              Else; Decelerate the rightmost vehicle based on traffic rule with red traffic light;
           end
       end
6      if Vehicle is an AV then
           The CU checks if there is any other request from another route with the same EAT ;
7          if There is another request at that EAT and the request is from HV then
               Reserve node for the HV based on priority rule;
               Decelerate the AV;
           end
8          if The request in line 6 is a lone request from an AV route for that EAT then
               Reserve node for the AV;
9              Else; Decelerate the rightmost AV based on traffic rule with red traffic light;
           end
           AV sends access request with route, speed, car, car size, RN and car type)to the CU;
           The Car goal for AVs is known, HVs decides its goal with car trafficator light.;
           For safety and reality, HVs nodes are reserved for the current car at every instance.;
       end
10     if Each vehicle arrival route has vehicles then
           The CU compute all RNs on its route, with their EAT and send to all AVs;
           Grant priority to all HVs based on rule in line 3, Decelerate the rightmost vehicle for all AVs;
       end
11      Update the intersection environment with vehicle presence parameters;
12     if The reservation nodes are free during requested times to be checked by the coordination unit then
           Assign the reservation node to the requested vehicles and keep priority;
           coordination unit sends back reservation information to the car;
       end
13     Notify cars about the owner of each collision points and Cars decide to decelerate depending on
        their relative distance to the RN and car type involved (either AV or HV);
       // (Platoon forming algorithms);
14     if if a Car arriving the ICR joins its leading car on the same lane within the crossing time t_i of RN
        then
           Allow the car to join the same platoon as its predecessor;
           All Cars that share a common RN and trajectory wait an additional time t_i ;
           Start the next platoon of vehicles at the next lane if there is no current Car
       end
       Else: // (Car cannot join the current platton);
       Car forms another platoon;
15     Increment the time steps in the reservation cycle ts_1 − ts_n
   end
```

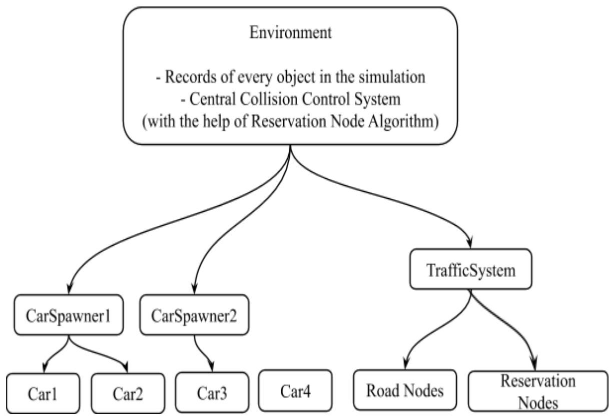


Figure 3.9: Schematic of the relationship between the Environment object and other objects in the simulation

One might tell that this is a hybrid of the reservation node algorithm and the car to car collision avoidance system. In this instance, vehicles on the road tell the central collision control system how far they are from each reservation node. The collision control system then compares the time (obtained by their distances divided by speed) it would take for each car to get to the reservation node and finds the closest car with the least time to a reservation node. This is done for all reservation nodes.
Each vehicle at every state of the traffic schedule is relevant to one reservation node at the intersection. As there is more than one active reservation node at any given time, multiple states of the reservation node catalogue Table 3.4 are produced at any given instance in time. This information is needed to work out which cars to signal to stop, brake or give the right of way.

The Schematic of Intersection Management Process: This project uses the Environment object as the central collision control system. It stores the entire state of the simulation process. It housed various objects in the simulation e.g., cars, car spawners, road nodes, and reservation nodes. It is responsible for making the decisions that govern the dynamics of the simulation. From Figure 3.9, all reservation nodes will be used at all times, so for the environment to know which reservation nodes to consider checking against, it needs to take stock of all the routes in the system specified in the car spawners. It then get their unique nodes and compare them against the reservation nodes and see if their IDs/numbering match. The Coordination protocol for Car Reservation Node calculates the distance from each car to the reservation node and, using their current speeds, calculates the time it takes to get to the reservation node and communicates them to the central collision control system. The central collision control system finds the minimum time among them and signals any car that does not have the minimum time, which will not get to the reservation node first and checks to see if they are too close to another vehicle and signals them to slow down. The traffic flow description could be developed for a more complex road intersection with multiple lanes and different types of traffic participants 'k' as reflected in Figure 2.3. Using the types of traffic participant k-vehicle (AV, HV) and the traffic flow of k on lane l_i could be formulated as follows:

$$v_{l_i}^k = x_{l_i}^k \cdot (\frac{U_k}{A_k}), k, l_i \tag{3.9}$$

Where v = velocity
i = the car id
l = road lane id
k = car type
u = flow conversion coefficient (constant)
A = number of car in type
$v_{l_i}^k$ = Traffic flow of cars type k on road lane l_i
$x_{l_i}^k$ = Number of cars type k on lane 'l_i'
U_k = Traffic flow conversion coefficient of the car type k
A_k =Queue length of k

How Reservation Node Algorithm is Applied in Code: The reservation node-based traffic management system adds the time component into the decision-making process of node allocation. The Allocation of nodes' decisions is made in such a way as to maximise the scheduler's ability to continue to start jobs in existing nodes. Making the node allocation decision is essential in an environment that involves mixed-vehicle with different rules and behavioural attributes. The reservation node allocation policies allows the intersection manager to specify how the available node resources are allocated to vehicles.

3.5 Abstraction of Traffic Flow Model

The quality of dealing with the ideas in developing a traffic flow mathematical model relies upon the parameters of traffic flow characteristics involving vehicles, driver behaviours, the ratio of the mix of vehicle type, and the intersection design. Besides, simplifying assumptions are therefore made. The road intersections are made up of the following components: traffic characteristics, alignment and profile, channelisation, Auxiliary lanes, control radii, and turning process. This investigation looks at drivers and vehicle's features such as mitigating collision risk, utilising the intersection space, reaction time, and safe distance, which follows an empirical statistical distribution. The developed algorithm 6, describes the basic idea of how a vehicle accesses an intersection using the reservation nodes strategy.

The developed AVHV control model simulates the two different vehicle types' behaviour: human-driven and autonomous vehicles. The AV and HV maintain the same physical dimension of 4metres length. The fundamental difference between AV and HV is the delay for reaction time, distance headway, and priority rule. The model performance is based on the vehicle parameters. Vehicle speed is being managed in a discrete form at the start of simulation from the car spawner, after which the vehicle speed changes to random after each time step. For this research, consideration for the developed vehicle model types was based on two categories of how they are being driven: self-driving vehicles and human-driven vehicles:

1. Autonomous Vehicles (AVs): AVs combine software applications and navigation sensors to control and direct their movement with features of an intelligent transportation systems (ITS). The fundamental hypothesis concerning AV is that it gives priority access to the HVs whenever they come in conflict within an intersection. This rule is designed for safety purposes. These rules make the AV show a disinterested and selfless concern for others' well-being or selflessness (more altruistic behaviour). However, two main intersection scheduling rules are considered based on priority and waiting for time rules (fairness). Vehicle crossing of the above rules' intersection criteria must be obeyed by all the vehicles before crossing the facility. The AV is modelled with a gentle driving style where the car can

avoid all obstacles and mitigate its movement through the environment. The AV driving system has the following features as implemented:

- High precision in obstacle avoidance and manoeuvring, thereby controlling the velocity and acceleration seamlessly.
- The vehicles maintain a randomised realistic, safe distance. The safe distance value was designed to be manageable to reflect the real-life situation.

2. Human-driven vehicles (HVs): These are vehicles with no intelligent transportation system but use a human driver who engages their sense of sight and hearing to watch for traffic signals from traffic signalling devices and control the traffic flow. The HVs have a higher reaction time than the AV; this is because of the driver's response time and its aggressive behavioural nature. Besides, the HVs is modelled with a random braking system to capture the different attitude of human drivers, and it will be difficult for human drivers to keep a constant speed in a specified distance. The human vehicle speed is captured as a random event as it increases and decreases at every time step. The behaviour of human-driven vehicles is highly stochastic in nature and very unpredictable. For instance, a common scenario shows a slower preceding vehicle would lead the following drivers to consider overtaking instead of following the vehicle in front gently. A speed randomisation policy was applied to the HV, enabling the human drivers to maintain accelerate and decelerate rate to adapt to a minimum spacing with the vehicle in front.

The HV driving system is implemented as a conventional system of driving with features as listed below:

- The human drivers' response time to a stimulus is varied individually when compared to the autonomous cars, which stimulus-response is a real-time
- The HV has a randomised safe distance of a realistic human behaviour [LPS98].
- The braking distance for HV is higher than that AV because of the high reaction time of human beings.

The autonomous vehicle and human-driven vehicles do not yet totally get along the same road. While autonomous vehicles meticulously follow a set of designed protocols, human drivers use driving rules that are not precisely followed due to human tendency. Because of these distinct differences between the AVs and HVs, which is ITS's presence in AVs and the absence of the same in HVs, there will be challenges in implementing a safe distance model that produces collision avoidance traffic flow due to the different vehicle behaviours. Human drivers' motion is unpredictable with stochastic, less precise behaviour, which is more prone to traffic mistakes. According to [vWB20], it was observed that human drivers respond to unforeseen events in about 6 seconds, while autonomous driven vehicles react to an unexpected event in close to real-time.

Other assessment parameters responsible for vehicle motion behaviour Mixed traffic behaviour could be observed, described, explained, and predicted using the following two parameters:

1. **Shortening of Distance Headway Between AVs:** This is the time between a vehicle and the following vehicle.
2. **Vehicle group speed:** At constant density, the system will experience an increase in the speed of vehicles with a corresponding increase in the traffic volume. However, the negative aspect of this is high risk.

Vehicle movement algorithm: The car movement pattern is an essential aspect of this model as speeding is risky, but according to [MM08b] the safest speed is not always the slowest speed because of the impact on other traffics using the road at the same time. If a driver moves much slower than the surrounding traffic, this will negatively impact other vehicles' speed sharing the same route. In this scenario, other drivers might get frustrated and try to pass the slow-moving vehicle. There is a need to maintain a fair pace; the aim is to keep a speed appropriate for the environmental conditions (weather, road, or traffic) in which you are driving. The vehicle movement algorithm 7 represents how the vehicle moves from start to target node. In a vehicle merging scenario, some factors determine drivers' behavioural patterns; this includes waiting for time, lateral gap, vehicle type, and road geometry. Research needs to evaluate further the impact of this behaviour under different driving regimes, densities, and traffic quality of service.

Human Drivers' Psychology: The drivers' psychological behaviour is captured in the vehicle movement process by focusing on the human mental processes of perception, memory, judgement, reasoning, and the traffic decision-making dimensions. The vehicle could safely and legally transit the road intersection by observing the following sequential steps:

1. Prepare for decelerating before getting to the intersection. Make a turning decision ahead of time and the turning point. It is still better to maintain a slow velocity for safety reasons before deciding the desired direction.

2. Get into the correct running direction lane at the shortest possible time.

3. Take a look behind using the side mirrors to estimate oncoming traffic relative to changing lanes and turn process safely.

4. Trigger a signal for an intention to change lanes and make turning movement at a given location and time.

5. It is advisable and safer to reduce speed before one reaches the intersection crosswalk and complete the turning process while maintaining the same speed.

The driving process has an essential impact on the road intersection capacity, especially as it concerns different vehicle types. In this case of mixed traffic, there is AV's and HV's, and the road infrastructure (road system, signage, and the traffic control devices). A good understanding of these details will help develop an optimal traffic flow with safe and efficient traffic movement.

3.6 Mathematical Model for Vehicle Dynamics and Kinematics

This simulation driving experience claims to be genuine and uses physics-based algorithm 10, given that the laws of physics govern the vehicle motions. The model is physically realistic of the vehicle performance using calibrated traffic parameters. This involves capturing the basis of the underpinning car physics theories, which revolves around the car dynamics and kinematics with other variables involved in the vehicle movement process. The impact of different types of forces that act on the vehicle to accelerate and decelerate at different scenarios of the road system is added. To replicate the car and driving dynamics' underpinning features, consideration is on the linearised model and perturbation influence on a car, which modifies its behaviour when in motion. The model looked at several features, including the car's environment: geometries, multidimensional, aerodynamic effects, and the tyre model. In simulating vehicle movement in space, there are two significant aspects of the model considered:

- The mathematical model of the car dynamics.

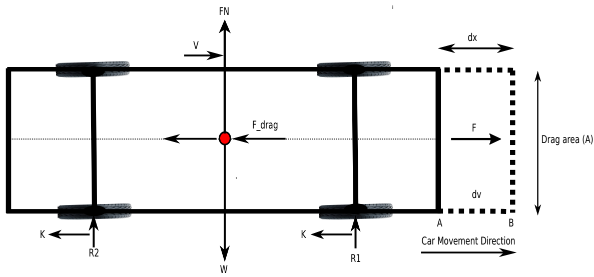


Figure 3.10: Vehicle dynamics forces.

- A model of cooperation between the car and the environment, which involves the tyres and the road surface.

and a In dealing with car physics, a detailed review of the underlying physics principles according to [Gia16, Rot01, BGH06] were conducted. Going by the above principles, the car dynamic Figure 3.10 and kinematic Figure 3.11 model are developed. The kinematic model extended to car movement scenarios involving straight and curved Figure 3.12 which is part of the core physics principle.

Car Dynamics Model

This is the baseline for explaining the critical points in simplifying how vehicle forces control the car body's lateral and longitudinal directional movement. The engine force, braking force, rolling resistance force, and drag (air resistance) force are the major forces that impact a car's motion. These forces control the car motion of acceleration or deceleration and speed process. Figure 3.10 ex-rays the physical image of a vehicle structure, the forces with its actions, and how the vehicle responds to the driver. This process deals with the engineering aspect of vehicle motion in proper user operations. The Dynamics of vehicles always use mechanical engineering physics and control theories and methods for the car with engineering and human behavioural science [Sri12]. The dynamics of a vehicle could be approached based on the primary characteristics of the vehicle's subsystems [Kos14]. For a better and fundamental understanding of the dynamics, considerations based on using an HV subsystem to analyse the vehicle's behaviour:

1. Longitudinal dynamics (introduces subsystems for propulsion and braking) involves the action of driving or pushing forward. It captures the mechanism of this process.

2. Lateral dynamics (introduces subsystems for steering) involves the steering system which allows the driver to guide the vehicle movement.

3. Vertical dynamics (also introducing subsystems for suspension): This involves the car tyres, shock absorbers, and connection between the vehicle to its motion wheels and the suspension springs, allowing for relative motion between components. The suspension systems support the road-holding/handling and ride quality.

Description of the vehicle dynamic variable parameters:

- $F_{traction}$- This is the car engine's force to the wheel via the gear and the axil system.
- $F_{kinetic_frictional}$- This is the force that exists between the road surface and the tyre. This force on the wheels pushes in the reverse direction, which in reaction, the road surface reacts in a forward movement, which makes the car move.
- F_{normal}- The Normal force acts perpendicular to the car.
- W - Mass
- C_{drag}- This force acts in the opposite direction of the motion, the parallel force.
- F_{drag} -The air resistance force is acting in the opposite direction of the motion.
- μ- the coefficient of static friction
- R1 and R2 - Ground reaction force on the tyres.
  Below is a list of alphabets in Figure 3.10 and what they represent:
  - A- Defines the area of the vehicle which the drag force is acting upon
  - dx- Distance covered in-between two points- A and B.
  - Red dot- Centre of gravity of the vehicle

Car Kinematics Model

This involves the car (x, y), which are the coordinates of the rear axle midpoint (Θ), which is the car's orientation. This describes the motion of the car without considering the forces that cause them to move. Vehicles making turns involve drivers controlling it in the road path with a varying radius of curvature. It is assumed that car wheels are not moving in the direction they are pointing for a car on the motion. This directional motion is because of the impact of the car body with a certain mass and reaction time to steering forces. The curvature motion builds up gradually over time like the linear velocity. The angular acceleration determines the force, which depends on the rotational equivalents of force and mass (torque and inertia). However, thinking of a driver going under a curve, the car may be pointing in one direction but is moving in another direction, this scenario is prevalent for turning cars. The side-slip angle θ exists between the car's direction and the velocity vector as reflected in Figure 3.12. The impact of this scenario is noticed in two front-wheel tyres.

The kinematic model of Figure 3.11 involves a car moving on a rough surface involving the reaction at each instant of the vehicle. Each of the car's four wheels is in contact with the ground to control the car body. Figure 3.11 explains the impact of forces acting on a curve centre of a moving car, while the impact on the steering and the wheelbase formulation using geometry is reflected in Figure 3.12,

Considering a car moving in a straight-line direction, below is a list of the forces that supports the car's motion:

- $F_{traction}$: This is the force powered by the engine force transmitted to the car's rear wheels. When powered, the engine turns the axial system through the gear system to the wheels. The car wheels reverse backward on the road surface, and in reaction, the road surface pushes back in a forward direction. The magnitude of this force is equivalent to the F_{engine}.

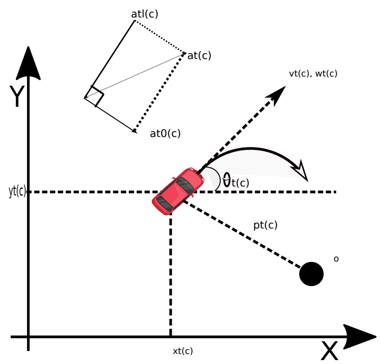


Figure 3.11: Kinematic model of a car

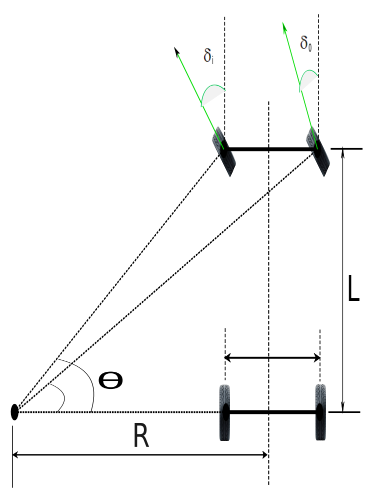


Figure 3.12: Steering angle of wheelbase

$$F_{traction} = \mu \cdot F_{engine} \tag{3.10}$$

Where

- μ the coefficient of static friction
- $F_{engine} = mass \cdot g$

In a scenario where this force is the only force acting on a vehicle, the vehicle will accelerate infinity. However, it is not the case in a real-life situation because of drag (air resistance force).

F_{drag}: This is the air resistance force that acts in the opposite direction to the car's movement; this force is directly consistent with the square of the car's speed.

$$F_{drag} = -C_{drag} \cdot v^2 [\text{Whi84}] \tag{3.11}$$

Where

C_{drag} = Drag coefficient (a constant)
v = speed

The speed is a scalar which is the magnitude of the velocity vector v.
hence from [Whi84], we have :

$$speed = \sqrt{(v_x \cdot v_x + v_y \cdot v_y)} \tag{3.12}$$

$$F_{drag}.x = -C_{drag} \cdot v_x \tag{3.13}$$

$$F_{drag}.y = -C_{drag} \cdot v_y \tag{3.14}$$

[$F_{rolling\ resistance}$]- Is due to the friction exerted between the road surface and car tyres.

$$F_{rr} = -C_{rr} \cdot v \tag{3.15}$$

where C_{rr} is a constant while v is a velocity vector.

However, for a vehicle moving at a low speed, the rolling resistance acts as the main resistive force, while the drag force acts to resist the movement at high speed. Therefore, the total longitudinal force is the vector sum of the above forces:

$$F_{long} = F_{traction} + F_{drag} + F_{rr} \tag{3.16}$$

Note

- For a vehicle moving in a straight-line direction, the rolling resistance force is opposite from the traction force, which means that the resistance force's magnitude is subtracted from the traction.
- 2. For a car cruising along a curved path at a constant speed, the above two forces ($F_{traction}\ and\ F_{rollingresistant}$) are equal or in equilibrium ($f_{long} = 0$) [Whi84]

From the wheel's point of view in a car motion scenario, because wheels roll with a relatively low resistance to motion in forward or reverse direction, the sideways speed of the tyres is calculated, while the perpendicular direction has excellent opposition to the movement. Because of the maximum static frictional force needed to move the wheel, pushing a car sideways can be very hard because one needs to overcome the leading static frictional force to slip the wheel. The cornering or lateral force depends on the slip angle "α", which the tyres develop that heads in the travel direction.
The slip angle is directly proportional to the cornering force, while the cornering force of the tyres is dependent on vehicle weight. At low slip α, the relationship between slip angle and cornering force is linear. In other words.

$$F_{lateral} = C_a \cdot \alpha \tag{3.17}$$

Where
"C_a" = Cornering stiffness.

The diagram Figure 3.12 is used to explain the vehicle turning scenario. The python class (vector2) contains the method used for vector movements: force, velocity, acceleration, displacement, and momentum of the car with the angle α relative to the direction in which the wheel can roll.
For positioning the car object on a 2D space, think of Pythagoras theorem:

$$Z^2 = X^2 + y^2 \tag{3.18}$$

Vector2 consists of two-component vectors:

- The longitudinal vector with magnitude $\cos\alpha \cdot v$). Corresponding to the wheel's rolling motion.
- The lateral vector with magnitude $\sin\alpha \cdot v$). This produces a force resistance in the reverse direction of the curvature force.

The slip angle is determined by the car's sideslip, the angular turning around the up axis (yaw rate) for the front wheels, and the steering angle.

The sideslip angle denoted by β describes the difference between the orientation of a car's, and its movement direction; in other words, the angle between the longitudinal axis and the actual travel direction. Similarly, this represents the slip angle responsibility for the tyres. Cars experience a sideway's motion because it's movement deviate's from movement direction and pointing direction.

$$\beta = arctan\ (v_y/v_x) \tag{3.19}$$

In motion, we can no longer assume that car wheels are moving in the direction they are pointing because of the car body, which has a certain mass and takes time to react to steering forces. Just like linear velocity, this takes time to build up or slow down. This is determined by the angular acceleration, which depends on torque and inertia (the rotational equivalents of force and mass). The angle between the car's orientation and the car's velocity vector is known as the sideslip angle (beta).

Nevertheless, according to [Whi84]when a car turns with the same rate around the centre of geometry (CG) at the ω (in rad/s), the front wheels describe a circular path around CG at the same rate. When the car turns full circle, its front wheel describes a circular path of distance $(2.\pi.b)$ around CG . CG is $(1/(2.\pi \cdot \omega))$ seconds where b is the distance from the front axle to the CG. This means a lateral velocity of $(\omega * b)$. For the rear wheels, this is $(-\omega * c)$. Note the sign reversal. To express this as an angle, take the lateral velocity's arctangent divided by the longitudinal velocity (just like for beta). For small angles, the approximation can go thus.

$$\omega = \arctan \frac{(\frac{vy}{vx})}{(\frac{vx}{vy})} \tag{3.20}$$

The angle which the front wheels make relative to the car's orientation is called steering angle (δ), but the steering angle does not exist for the rear wheels, which are always in line with the body of the car orientation. If the car is reversing, the effect of the steering is also changed.
The following equations from fig. 3.12, (δ) gives the slip angles for the front and rear wheels:

$$\alpha_{front} = \arctan[(v_{lat+\omega * b)} \ / \ v_{long}] - \sigma.sin(v_{long}) \tag{3.21}$$

$$\alpha_{rear} = \arctan[(v_{lat} - \omega * c) \ / \ v_{long}] \tag{3.22}$$

The four tyres' lateral forces produce the net cornering force (at a right angle to CG, which describes the path) and torque around the yaw axis.

$$F_{cornering} = F_{lat,rear} + cos\delta * F_{lat,front} \tag{3.23}$$

We can find the radius of the circle from the centripetal force using the following equation.

$$F_{centripetal} = Mv^2/r \tag{3.24}$$

The efficiency of traffic flow depends on the capacity of an intersection and the traffic signal performance. The traffic state is represented as:

$$q = k.v_t \tag{3.25}$$

(where q = volume, v = speed and k = density)

$$v_k = v_f - \frac{v_f}{k_{max}} \cdot k = v_f(1 - \frac{k}{k_{max}}) \tag{3.26}$$

where v_f = free-flow speed
k_{max} = max traffic density.

From Equations (3.25) and (3.26), we have :

$$q_k = v_f \cdot (\frac{k - k^2}{k_{max}}) \tag{3.27}$$

Safety Distance: The safety distance apart to be kept between vehicles is very important to avoid a collision. From the research of [DA18], the distance between the rear bumper of the first vehicle and the front bumper of the following vehicle is usually measured in seconds and is called inter-vehicle space. It is common knowledge that HVs are made up of radical drivers who usually exhibit aggressive behaviours when they come in contact with AVs. The control protocol is designed to assign HV the priority to access and eliminate AVs by forcing the AVs to stop and give them the right of way rather than waiting or following them from behind. This safety distance could be represented as:

$$s_r = v \cdot t_r \tag{3.28}$$

For AVs

Where: s_r = distance, v = speed and t = time.

While that for human-driven vehicles will be:

$$s_r = v \cdot t_r + 6 \tag{3.29}$$

Where 6 seconds is the reaction time for human drivers according to [KNWK17, JR71].
This safety distance play a role in vehicle groups and could represented in terms of time in relation to the vehicle speed as thus:

$$s_t = \frac{T_h}{\frac{L}{v}} \tag{3.30}$$

Where s_t = safe time
T_h = time for human to decide
L = length of car
v = volume of traffic

3.6.1 Engine Force

A vehicle engine delivers an amount of Torque, which is the measurement of how quickly the vehicle will accelerate and this is determined by the speed of the turning of the vehicle's engines ($Torque = force \cdot distance$). The engine Torque is converted through the gear and differential unit and then applied it to the rear wheels to activate the car movement. The gear system increases the engine Torque by a number or quantity depending on the ratio of the gear system. However, Torque acts on the vehicle wheel by dividing the wheel radius.

$$\mathrm{T}orque_{engine} = Throttle \cdot Torque_{max} \tag{3.31}$$

The drive Toque is a product of engine Torque transmitted through the gearbox, thus:

$$\mathrm{T}orque_{drive} = Torque_{engine} \cdot Gear_{ratio} \cdot Differential_{ratio} \cdot Transmission_{efficiency} \tag{3.32}$$

$$\mathrm{F}_{traction} = u \cdot \mathrm{F}_{engine} \tag{3.33}$$

Where:
u = vehicle directional unit vector.
The air resistance forces (drag) is equal to

$$\mathrm{F}_{drag} = -C_{drag} \cdot v \cdot |v| \tag{3.34}$$

Where:
C_{drag} = constant
v = velocity vector
$|v|$ = magnitude of vector v

A rolling resistance force F_{rr} brought about by friction from road surface and tyre.

$$F_{rr} = -C_{rr}\dot{v} \tag{3.35}$$

Where $_{Crr}$ = constant
v = velocity vector.

Therefore, sum of the longitudinal force = vector product of these three forces (3.36).

$$\mathrm{F}_{long} = F_{traction} + F_{drag} + F_{rr} \tag{3.36}$$

It is observed that straight driving, which is in the direction of traction force, opposes the drag and rolling resistance forces and makes them to be in the opposite direction. Figure 5.5 illustrates the impact of velocity on a moving vehicle with respect to time time. The force acting on a moving car changes with a change in car speed at the following 3-different stages.

- At point A: This is the beginning of the car movement; the driving force "F" is higher than the air resistant "A".
- At point B: as the velocity increase, air resistance increases, then the resultant force decreases with a lower acceleration rate.
- At point C: When the air resistance balances the driving force, the velocity stops increasing (this is called terminal velocity).

3.6.2 Acceleration

From Newton's Second Law, a car's acceleration is the product of all the forces acting on the vehicle. The acceleration vector is the product of the net force acting on the car in the same direction, using the vehicle object's mass as a proportionality constant driven from the acceleration magnitude. A vehicle moving straight with an initial velocity of 0 and gradually increases its speed in the direction of its travel. Whenever the car turns, the forward acceleration changes to the new direction, the passengers will experience a reaction of backward force on their seats. Besides, the passenger has experienced a sideways force due to the orthogonal force when changing direction. An acceleration in the opposite direction of the vehicle's velocity decreases the car speed (deceleration process). The deceleration process causing a forward push reaction force is experienced by the passengers. The acceleration and deceleration process changes the velocity component and is treated the same way. The car passengers feel the change in car acceleration (tangential, radial, deceleration) until their velocity (speed and direction) matches that of the uniformly moving car. The change in velocity (dv) divided by the duration of the period (dt) gives the object's average acceleration rate over some time.

Mathematically:

$$a = m \cdot \frac{\delta v}{\delta t} \tag{3.37}$$

The acceleration $\boldsymbol{a}$ of the vehicle is determined by the net force and car's mass. $\boldsymbol{m}$:

$$F = m \cdot a, \ which\ is\ equivalent\ to \qquad [F] = \left(\frac{m}{s^2}\right) \tag{3.38}$$

The rolling resistance force is

$$Frr = uHf \cdot g \cdot \frac{m}{2} \tag{3.39}$$

Assume friction of 0.5

$$F = m \cdot a \tag{3.40}$$

$$a = uHf \cdot \frac{m}{2} \tag{3.41}$$

The car's position can easily be update by

$$p = dt \cdot v \tag{3.42}$$

3.6.3 Deceleration Process

Deceleration process involves slowing down or reducing the speed of a car in motion; hence deceleration means negative acceleration. In the car movement model, the maximum deceleration is caped at 40 m/s for effective speed control which enables the car to maintain a gradual, steady deceleration like in real life. This approach makes the model testing more realistic than the actual traffic situation. According to ISO 611, the braking process involves operations starting from when the braking device is activated to the point at which the braking process ends and the car stops with a 0 velocity.

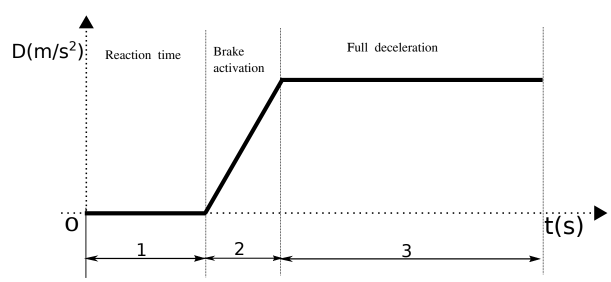


Figure 3.13: Basic braking process stages

Where
$D(m/s^2)$ = distance
t(s) = time

Braking and deceleration

Braking leads to the deceleration of a car. In this scenario braking replaces the traction force with the braking force oriented in the opposite direction. The total force in the longitudinal direction will be the vector sum of braking, drag, and rolling resistance forces put together.

$$F_{long}s = F_{braking} + F_{drag} + F_{rollingresistance} \tag{3.43}$$

The braking process can easily be approximated using Figure 3.13

$$s = \frac{v_f - v_i}{t} \tag{3.44}$$

Deceleration distance

The distance travelled during braking (X_b) can be calculated by

$$X_b = \frac{v_f^2 - v_i^2}{2 \cdot a} \tag{3.45}$$

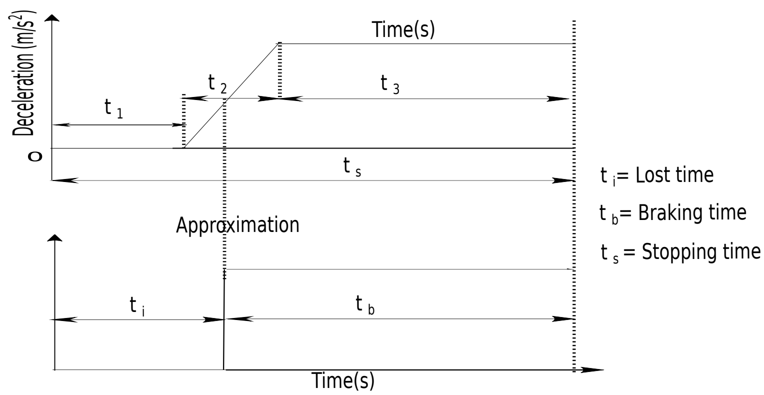


Figure 3.14: Braking approximation by 2 phases

Braking Distance

The braking distance, s_1, is the total distance advanced by a vehicle at an effective braking time $(t_3 - t_2)$ as indicated in Figure 3.14.

$$s = \frac{v_i^2}{a} \tag{3.46}$$

However, from Figure 3.14 the braking distance can also be evaluated thus:

$$s_b = \frac{v_{0^2}}{2} \cdot a_F \tag{3.47}$$

Where v_{0^2} is the initial velocity and and a_F is the acceleration force.

3.7 Behavioural Model for Vehicles

The human understanding and training experiences are represented in theoretical models driven from conceptual cognitive psychology [MCGLW16]. Besides, mental models describe human information processing, store, and responds to environmental conditions. Also, mental models conceptualise characterisation of knowledge and practical supposition to acknowledge and forecast users' behaviour in their relationship with automated vehicles. [LOD18, SAMR18] suggest that with an increase in the degree of vehicle automation, the role of human drivers in the decision-making process for a vehicle on motion is replaced by automated systems. The mixed behaviour results in a highly complex traffic situation, which has a significant impact on the capacity and performance of traffic intersections. Vehicles with different behavioural patterns are treated with a synchronised protocol at intersections. Each car behaves differently, uses different communication media, and obeys rules at the intersection control zones; hence the algorithm is robust enough to capture this complexity.

3.7.1 Mixed Traffic Characteristics and AV/HV conflict

Autonomous and human-driven vehicle conflicts represent the majority of problems encountered in a traffic-mixed intersection environment. The impact of these conflicts causes a noticeable decrease in the intersection efficiency, dramatically increases the risk level, and considerably reduces the benefit of intersections in traffic management. In several large cities, the need for autonomous vehicle integration can not be over overemphasised. The human drivers' behaviour is unpredictable and negatively impacts mixed-traffic performance and migration to an autonomous vehicle driving system. This research focuses on the impact of autonomous vehicles on the human-driven vehicle in the road intersection space. Simulating the management of traffics with different characteristics means of communication and control involves a challenging task because of the different vehicle behaviours involved. Besides, part of this control complexity is related to how vehicles and drivers receive control information from their environment. Also, how autonomous vehicles respond to the environmental stimulus can nevertheless be delegated to agents who verify road devices (intersection types, roadside devices like traffic signs, lights), as suggested by Jason in his avoidance theory of [Jan05]. This work aims to replicate a representational model of the human-driven vehicle and driver-less vehicles abstractly, guarantee that vehicles move in a method compatible with knowledge and observations, and preserve the car behavioural diversity for a proper co-existence. Traffic flow for human-driven vehicles at intersections is controlled through traffic signals, and their interaction access process is through merging and diverging based on their destinations. As vehicles from different directions begin to diverge and then merge, causing travel disruption of normal flow with its associated delays, human drivers have the responsibility to manoeuvre their way within the traffic based on predefined rules. The human-driven vehicles' control process at intersection involves an individual vehicle with its associated unpredictable human behaviour, hence the higher the safe distance associated with human-driven vehicles. The seamless control of autonomous traffic flow at intersections is through vehicle-vehicle and vehicle-infrastructure communications. AVs' realistic behavior is modelled with a precision driving style where the car is responsible for using its sensors accurately in navigation, obstacle avoidance, and manoeuvring, thereby controlling the velocity and acceleration seamlessly. It appears to be challenging to model the human driver's realistic psychological behaviour; hence, we incorporate an aggressive factor to capture the randomness of human driver attitude.

Real-time traffic information forecasting or prediction observes calibrated car data, or floating car data, and historical traffic data from the fundamental traffic parameters of volume, speed, density, and traffic incidents. Though few traffic problems are not avoidable, meticulous traffic predictions could help make an innovative and efficient choice to save time, money, safety and address some environmental issues associated with traffic. Traffic congestion is an opportunity cost to road users, costs people valuable time, fuel, and frustration every day. At the same time, large amounts of congestion impact governments who need to keep traffic flowing for the movement of goods, reducing pollution in certain areas, and for the safety of those on the road area. Congestion is an opportunity cost for time, fuel, and frustration every single day. Advanced traffic prediction services guide most traffic navigational devices to estimate arrival time and optimal route choice in a journey.

3.8 Traffic Flow Model Design With Vehicle Type Contingencies Details

The developed model combined the microscopic and macroscopic vehicle level of vehicle modelling to address the longitudinal and lateral mixed-vehicle behaviour process. [MNHF+20], observed that the roadway and traffic impact driving behaviour features while the 2-dimensional behaviour of heterogeneous vehicles impacts the intersection capacity. This condition makes the driving behaviour control vehicles in the longitudinal direction and the lateral manoeuvre at the merging points. This bi-directional behavioural feature is sophisticated when compared with the car-following model for homogeneous traffic behaviour, giving rise to abreast carefully guide, filtering, tailgating, and co-existence. Therefore, the need for a rigorous investigation of the traffic parameters at the microscopic level to assess the traffic behaviour and model an all-inclusive numerical prototype is crucial. The mix-traffic simulation strategies are subdivided into two controlling approaches:

1. Longitudinal Control for Car Following model: One of the fundamental features of the car-following model is that vehicles observe an average spacing, "S,"(m) that one vehicle would follow another at a given speed, "V"(mi/hr). This parameter is of interest in accessing the throughput of the Car-following model. The average speed-spacing relation in Equation (3.48) proposed by [Rot92] deals with the longitudinal features of the road and has a relationship with the single-lane road capacity 'C'(veh/hr) estimation in the form:

$$C = (100)\frac{V}{S} \tag{3.48}$$

   Where the constant 100 represent the default optimal capacity of the intersection. This number is chosen sequel to a series of calibration test conducted with the size of the intersection area
   However, the average spacing relations could be represented as:

$$S = \alpha + \beta V + \gamma V^2 \tag{3.49}$$

   Where
   α = vehicle length, L
   β = the reaction time, T
   γ = the reciprocal of the average maximum deceleration of a following vehicle to provide enough space for safety.

2. Lateral control of vehicle impacts macroscopic and microscopic behaviours on a car-following model. The lateral control causes a lateral interference in a car-following model designed to impact its management only on the longitudinal pattern [MGSG19]. The essence of the lateral behaviour in this AVHVcontol model is to address the driver behaviour characteristics in a mixed vehicle environment. The AVHV control introduces the coupling model between lateral and longitudinal vehicle dynamics through velocity v_x control process and the front wheel steering angle λ_i derived from the steering angle β_v. The relationship between the vehicle velocity v, the longitudinal velocity components v_x, and the vehicle's side slip angle θ is represented in Equation (3.50)

$$v_x = v \cdot \cos\theta \tag{3.50}$$

   In addition the steering angle θ of the vehicle front wheel λ_i the angle of the steering wheel, β_v and steering ration i_u is represented in Equation (3.51).

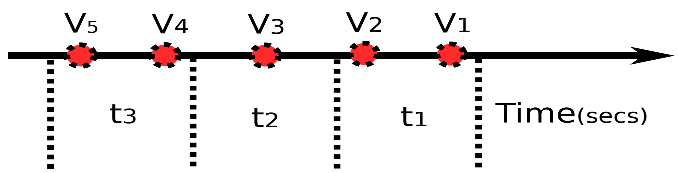


Figure 3.15: Vehicle generation model

$$\lambda_i = \frac{\beta_v}{i_u} \tag{3.51}$$

A mix of these two vehicle control approaches: the longitudinal and lateral is vital in modelling a mix-traffic involving AV and HV. The longitudinal car-following model used the optimal velocity function to relax the equilibrium value of the gap between vehicles. Besides, there is still the existence of high acceleration and deceleration problem after a vehicle cuts in front, but this problem was addressed by the intelligent Driver Model. The lateral model uses the technique of maintaining the safe distance braking process to decide the possibility, necessity, and desirability of lateral control of vehicles. The lateral approach model is addressed on a simplified decision-making process using acceleration according to [KTH07].

From the proposed traffic model Figure 3.2, the intersection area, which contains red spots, represents the shared intersection region ($50m^2$ by dimension) of a four-way intersection system with a double carriage lane in a cross intersection with 20 number cross collision points (ccp). The intersection region is defined by wireless synchronisation between the traffic light, autonomous vehicle, human-driven vehicle, and the input from the intersection control region with a view of avoiding vehicle collision at the 20 predefined cross collision points. L1 to L8 in Figure 3.2 defines the entering lane for a vehicle into the intersection's control region.

3.8.1 Traffic Flows Generation Method

Traffic generation process is a stochastic vehicle generation source model. Each new vehicle assumes the maximum speed with a destination address obeying the Poisson Distribution as represented in Figure 3.15, representing a realistic traffic movement. In Figure 3.15, $V_1\, to\, V_5$ represent a random vehicle distributions, while $t_1\, to\, t_3$ represents time intervals. The vehicle demand is represented by a time-sliced Start/Destination matrix, which specifies the spawning rate of the trips for all vehicle types. In this project, a car spawner is used to implement this vehicle generation process where traffic parameters of the vehicle are defined upon entering the intersection control region. Such parameter includes the following:

1. Vehicle identity: This identifies code for each vehicle in the simulator, as no two vehicles in operation have the same identity. The system of identifying vehicles is by a serial numbering system, starting

with the vehicle type represented by Gc_1 *to* Gc_n, *where* Gc_1 *represent Gentle car*1, *and* Gc_n represent the nth number of gentle car.
For AV, we have Ac_1 *to* Ac_n, *where* Ac_1 *represent Autonomous car*1, *and* Ac_n represent the nth number of Autonomous car.

2. Time of entry: This is a record of the exact time a vehicle enters the intersection control zone. This entry time is measured in milliseconds.

3. Initial speed: This is a record of the vehicle speed at the point of the entry into the control zone; the loop detector does this. The maximum velocity is 10m/s.

4. Maximum acceleration is $6m/s^2$ (The maximum acceleration is dependent on the coefficient of static friction (μ). If $\mu = 1$, then maximum acceleration = $9.8m/s^2$.)

5. HV safe distance = 15 - 20 m: This is the distance between a reference vehicle and the vehicle in front. The safe distance primary aim is to avoid vehicle collision if the car in front brakes or stops. Based on standards, the safe distance corresponds to the distance covered by the vehicles in at least 2 seconds based on its speed [LPS98]

6. HV reaction time = 0.3 - 1.2 secs. The time it takes for a driver to respond to a given stimulus or emergency by applying a brake. This could mean the difference between a collision or the avoidance of one

7. AV reaction time = 0.1 seconds, It should be noted that some of these parameters varies subject to the percentage utilisation of the the road system (the model compared the variations using 50% and 100% road utilisation)

8. HV spawning distance = 20 to 25 m (This is the interval or rate of the process of releasing cars from the spawner)

9. AV spawning distance = 15 to 20 m

10. Acceleration and deceleration rate: Defines the maximum acceleration and deceleration of vehicles from start to destination.

The intersection capacity is one of the primary matrices for analysing or measuring the efficiency of any road traffic intersection system. Based on the intersection's critical nature and its role in traffic efficiency, the high level of safety and efficiency of traffic required of it, a robust strategy is needed to control traffics. By considering all vehicles' states at every time instance, the intersection reservation nodes which are represented as cross collision points (CCP) are assigned to vehicles based on a predefined set of rules. Vehicles cross the intersection simultaneously based on the protocol defined in the car decision-making process. Minimisation of risks helps in generating safe trajectories of vehicles by reducing available time and space in the intersection area and, consequently, enhances the traffic handling capacity of the intersection and improves traffic flow efficiency as proposed by [KIH+15].

3.8.2 Injection of Cars Into the Intersection

The Car Spawner is used to inject new cars in the simulator. The car spawning process releases cars at a predefined interval before the car joins other vehicles on the road. The car spawning interval or distance is usually a constant using a discrete event simulation modelling approach. The spawner is implemented with a vehicle queuing gap (denoted by g), which deals with the time interval or rate at which vehicles are reproduced or spawn from the car spawner. The queuing gap is very akin to distance headway, except that it is a measure of the time that elapses between the departure of the first vehicle and the second vehicle's arrival at the designated test point. The gap measures the time between the rear bumper and the front bumper of the leading and the following vehicles. The distance headway focuses on front-to-front times. Below is a list of parameters used in injecting a new car into the street:

1. Car mass = 1122.366kg (This is the maximum operating weight/mass of a car as specified in the model for the effective car acceleration)
2. Moving force: 1200N (This is the power or energy behind the car in motion)
3. Maximum Braking force = 1200N :This is the force generated to slow down the car when the driver operates the brake pedal. The braking force is a factor of car mass combine with the deceleration rate.
4. Braking starts 10 meters before the safe distance is reached. This value was arrived at after different calibrations with a range of values.
5. Vehicle goal or destination: The start and destination of every vehicle in the simulation are defined. This is implemented with a node dictionary containing all the road nodes (node 1 to node 19).
6. Vehicle route: Each vehicle route is defined based on its destination, and the routing process is predefined in the routing table. The routing system is implemented using the edges in a routing table.

Here is the process that sets the spawning distance depending on the vehicle type. There are two intersection capacity cases for the road here, full (100% utilisation) and half (50% utilisation). In full, there is less spawning distance given between each car, simulating a denser traffic situation. Spawning distance is defined as the random integer value between a minimum and maximum value for a whole traffic situation and the sum of the specified safe distance and the random integer value between a minimum value and a maximum value. Before a new car spawns, the spawning distance has to be met or exceeded by the distance from the last vehicle to the originating node.

- Check the $Intersection_{capacity}$ status: not 50% or 100% utilisation.
- For Gentle Cars, $spawning_{distance}$= a random value between 10 and 15 meters.
- For Aggesive Cars, $spawning_{distance}$= a random value between 15 and 20.
- Check the Spawning distance condition
  - If the distance to the car is greater than the minimum safe distance, it's safe to spawn a car
  - Check if the last and the distance to the last car is greater than the spawning distance before you spawn a car.
  - Spawn another car

To spawn a new car, the $spawn_{another\ car}()$ method gets the route parameter passed to the Car spawner from the test file, loops through it if it is a valid list, and converts each node number to a road node object as shown below.

- Check if route is None before spawning another car.
- Check the length of routes from start to destination.

- Routes = $environment_{nodesofroadsystem}$
- Update the route list.

The mix of different vehicle types (AH and HV) is detailed separately. This vehicle mix identifies each vehicle type, the percentage of the total vehicle stream, and the characteristics capability of receiving information along its route. A separate process does the generation of traffic for each Start/Destination pair, while the inter-arrival times follow a normal distribution. When a new vehicle is generated, the start and destination nodes are defined with all the required nodes to its trajectory. However, vehicle types are determined according to the vehicle mix-proportion described initially, and then a route is chosen from the set of known routes from the start to the destination. The changes in demand over time for different start-destination-pairs are treated as event-driven. This allows for a flexible representation of the demand across the routes. The route choice mechanism is predefined at the generation level of the car spawner with the traffic nodes' help from start to destination. The model route, the utility function used in the route choice, is only a function of the time-dependent travel time on the road. Also, the set S of eligible routes can be made time-dependent.

The CarSpawner module contains the car spawner class definition, which describes how cars should be created in the simulation, how many, what type (Aggressive or Gentle) as well as the distance and time to consider when spawning the cars based on the kind of car meant to be generated with a bit of stochasticity. The spawning behaviour is defined in the test files. Bearing in mind the multiplicity of the car type characteristics and the need to extend them according to modelling objectives and goals, a test and review approach is implemented to establish all the traffic parameters' optimal values. This opens up the idea of the design of agent-based reusable, separate, and relationship libraries, refined by a generic simulation engine. Precisely, full details of the agents used in Carspawners are described below. A dictionary ensures the correspondence relationship between the RoadNode, RoadEdge, road layout, and how they are connected. To prove that this car spawning concept works, experimental tool is developed and tested the capacity of this intersection to use the dictionary of RoadNodes, and RoadEdges from various contexts, then executed "basic" behaviours like collision-avoidance and inter-vehicle space methods. Vehicles could maintain the desired speed (which they aim to reach) and an instantaneous speed based on the prevailing road's current situation. They also calculate the car mobility average speed (over the last simulation cycles). According to the work of [BMP16], all vehicles move along the road edges (links between two nodes), which are logically affected by traffic movement design. The perception of the vehicle is customisable; by default, each autonomous vehicle uses a vision cone in the front and back. At each node, it chooses a destination node and memorises its source. Vehicles are categorised into autonomous(AV) and human-driven(HV) vehicles with perception and action capabilities. Figure 3.18 is a visualised simulation result of how a 4-way road intersection system will look. The figure is a network representation of a cross intersection using nodes and edges; the nodes' layout is numbered for car routing and traffic scheduling system. According to [BLY05] whose research identified the critical parameters of traffic simulation models and concluded that it is better to use values that are realistic and safe than values that are safe but unrealistic.

Then it creates a new car instance with all the related properties such as name, $safe_{distance}$, to mention but a few, and anything specified in the test file, passes the route list from above into its route parameter and appends the car to its list of vehicles. This process involves:

- New car = name (AV or HV) plus the route involved in its destination.
- Apply the $Safe_{Distance}$ to the created new cars. Make the value random for HVs and contant for AVs.
- Apply the $Time_{Reaction}$ to the newly created cars. Make the value random for HVs (0.3, 1.0) and constant for AVs (0.1).

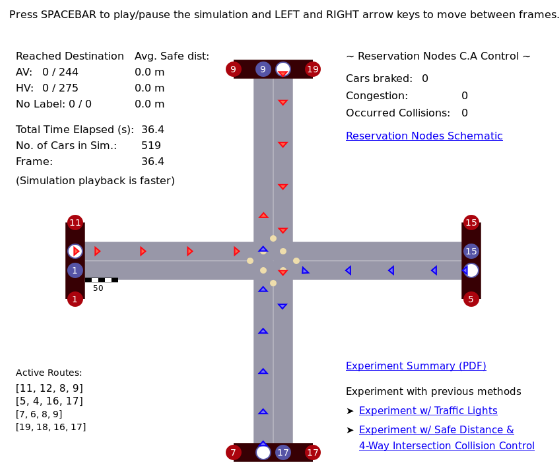


Figure 3.16: Simulation of environment objects[Road system]

- Update the $File_{path}$ for all the vehicles.

Finally, it adds the car object to the environment and returns the last car in the list or the most recently spawned car so that it does not copy several cars over and over again.

3.8.3 Vehicle Arrival Process

Traditionally, the Poisson distribution models any random operation such as the number of vehicles arriving at the road intersection. The Poisson distribution is a discrete function, meaning that the event is occurring or not occurring. A discrete system's variables can only be in whole numbers rather than an interval in its occurrence. A discrete event simulation process is applied to handle the vehicle arrival module, and this method uses random vehicle arrivals with an arbitrary number of vehicles in each duration. In explaining the numerous ways of assessing the performance of a distribution: if we have 3, 2, 3, and 1 vehicle arrived from each lane in the time interval t1, t2, t3, and t4, respectively, any discrete distribution that best fits the observed number of vehicle arrival in each time interval. Also, any continuous distribution that best fits the inter-arrival time used in the model, hence the process can be modelled first by modelling the number of vehicles that arrive at a given duration of time. Poisson distribution is ideal to represent such a random process of car arrival. The probability density function p(x)

$$p(x) = (\mu^x.e^{-\mu}) \div x! \tag{3.52}$$

where
x = no of occurrence of an event at a given interval.
μ = expected rate of occurrence.

However, because the random events are discrete in occurrence, the likelihood that a certain number of vehicles (n) arrives in an interval is given as:

$$p(x \leq n) = \sum_{i=0}^{n} p(i), i \in I \tag{3.53}$$

Similarly, the likelihood that vehicles arrive at interval is the range (between a and b, both inclusive and a < b) is given as:

$$p(a \leq x \leq b) = \sum_{i=a}^{i} p(i), i \in I \tag{3.54}$$

In a simulation example, using Poisson distribution to model road intersection with a 120 vehicle hourly rate of flow in a road intersection could be represented as:
Flow rate = $(\mu) = 120vph = 120/60 = 2$ vehicles per minute.
The likelihood of zero vehicles arriving in one-minute p(0) could be represented as:

$$p(0) = (\mu^x.e^{-\mu}) \div x! = (2^0.e^-2) \div 0! = 0.135 \tag{3.55}$$

3.8.4 Intersection Capacity

The road intersection section is the entire width of the road between the boundary lines that have been specially built for sharing of traffics from different routes. Each road comprises several lanes, while the intersection is made of links to the road lane where traffic gets on and leaves. The city road traffic system's performance depends mainly on the intersections' capacities and the traffic signals. The intersection capacity analysis is considered using different traffic scenarios with various human and autonomous vehicles' ratios. The road intersection capacity is determined by the highest number of vehicles that access the intersection space per unit of time. The intersection capacity is determined by the vehicle platoon's density, distance headway, and the speed of the platoon along the intersection. Below is a representation of the traffic state equation, which describes the correlation between these rudimentary characteristics of traffic flow:

Road Capacity = max traffic volume

$$q = k.v_t \tag{3.56}$$

Traffic density

$$k = \frac{1}{x_{safe} + L} \tag{3.57}$$

x_{safe} = Safe distance (inter-vehicle gap)
L = length of vehicle

For HV

$$C_{Hv} = q_{max} = \frac{v}{x_{safe}(Hv) + L} \tag{3.58}$$

for AV

$$C_{Av} = \frac{v}{x_{safe}(Av) + L} \tag{3.59}$$

When we combined HV and AV From this, one will be able o generate the expected impact of AV on HV when implemented on a graph with varying parameters.

$$\frac{C_{Va}}{C_{Hv}} = \frac{x_{safe}(Hv) + L}{x_{safe}(Av) + L} \tag{3.60}$$

For a traffic mix, n represents AV
capacity (cm) is now dependent on n
$H - V$ represent the integration ratio.

$$cm = \frac{v}{nvx_{safe}(Av) + (1-n)x_{safe}(Hv) + L} \tag{3.61}$$

Considering a different distance by AV to a vehicle steered by HV to avoid harassment of drivers.

$$cm = \frac{1}{n^2 x_{safe}(Av) + n(1-n)x_{safe}(AvHv) + (1-n)vT_{hx} + L} \tag{3.62}$$

The capacity parameters' values are empirically demonstrated for different traffic mix ratios to evaluate the impact autonomous vehicles have on intersection capacity. A constant speed of $10m/s$ is fair enough based on city traffic rule and to assume that the intersection capacity is reached for a real-life city road traffic system. In investigating the impact of AVs or HVs has on road intersection capacity, some assumptions were made. Firstly, the number of vehicles was kept constant at 100 cars, while the ratio of the mix patter changes to ascertain the time it takes for the 100cars to move from start to destination. The Autonomous and Human-driven vehicles are filled out; let say HVs are on-road A and AVs, on-road B for simplicity. Road A is a straight road, and the HVs proceed without making any turns or bends. While road B merges or join road A midway at node 8 from Figure 1.2 after a curve. On approaching the curve at node 12 in Figure 1.2, the AVs slow down considerably and, depending on how close they are to the intersection node 8, get a sense of how far the other car (HV) might be from the nearest RN. More importantly, the RN server judges how far away both vehicles are from each other. The RN control unit then uses this information to grant a car the right of way – it signals the AV to decelerate, keep moving or halt and displays a traffic signal for the human driver in the HV that prompts them to move or slow down or halt as well.

As a result of this, other cars behind the car that slows down while communicating with an RN node or due to traffic or while arriving at an intersection will also slow down to obey the safe-distance model by judging how far they are from the car ahead of them (which is where Inter-Vehicle Communication applies). However, it observed from the occupancy/time graph Figure 6.4 that the time start increasing at the merging node (8) in Figure 1.2. At this point, two vehicles from different roads obey the merging algorithm rule before fusing and form a platoon. This is believed to be due to the joining of the two different vehicles' behaviours, which leads to clustering of traffic and eventual deceleration. Once the vehicle from the 2 lanes merges, the flow efficiency can then be increased because it is a single lane assuming no vehicle overtaking.

3.9 The Road System Infrastructure Design

The first step in developing the simulator started with designing the road intersection system Figure 3.18. Road intersections may be classified based on the number of road segments and lanes that meet intersection points, traffic control methods, or road lane geometric design. Consideration in this project is based on a 3-way and 4-way road intersections system. During the road design and implementation, one needs to establish the coordinate of reference Figure 3.17 shows the road coordinator to which the road and vehicles (x,y) could be referred to in analysing a physical system.

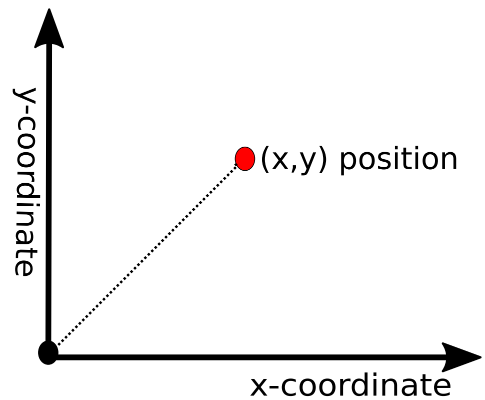


Figure 3.17: Road Coordinate

In controlling traffics at road intersections without a traffic light, various mathematical parameters related to the interface of the vehicles being control are involved. The road design is developed according to the standards and limitations of road geometric design engineering. These standards are concerned with the dimension and layout of the road intersection's physical elements and features and are essential tools used in controlling the traffic based on standard rules and regulations. The following dimensions are used for the design of the model:

- The road width = 6 metres.
- Number of road lane considered = 1 (no overtaking)
- Intersection size = 6metres square.

This prototype geometric road design provides a three-dimensional design structure for a roadway, which includes:

- Alignment - This is the road's route, representing a series of horizontal tangents and curves. The vehicle movement pattern is designed based on the road alignment, which guides vehicle movement from one road node to another. At each instance, each road node's route decision-making process is concerned with the vehicle's goal.
- Profile - It is the representation of roads in outline, especially the vertical aspect, the curve section, and the straight grade lines connecting the nodes in a road.
- Cross-section - The road system's representative details like the number of lanes, sidewalks, crossing slopes, and curbs.

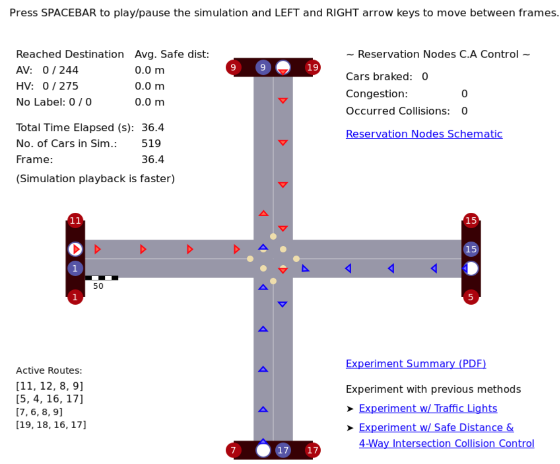


Figure 3.18: Road System Geometry

Road Node: The Road Node object is a vector characteristic of the points between the route that helps track a car at any given point in time. Table 3.5 is a list of all the road nodes and their coordinates in the road layout. The road is a point of interest on the road system that acts as connection points for the road intersection routes connecting vehicles arriving from road lanes to its departure lane. It helps define the collision-prone points within the road intersection. Besides, the road nodes are used by vehicles as reference points for the simulation to check for possible vehicle collisions in the future and prevent them.
The essential component is the curvature, which describes how the host vehicle's curved movement is implemented in describing the road geometry. In modelling a vehicle's curved movement, the "X and Y" coordinates of the road structure are introduced for vehicle reference. The road design is concerned with the roadway's physical elements according to standards and constraints with routes alignment of the road defined as a sequence of a horizontal tangent. The road system model Figure 3.18 is made up of interconnecting road nodes (a spatial point object that represent connectivity between two road links) that represent a system of roads for a given intersection and edges (line along which two nodes or surfaces of a road meet) points. From Figure 3.18, TrafficNode 1 to 19 is created with the same number of RoadEdges indicating the traffic movement pattern based on UK road driving regulations.

The road system design Figure 3.18 is represented as a series of RoadNodes suggestive that they are practicable inter-connectivity. Vehicles' motion across the intersection in straight and curved road edges from node to node and get the next possibles routes when they arrive at a target node. The car spawner generates vehicles with a route comprising nodes from start to target. Vehicles follow from node to node in a logical axial line of the road system as can been seen in the visualisation of the road. Thus, the simulator environment's initialisation requires reading routes, nodes, and edges from a dictionary, to instantiate them and build a traffic flow trajectory graph defining the intersection network topology. Nevertheless, some nodes are just an inflection point in the road (only one possible output). In contrast, others have more complex trajectories that bring several directions and imply that they have to choose based on the routing algorithm.

The road infrastructure was verified in the simulation (e.g., traffic signals, stops, signs, roadside devices) to enhance vehicle behaviour realism. More generally, intersection scalability is potential by integrating other road network elements like pedestrian and cyclist crossing within the environment. Finally, to test the simulator scenarios for experimental purposes, the simulation needs to include car spawners that can reproduce traffic from actual data and measurement tools. The different mechanisms of road systems from the pieces of literature were considered before designing and implementing the various road intersections thus:

- The 4-way road (Cross road)
- The 3-way road (T-junction) with merging section.

The series of experiments carried out were done based on the above intersection types. The traffic signals and other road signs are created to support vehicle movement; simultaneously. The Carspawner is responsible for generating vehicles at a given interval with its characteristics, which reflect discrete event systems. The road infrastructure is customizable for scalability purposes in more complex traffic scenarios. Event managers of several kinds allow extending the actions that can be performed over vehicles or other agents according to specific scenarios; primarily,

- Deceleration factor limits.
- Vehicle speed within a curved section of the road intersection.
- The drivers' behavioural factor.

The Traffic monitors help evaluate the impact of emergency measures, such as the speed control policy in response to the autonomous vehicles' integration process because it updates the real-time traffic data.

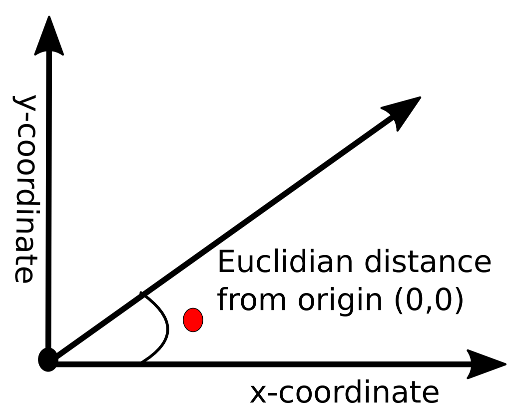


Figure 3.19: Road node addition

A top-down view of a Road Node; basically a vector point with magnitude and direction '0', is represented in Figure 3.19

3.9.1 Model Performance Measures

Traffic Signal Control Systems gather and analyse vehicles' driving details, perform the control protocol for an optimal traffic signal utility following the real-time traffic event. After processing the received traffic signal information, the system provides valuable traffic information to guide vehicles and drivers based on the data collected. To evaluate the new design and assess its quantitative and qualitative properties. Below is a list of standard performance measurement analyses used in all the report chapters.
The considered performance metrics are as following:

- Reliability: This is the probability that this proposed model performs correctly during a specified simulation duration. Besides, during this correct operation, the simulator is stable and does not require further calibration on the parameters used. Furthermore, the model adequately follows the defined performance specifications.
- Safety: This deals with the proposed model safety strategies for preventing a potential traffic collision risk based on identification, analysis of hazards, and application of the mitigating method.
- Efficiency: This signifies a maximum throughput or level of traffic performance that uses the least amount of time to achieve the highest volume of vehicles accessing the intersection. The essence is to minimise traffic delay to its lowest minimum while accomplishing the desired output

3.10 Summary

In summary, this chapter presents a careful and detailed approach to the proposed mixed-traffic management strategy using the traffic flow theories and models. The chapter started with a clear statement of the research hypothesis, followed by the research method to support the thesis. Optimising and synchronising the traffic light control sequence with the vehicle and road communication devices is a highly complicated problem. Modern traffic lights use real-time event-driven-based control models but are designed to model a homogeneous traffic system. However, the AVHV control model supports a traffic schedule with a traffic signal light to control HVs and wireless communications for controlling AVs. This control method involves the dynamic representation of a mix-traffic system at road intersection to better help plan, design, and operate traffic systems moving it through time. The research direction taken was the utilisation of reservation nodes to improve the traffic flow performance. By the reservation of any of the 12 intersection reservation nodes for a vehicle at every time instance, the traffic flow throughput increases better than when using traffic light or collision avoidance methods are in use. A detailed assumptions for the model is followed with the strategy works and its algorithm. The focus is basically on the vehicle model with the response to drivers' behaviour and independent elements. The proposed nodes reservation-based systems communicate with oncoming traffic and permit cars to pass. it is intended as a more efficient alternative to the existing mixed-traffic models. This method will require vehicles to request and receive time nodes from the intersection manager, during which time they may pass through. The node reservation-based scheduling scheme makes use of a reservation-based scheduling approach to reserve intersection nodes to vehicles. The scheduling is formulated as an optimisation problem to find the best vehicle entrances sequence into the intersection based on some priority rules. The scheme is made more realistic by allowing the vehicles to move at any speed within a real-life city traffic speed limit.

The extension of the existing road infrastructure with collision points identification, control unit node reservations improves traffic performance. However, node reservations at the intersection collision points will guarantee safe and optimal intersection management and potentially less expensive strategy to improve efficiency in a mixed-traffic environment. All cars are checked in the intersection environment at every instance in time (0.1 seconds) to update the intersection state. This strategy will efficiently, safely manage, and easy-off traffic congestion at the road intersections. The baseline assumption is that vehicle navigation is purely control by autonomous agents. The advanced traffic simulator measures the different delays associated with conducting traffic through an intersection. Intersection performance metrics were defined for the performance assessment of the strategy. With the autonomous vehicle features such as cruise control, GPS-based route planning, and autonomous steering, it is assumed that there will be an enhancement in the management of a mixed-traffic multi-agent behaviour, thereby improving the performance of HVs. The aim is to compare the performance of the following traffic intersection control strategies: reservation node, cross-collision avoidance, and the traffic light method. A framework has been developed to integrate the autonomous vehicle process in a hybrid model. This framework contains the integration architecture of AV and HV.

Algorithm 1: 4-Way AVHV control Algorithm with three Vehicle $Side - by - Side\ in\ a\ 4 - way$ junction Case

Result: 3-Vehicles arrived side by side. // (As can been seen in fig. 3.4

```
for A, B and C arrived side-by-side on lanes 12, 4 and 6 respectively: do
    if A arrives first: then
        Move A, then move B and C according to rules (2), (3) and (4);
    end
    if B arrives first: then
        Move B, then move A and C according to rules (2), (3) and (4);
    end
    if C arrives first: then
        Move C, then move A and B according to rules (2), (3) and (4)
    end
    for A, B and C -all arrives at the same time: do
        Move left most vehicle first (or vehicle with no vehicle on its left hand side), move the rest
          according to rules (2), (3) and (4);
    end
    // (When 4-vehicles arrives at the intersection;
    When A, B, C and D arrived side − by − side on points 12, 4, 6 and 9 respectively:;
    for A arrives first: do
        Move A, then move B, C and D according to rules (2), (3) and (4);
    end
    for B arrives first: do
        Move B, then move A, C and D according to rules (2), (3) and (4);
    end
    for C arrives first: do
        Move C, then move A, B and D according to rules (2), (3) and (4);
    end
    for D arrives first: do
        Move D, then move A, B and C according to rules (2), (3)and(4)
    end
    // (When 4-vehicles arrives the intersection at the SAME TIME;
    for A, B, C and D all arrive at the same time do
        No left most vehicle, pick an arbitrary vehicle to go first through hand gesturing, infrared
          signalling, etc, then obey rules (2), (3), and(4)
    end
end
```

Table 3.3: Incompatible Traffic Streams For a 4-Way Single lane Road Intersection

Traffic Flow	L1	L2	L3	L4	L5	L6	L7	L8
L1	1	1	0	1	1	0	0	0
L2	1	1	0	0	0	1	1	0
L3	0	0	1	1	0	1	1	0
L4	1	0	1	1	0	0	0	1
L5	1	0	0	0	1	1	0	1
L6	0	1	1	0	1	1	0	0
L7	0	1	1	0	0	0	1	1
L8	0	0	0	1	1	0	1	1

Algorithm 2: RN Scenario using Figure 3.3

```
Result: 3-Vehicles A, B, and C arrived from different lane to the intersection. // (As can been seen
        in Figure 3.3
for A nearest to reservation node and B is too close to A: do
    Decelerate B;
    Maintain B's velocity;
    if C is too close to A: then
        D
    end
    ecelerate C;
    Maintain C's velocity;
    if B is nearest to reservation node and A is too close to B: then
        Decelerate A;
        Maintain A's velocity
    end
    if C is too close to B: then
        Decelerate C;
        Maintain C's velocity;
    end
    if C is nearest to reservation node and A is too close to C: then
        Decelerate A;
        Maintain A's velocity;
    end
    for B is too close to C: do
        Decelerate B;
    end
    Maintain B's velocity;
    Repeat this process for every time interval t, where t can be as small as 0.1 sec.
end
```

Table 3.4: Reservation Node Catalogue

Reservation node	Applicable Route(s)	Start to Target Nodes	Node Coordinates
301	[11, 12, 14, 15], [7, 6, 8, 9], [19, 18, 2, 1]	[12 and 14], [6 and 8], [18 and 2]	[-22.5, -10]
302	[11, 12, 14, 15], [5, 4, 8, 9], [19, 18, 16, 17]	[12 and 14], [4 and 8], [18 and 16]	[22.5, -10]
303	[5, 4, 2, 1], [7, 6, 14, 15], [19, 18, 16, 17] ,	[4 and 2], [6 and 14], [18 and 16]	[-22.5, 10]
304	[5, 4, 2, 1], [7, 6, 8, 9], [11, 12, 16, 17]	[4 and 2], [6 and 8], [12 and 16]	[22.5, 10]
305	[11, 12, 8, 9], [7, 6, 8, 9], [5, 4, 8, 9]	[12 and 8], [6 and 8], [4 and 8]	[-10, -25]
306	[19, 18, 16, 17], [19, 18, 2, 1], [11, 12, 14, 15]	[18 and 16], [18 and 2], [14 and 15]	[10, -25]
307	[7, 6, 8, 9], [7, 6, 2, 1], [7, 6, 14, 15]	[6 and 8], [6 and 2], [6 and 14]	[-10, 25]
308	[19, 18, 16, 17], [5, 4, 16, 17], [11, 12, 16, 17]	[18 and 16], [4 and 16], [12 and 16]	[10, 25]
309	[11, 12, 14, 15], [5, 4, 8, 9], [19, 18, 2, 1]	[12 and 14], [4 and 8], [18 and 2]	[0, -10]
310	[7, 6, 8, 9], [11, 12, 14, 15], [5, 4, 2, 1], [11, 12, 16, 17], [19, 18, 2, 1]	[6 and 8], [12 and 14], [4 and 2], [12 and 16], [18 and 2]	[-10, 0]
311	[19, 18, 16, 17], [11, 12, 14, 15], [5, 4, 2, 1], [7, 6, 14, 15], [5, 4, 8, 9]	[18 and 16], [12 and 14], [4 and 2], [6 and 14], [4 and 8]	[10, 0]
312	[5, 4, 2, 1], [11, 12, 16, 17], [7, 6, 14, 15]	[4 and 2], [12 and 16], [6 and 14]	[0, 10]

Algorithm 6: Pseudo-code for Traffic Flow at an intersection

if car distance to road node is less than the next car distance to node;
check if this car is closer to the intersection;
1 **for** *Car distance to node is less than next car distance to node:* **do**
2   Get the direction of the next node from next car;
3   Check if the other car is on the priority lane;
4   **for** $next_car_direction_to_next_node == +or - 90.0$ **do**
5   check if the other car on the priority lane is moving faster than this car
    end
6   **for** *decelerate of the car = true* **do**
7   Apply decelerate to maximum;
8   Else; GOTO 10;
    end
9   Else;
10   Move on
end

Algorithm 7: Car Movement Algorithm

function *Start to destination node movement*;
Assign vehicle type upon entering the intersection zone ;
for *Car movement is equal true* **do**
    $Car_{speed} = car_{velocity}$ multiply by the $car_{magnitude}$;
    $car_{velocity}$ on x_{axis} = speed multiply by *cosine theta*;
    $car_{velocity}$ on y_{axis} = speed multiply by $sin\ \theta$.
    for *Car movement is equal to False:* **do**
        Decelerate by initialising the acceleration to zero;
        Stop
    end
    $car_{acceleration}$ on $x_{axis} = 0.0$;
    $car_{acceleration}$ on $y_{axis} = 0.0$;
    $Car_{speed} = car_{velocity}$ multiply by the $car_{magnitude}$;
    $car_{velocity}$ on x_{axis} = speed multiply by $cosine\theta$;
    $car_{velocity}$ on y_{axis} = speed multiply by $\sin\theta$;
    for *All the next node is a Road node* **do**
        if node is a valid RoadNode object;
        check edges and append connected nodes to destination list;
        append this node to destination lists of connected node;
        Decelerate the car by multiplying the acceleration by 0;
        Stop
    end
end

Table 3.5: Road Node List and Dimension

Node id	Dimension	Node id	Dimension
1:	[-300, 15]	11:	[-300, 15]
2:	[-50, 15]	12:	[-50, 15]
4:	[50, 15]	14:	[50, 15]
5:	[300, 15]	15:	[300, 15]
6:	[15, 50]	16:	[15, 50]
7:	[15, 300]	17:	[15, 300]
8:	[15, -50]	18:	[15, -50]
9:	[15, -300]	19:	[15, -300]

Chapter 4

The Traffic Simulator

Chapter Overview

This chapter presents a detailed description of how the prototype simulator was conceived and implemented based on the mathematical model and high-level abstractions discussed in Chapter 3. The introduction of the proposed traffic simulator architecture, its essential components, and their descriptions are presented in Section 4.1. The implementation of the simulator's mathematical abstraction with its numerical description is presented in Section 4.3. The simulator visualisation and analysis component details are introduced in Section 4.4. Those details include the drawing outlook and function or workings of the road system and intersections. The actual implementation for the traffic scheduling and routing process is described in Section 4.5. Following this is the test procedures and validation process for the simulator conducted using different traffic scenarios and a review of the output. The validation process includes a small experiment demonstrating that the mathematical model is well approximated and the resulting car behaviour matches our expectations. Finally, the chapter is summarised in Section 5.4.

4.1 Architecture of The Traffic Simulator

The simulator is designed to consider the realistic limitation of a hybrid vehicle's controls and operational (AV and HV) behaviour. Figure 4.1 describe the simulator block diagram and workings of the road system and intersections control management. The fundamental diagram for AVHVcontrol is created using a single-lane road intersection consisting of 8 road lanes which is 50 meters long and a maximum vehicle speed of 10m/s (similar to city intersection traffic speed).
The developed traffic simulator prototype provides a safe virtual environment for testing different traffic control strategies with the repeated calibration of realistic parameter values to optimise the traffic flow performance undertaken at minimal risk. It is a discrete event-based traffic simulator that places the driving system in an artificial environment with real-life parameter values of the actual driving experience. According to [BH87], the critical automation in a traffic simulator is the real-time vehicle dynamic process of controlling how the driver interacts with the vehicle. The measurements obtained from the simulation process could help in the prediction of equivalent measurements in the reality that may lead to an enhanced understanding of the complex nature of mixed driver–vehicle–roadway interaction at intersections. The decision-making process on driver agent behaviour is independent of the simulation and based on the vehicle type contingency model. This prototype simulator developed from physics's theoretical foundations provides a realistic imitation of the controls and vehicle operation.

The simulator module ties the other modules together and exposes its simulation class for use in the testing

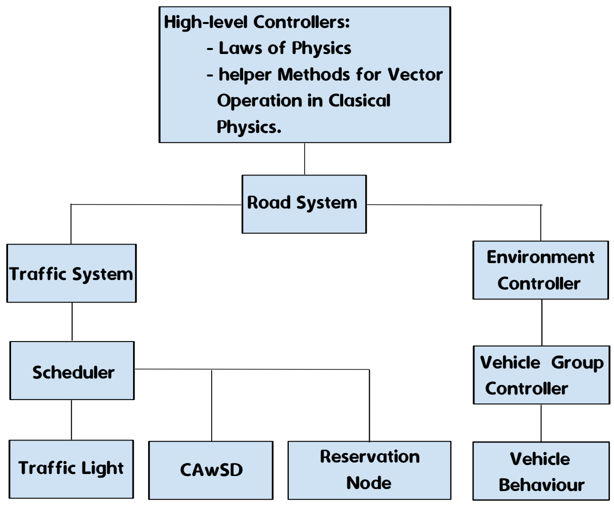


Figure 4.1: The System Block Diagram

files and receiving object parameters. This includes the traffic intersection scenario environment with all its features. The simulation draws the road layout on a web page and steps through the time specified by the time-increment parameter, which tells it how frequently the state should be updated. Each state of the simulation is saved to an SVG file, which can be viewed in succession as an animated video on a web browser. It also gets all the appropriate file paths and writes statistical reports of the states of the environment objects into them.
The simulation process is conducted with the following parameters:

- The road system is designed for single-lane traffic with no vehicle overtaking provision.
- The road intersection design used for the simulation process is a 4-way road junction. In the 4-way intersection, a section of it that represented a 3-way intersection is adopted as part of the investigation.
- Vehicles were generated randomly using a probability distribution.
- The road intersection model covers an area of 600m x 600m (this is currently a constant for this investigation purpose). Each vehicle is 4.4m in length by 1.9m width[1], while the single lane road system is 3.9m wide. There was no provision for overtaking.

The conceptual simulator's model diagram (Figure 4.3) is a specific class diagram designed for the development and management of the traffic simulator, which can be adapted to perform different traffic management strategies. This model is a real-time intelligent traffic intersection control system deployed in a mixed traffic environment of different intersection types. This research's primary focus is to develop an algorithm for mixed traffic with a safe and efficient throughput. The model framework comprised of the following main sections:

- Higher-Level Controllers: This provides relationship between the lower-level and middle-level controllers. It controls/supervises the activities of a collection of roadside controllers from different road lanes. For optimal performance, the idle time (time-idle) may be set to higher than 0. This is when

[1] Using the size of the Toyota Corolla 2015 model.

no updates are made on the car's state. By default, idle time is 0. next-node performs a first in first out (FIFO) operation on the car's route list to keep track of how many nodes are left for it to reach its destination.

Helper methods and vector operations in classical physics Force, velocity, and displacement are vector quantities in which both the magnitude and the direction must be stated. In order to find the magnitude of two vectors represented in Figure 4.2, we may use the Pythagoras theorem:

$$c^2 = a^2 + b^2,\ therefore\ c = \sqrt{a^2 + b^2} \tag{4.1}$$

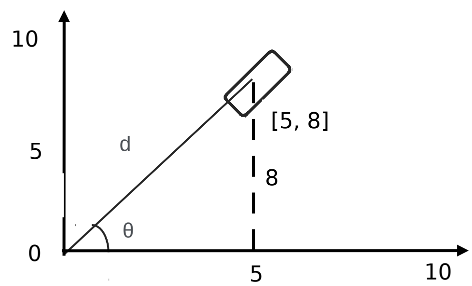


Figure 4.2: Vector Operation in classical physics

Taking it further, if we have a car on a 2D space with x and y coordinates, the above formula is used to calculate its displacement from the origin. From Figure 4.2, the car is displaced 5 units along the x_{axis} and 8 units along the y_{axis}. Therefore the car displacement could be calculated thus: $d^2 = (5\breve{\ }0)^2 + (8\breve{\ }0)^2 = 9.43$, and the direction angle is approximately 58 degrees by taking the inverse $\tan of 8/5$.

Classical Physics: This is the part of Physics that predates Modern Physics. It contains Newton's laws of motion (and their derivative Newtonian Physics) amongst other branches of Physics such as Thermodynamics and General Relativity. These are grouped as classical Physics to distinguish them from Modern Physics which contains Quantum Mechanics and Quantum Field Theory. Of all these, Newtonian Physics within Classical Physics is what is of interest to us in this project.

The Vector2 class The name was used in order not to conflict with an inbuilt Python library called "Vector." This class contains the helper methods, which help the car's movement algorithm change the car's vector properties such as acceleration, velocity, and displacement.

Helper methods with their Vector Operations: With the above vector properties in mind, here are the helper methods with the vector operations responsible for every object with vector properties:

- **Distance:** Calculates distance between two coordinates – using Pythagoras theorem

$$Distance = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \tag{4.2}$$

- **Direction:** Finds the direction of the magnitude of a vector – using inverse tan. The method also checks that input to the function is a vector first.

$$Direction = \tan\theta(y_2 - y_1 x_2 - x_1) \tag{4.3}$$

- **Redirect:** This method applies a magnitude in a direction (redirecting it). Direction:

$$x = magnitude * \cos(\theta),\ y = magnitude * \sin(\theta) \tag{4.4}$$

  vector.

- **Cap:** This method prevents the object from exceeding its maximum possible values, e.g maximum velocity. In this case, one need to specify the cap of the values:

$$x = bound, x > bound,\ y = bound, y < bound \tag{4.5}$$

- **Scale:** This scales the vector's coordinate values by the supplied value. hers, one need to specify the scale needed.

$$vector.x* = scale,\ vector.y* = scale \tag{4.6}$$

- $Round - To$**:** Rounds vector's coordinate values to supplied decimal places. For example, we have

$$vector.x = round(vector.x, decimal\ places,\ \ vector.y = round(vector.y, decimal\ places) \tag{4.7}$$

- **Add:** Adds vector's coordinate values to another vector's coordinate values.

$$x+ = add\ x, y+ = add\ y \tag{4.8}$$

- **Copy:** Returns a copy of the vector. ("copy" is an inbuilt Python function)

$$vector = vector.x+ = add_vector.x,\ vector.y+ = add_vector.y \tag{4.9}$$

- **Get Value:** Displays the value of the vector. It will return the value, eg

$$Speed = \sqrt{x^2 + y^2} \tag{4.10}$$

- **Speed:** Returns the speed (if the vector is a velocity), using Pythagoras theorem 4.10.
- *Reset***:** Resets the vector X and Y coordinate values to 0.

$$x = 0,\ y = 0 \tag{4.11}$$

- **Draw:** Draws a line by connecting 2 vector points. Other helper methods in the Vector2 class are variations of the ones listed here.

$$add(Vector2([-offset.x, -offset.y])) \tag{4.12}$$

- **The Road System:** This represents the road intersection zone showing the interconnected lanes and points of interest.
- **The Environment Controller:** This uses roadside equipment like traffic detectors and inductive loops to control and tweak the traffic flow process. The controller allocates the appropriate speeds for each vehicle platoon, optimised safe distances between platoons, desired platoon sizes, providing route guidance dynamically for the vehicle platoons, and provides guidance for merging and diverging.
- **Vehicle Group Controller:** This supervises the management and planning of each groups of vehicle in the platoon. The vehicle group controller receives instruction from the roadside monitors and is mainly worried with implementing the inter-platoon manoeuvres such as integrates with other vehicle groups, splits or lane changes, and intra-platoon activities such as maintaining safe distances and acceleration for accomplishing the tasks assigned by the roadside controller.
- **Vehicle Behaviour Controller:** The vehicle behaviour controller present in each vehicle guides the behaviour of each vehicle from start to destination. They receive instructions from the intersection control unit and translate them into control signals for the vehicle actuators such as throttle, braking, turning and steering. The input and output parameters for the vehicle behaviour controller are listed as shown below:

  The vehicle behaviour controller Inputs

  - Cars' position
  - Reservation nodes' position
  - Cars' velocity
  - Cars' route nodes to check for shared node.

  The vehicle behaviour controller Outputs

  - Distance between cars and reservation nodes
  - Distance between cars and neighbouring cars
  - Decelerated velocities or unchanged velocities.

  Mathematically, the car behaviour is calculated using the above inputs and providing the outputs to prevent collision of vehicles based on reservation nodes and distances between cars This process involves the following steps:

  - Take an inventory of all cars in the simulation from the environment object.
  - Calculate the times to arrive at reservation nodes
  - Loop through all the $active_reservation_nodesandcars$
  - Reconfirm the RNs that are to be used by each car and calculate the expected arrival time at each RN and store the look in a dictionary.
  - Pass cars if $thetimes_to_reserved_nodes = 0$
  - Then calculate the distances from this car to other cars before it reached their destination.
  - Check if the minimum distances to other cars is less than safe distance to slow down or to continue if not.
  - Empty the dictionary for next iteration.

- **Traffic System:** This comprises the traffic scheduling process to address the traffic demand and its control policies for an optimal flow.

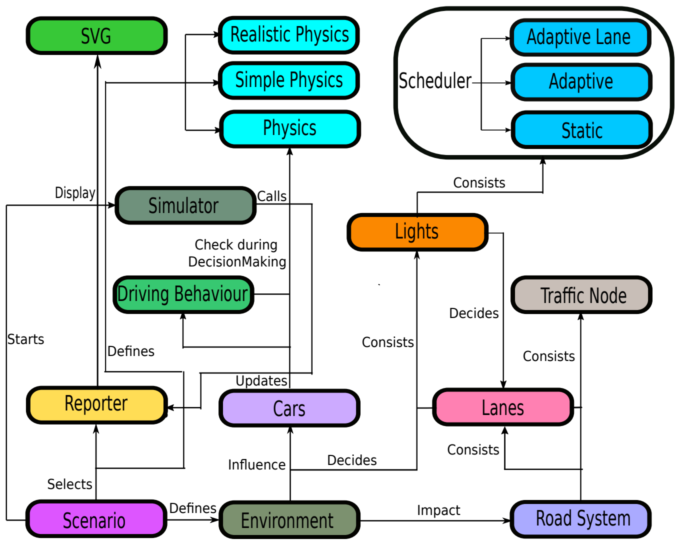


Figure 4.3: Simulator Architectural Diagram

4.1.1 Key Components Of The Simulator

Figure 4.3 represents the research conceptual model diagram designed for the AVHV control, developed as a framework for this research. This simulator design diagram could be adapted to perform different traffic scheduling strategies. The focus is on scheduling algorithms for mixed traffic with a safe and efficient throughput. The functional components are combined to achieve the above-stated objectives. The prototype simulator components and their descriptions are detailed below:

- Simulator- An XML-based Canvas for drawing complex 2D graphics road layouts of intersections allow for displaying and scaling vector images without sacrificing quality. SVG- Scalable Vector Graphics is a vector-based image format for 2D graphics that supports interactivity and animation used to visualise the model behaviour.

- Reporter- This generates statistical records of different parameters of the simulator.

- Scenarios- This deals with the creation of an intersection environment for a test case.

- Environment - It defines the intersection components: route, road system, traffic light, pedestrian, and road layout.

- Car - This defines the vehicle's basic parameters: position, velocity, acceleration, mass, speed, gravity.

- Road system - This comprises the traffic nodes and the road lane

- Physics- This defines the dynamic and kinematic model of the car.

- Lanes - Each road system is made up of lanes, which defines the section of the road the car is moving on based on traffic rule
- Traffic Nodes - Defines the different roads that make up the traffic intersection.
- Light - Contains the traffic lights of different colours, which directs human-driven vehicle movement.
- Driving Behaviour - This defines how Human-driven vehicles (HV) and Autonomous Vehicles (AV) react to the environment, with another car, and the road infrastructure using the physics principle in motion.
- Scheduler: This comprises the adaptive lane, and static schedulers that deal with lane priority, event-driven, and time-based scheduling systems. The scheduler is the core of this research.

Brief Description of the Simulator The developed simulator makes use of a traffic light control device with a vehicle to infrastructure communication control. The wireless communication control devices, traffic lights, and road infrastructure are the essential parts of the traffic intersection environment. The prototype simulator is designed to simulate mixed-traffic strategies for modelling and planning different vehicle coexistence. The autonomous vehicle emergence comes with growing concern in the existence of complex traffic systems. Various traffic control strategies are introduced to the simulator to assess its performance efficiency. Algorithm 8 describes how the current intersection status is updated with the current traffic situation before the traffic control decision is made at every instance of time. It also dispatches orders to environment objects, which it contains to draw themselves on the map. The environment objects include the agents and non-agents that contribute to the simulation's general state at any given time. It also tells the simulator environment to update their status and record the state to store or recall diagnostic use.

Algorithm 8: Intersection Control Update (Reservation Node (RN), CU, Cars and Traffic Light)

```
1  function Intersection Update (Time step, Real-time intersection detail) ;
2  output = Schedule vehicles to RN or traffic light, // (Update status of RN, Cars presence,
    traffic light;
3  for Every Time Step do
4      Update traffic lights;
5      Each car agent makes movement decisions;
6      Contact control unit to query state and update schedule;
7      Move all cars according to the laws of physics;
8      Update the (Control Unit) CU with the current status of the RN, Car, and Traffic light;
9      The CU synchronises the status of the RN with the traffic light (the two are assumed to be in sync
        always) ;
10     Record diagnostics for later analysis
11     for Every request from Car to use the intersection zone do
           Goto 6 ;
12         Record the details // (create a csv file);
13         Increment the timer // Next time instance;
14         Go to line number 3 // Update the intersection status
       end
       Go to 3 for the next time step;
   end
```

4.2 Car Behaviour model:

The car behaviour algorithm (9) contains how vehicles are defined behaviour-wise. It contains all real-life characteristics functionality for each car type in the simulation, and its behaviour is guided by what parameters are passed to it at spawning time. The behaviour model implements and overrides the physics methods responsible for triggering the physics updates of the car. The Obey Traffic Light method handles the business logic for the HVs movement across the intersection, but the traffic light control must be in sync with the vehicle to infrastructure communication protocol through the control unit. Turning takes care of direction updates for the car.

Algorithm 9: Car Behaviour Algorithm- Collision free method

```
Data: Default Gentle behaviour of AV, Aggressiveness in human drivers psychology (quantified by
      random values)
Result: AVs and HVs Behaviour
for Every HV : do
    Assign aggressiveness with the following attributes;
    Randomised Reaction time ;
    Randomised Safe distance (in time);
    if The Vehicle is AV then
        Maintain the constant Reaction time;
        Maintain the constant Safe distance (in time);
    end
    if AV and HV having the same expected arrival time (EAT),comes into conflict to share an
      available road space (eg RN, traffic light or CCP) then
        // (apply priority considerations);
        Assign priority to HVs to move;
        Decelerate the AV;
        Then move the next Car (AV);
        if the two Vehicle has diferent expected arrival time (EAT) then
            move the vehicle with the shortest EAT first ;
        end
        At Intersection;
        AV is guided by the Vehicle to Vehicle and to infrastructural communication;
        HV is guided by the traffic light control;
        The CU sync the 2 control methods
    end
    if Emergency situation occurs then
        The AV drives defensively by applying deceleration/acceleration as necessary ;
    end
end
```

Collision Avoidance: This is a proactive technique used to detect whether a car can safely transit the intersection without the risk of collision on the trajectory to the target. The risk of vehicle collision within the road intersection occurs at the reservation nodes. This reservation node strategy (5) aims to use the collision avoidance technique to eliminate situations where cars are sharing the same cross collision point and entering the intersection at the same time while coming from a different route.

4.3 Implementation of the Mathematical Abstraction and Model Description

A well-guided conceptual traffic simulator defines the studies' context, research objectives, model components, assumptions and enhances the possibility of a successful strategy for the mix-traffic simulation investigation. The prototype simulator uses physics' fundamental laws. The car's movement parameters are primarily controlled by the longitudinal and lateral forces separately for acceleration or deceleration and for turning, respectively. A detailed algorithm illustrating the vehicle movement schedule is presented in Algorithm 10. The prototype simulator is developed in a virtual environment using a physics engine to model the traffic system.

Notes about the direction's coordinate: Using analytic geometry, the direction of a vector is the cosine of the angles between vectors, and the three positive coordinate axes contribute each component of the basis to a unit vector in that direction. Horizontal and vertical straight lines on the computer screen can be represented below:

- -90.0 or 270.0 degrees - down to up movement
- 90.0 or -270.0 degrees - up to down movement
- 0.0 or -180.0 degrees - left to right movement
- -0.0 or 180.0 degrees - right to left movement

The curved movement method originates in the placement of route nodes in the road layout while moving cars are made to seek for them. If a robot is programmed to seek out points on a grid that is shaped like a cross, it will always go in straight lines no matter what else you write for it to do.

4.3.1 Straight Movement Model

The model Figure 4.4 uses physics' fundamental laws to move a car from point A to point B in a straight or curved direction. Where $l(v^i)$ = length of vehicle, $p(v^i)$ = Position of vehicle and $s(v^i)$ = Safe distance

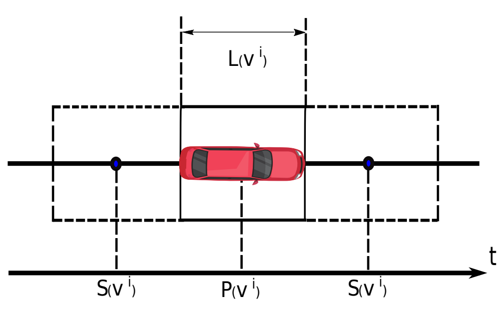


Figure 4.4: Model of straight vehicle movement

of vehicle

For the car to move, calculations of parameter values are based on Newton's second law of motion. The drag force F_{drag} and rolling resistance forces F_{rr} resist the traction force $F_{traction}$ while driving horizontally. If cruising at constant speed scenario, then F_{drag}, F_{rr} and $F_{traction}$ are in equilibrium, which makes the longitudinal force F_{long} to be zero.

$$F_{long} = F_{traction} + F_{drag} + F_{rr} \tag{4.13}$$

$$F = m \cdot a \ (N) \tag{4.14}$$

where a is the acceleration and m is the mass.
Expressing equation (4.14) in terms of the acceleration a, controlled by the net force $'F'$ and mass $'m'$ according to Newton's second law:

$$a = \frac{F}{m} \ (m/s^2) \tag{4.15}$$

Acceleration is a ratio of change in velocity to change in time thus:

$$a = \frac{\delta v}{\delta t} = \frac{v_i - v_{i-1}}{t_i - t_{i-1}} \tag{4.16}$$

Substituting equation (4.16) into (4.14):

$$F = m(\frac{\delta v}{\delta t}) = m(\frac{v_i - v_{i-1}}{t_i - t_{i-1}}) \tag{4.17}$$

Where:
δt, δv are the time variation of the successive calls to the physics engine and the variation of velocity respectively.

Using the Euler method for numerical integration, the car's velocity('m/s') is determined by integrating the acceleration over time. The car's distance covered (s) ascertained by calculating the integral of the velocity over time:
i = time interval

$$s = \delta t \cdot v_i \tag{4.18}$$

However, from the above equations, we can now calculate the car velocity thus:

$$v = \frac{\delta s}{\delta t} \tag{4.19}$$

The car's velocity increment is directly proportional to the resistance forces, and once the traction force exceeds all other forces, the vehicle starts accelerating. The car's acceleration decreases with a decrease in net force. The car's maximum speed is reached at a point where the resistance forces and the engine force cancel each other out.

Braking: The braking process replaces the traction force $F_{traction}$ by a braking force aligned in the opposite direction of movement. The process of braking (s) forms the total longitudinal force which is a vector sum of F_{drag}, F_{rr} and $F_{traction}$.

$$F = F_{braking} + F_{drag} + F_{rr}(physicsbook) \tag{4.20}$$

Therefore, the braking model:

$$F_{braking} = -u \, \dot{C}_{braking} \tag{4.21}$$

Where:
u and $C_{braking}$ = unit vector reflecting the car orientation and the braking coefficient respectively.
It is assumed that braking force is a constant, and its application will stop immediately the car speed is reduced to 0 to avoid reverse movement.

4.3.2 Curved Movement Model

The vehicle describes a curved circular path perfectly when the front wheels turns at an angle $'\theta'$, while the car is maintaining a constant speed. For optimal performance, keep the car speed constant while the physics of turning is simulated at low speed and high speed. Car wheels can sometimes have a velocity not aligned with the wheel orientation, and this is because, at high speed, one observes that the wheel can be heading in one direction while the car body is still moving in another direction. This means there is a velocity component that is at a right angle to the wheel, which generates frictions.

To simulate car movement at the curve, one needs some geometry, kinematics and need to consider forces and mass. The curve movement model is illustrated in Figure 4.5 and Figure 4.6 which describes how vehicles move in relation to their coordinate position. Without the curve movement model, this experiment will fail because of the vehicles' necessity to maintain lane track.

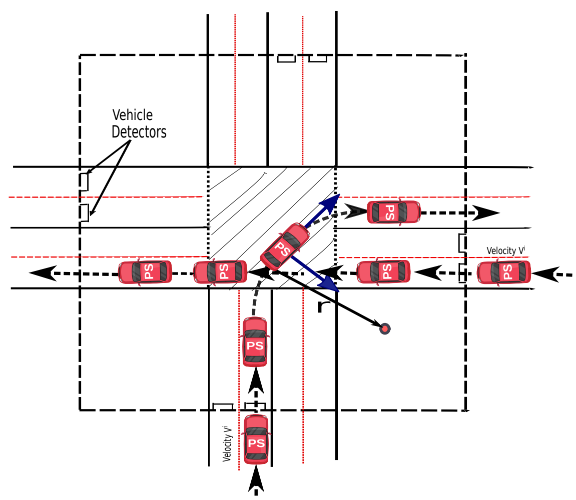


Figure 4.5: Model of curved vehicle movement

Accessing the bend: The angle of the curve is calculated thus:

$$\theta = 360 \cdot v / l_{circle}(arc) \tag{4.22}$$

$$\theta_{actual} = time \cdot \theta \tag{4.23}$$

$$v_{max(curve)} = x \cdot v \cdot r \tag{4.24}$$

The curve's angle α = the angle between two intersecting planes. Curved angle is a measure of the angle between two intersecting straight lines and the lines perpendicular to the intersection in respective lanes. This angle can be calculated thus:

$$\alpha = \frac{\theta_{actual}}{180 \cdot \pi} \tag{4.25}$$

The distance s in a curve can be calculated thus:

$$s_{curve} = \frac{\theta_{actual} - (\theta_{end} \cdot l)}{v} \tag{4.26}$$

The Car's Maximum Speed along a Curve: This is the optimal speed for crossing a curve. This speed depends on the chord's maximum radius that can drive a vehicle through a particular curve (it is assumed that curve has a constant radius).

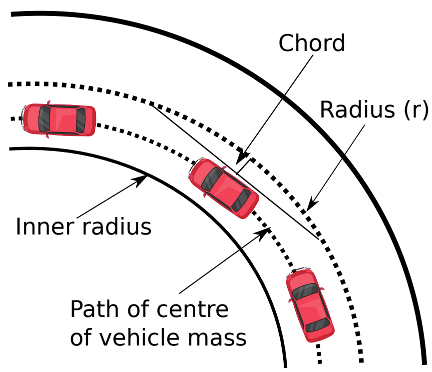


Figure 4.6: Car Maximum Speed in a curve

From Figure 4.6, the maximum curve radius is determined by the inner radius, which defines the curve itself, the available road width, and the curve turns' angle. It is assumed that if the radius of the outer front tyre of a vehicle could be determined over the early part of the curve, then the car's speed marking the curve is established. The reason is that the curve radius could be determined from a chord and middle ordinate measurement using the equation below. However, for the purpose of this research, the curved radius is a constant.

$$r = \frac{c^2}{8 \cdot m_o} + \frac{m_0}{2} \tag{4.27}$$

Where c = chord length, m_o = middle ordinate.

Once the radius is established, the speed of the vehicle making the marks can be determined from the expression,

$$v = \sqrt{r \cdot \mu \cdot g} \tag{4.28}$$

Where μ = static friction coefficient and g = acceleration due to gravity

Neades in [Nea07] developed a model (speed equation) for calculating the maximum speed at which the bend can be negotiated.

Algorithm for the car curved movement: The method of curved movement is summarised using an algorithm in 11. The process directs the car's motion to follow a curved centre slowly, turning the car with a reduced time step to avoid skidding off the road. Skidding occurs when the tires cannot grip the road as they should, the skidding is caused by how the driver steers, accelerates, brakes, and the approaching speed. The skidding process increases when the road is wet or icy, making the driver start to skid when it brakes too hard. The turning parameter calculation drives the car speed from the beginning of the turn to the end before maintaining a straight road.

Algorithm 10: Method for Vehicle Movement Schedule Using Physics

---

Data: Position (x), Mass (m), $MaxAccele\ a_{max}$, Drag (f_{drag}), $Max_{Deaccele}(d_{max})$,;
Accele(a), Velo(v), time(t), Car(c), radius(r), (C_{curve}), $start_{Degree}$ (θ_{start}), endDegree (θ_{end})
Result: Returns the Absolute Speed in m/s

// When the Car is moving on a straight road ;
1 **for** *Car Moving along on a straight road* **do**
  s = $\sqrt{v_0 * v_0 + v_1 * v_1}$ // calculate the car speed;
  Force = $\sqrt{a_0 * v_1 + a_1 * v_1} * m$ // calculate the engine force
end
// When the Car is moving on a Curved road;
2 **if** *Car is Moving on a Curve* **then**
  Obeying Physic // Implement physics of curve method from line no 6;
3   $\mu = 0.75$ // Coefficient of static friction;
4   $g = 9.8$ // acceleration due to gravity;
5   $a_{update} = (a_0 + \delta a_0, a_1 = a_1 + \delta a_1)$ // Update Car acceleration;
6   $v_{update} = (v_0 + \delta t * a_0, v_1 = v_1 + \delta t * a_1)$// Update Car velocity;
7   $x_{0,update} = (x_0 + \delta t * v_0, x_{1,update} = x_1 + \delta t * v_0)$ // Update Car position;
8   $s_{max} = \sqrt{g * \mu * r_{curve}}$ // Calculate maximum speed;
9   $l_{curve} = 2 * \pi * r$ // Calculate the curve length;
10   $\theta = 360 * s_{current}/l_{curve}$ // Calculate the curve angle;
11   **if** *Vehicle Reached End of curve = False* // Check if the car has not completed the curve **then**
12     $s = \sqrt{v_0 * v_0 + v_1 * v_1}$ // Calculate the updated curve length;
13     $x = x_{current}$
  end
14   **if** $\theta_{end} < \theta_{start}$ // Check if theta is -ve **then**
15     $\theta = -\theta$;
16     $\theta_{actual} = t_{current} - t_{start} * \theta$ // Calculate the current theta;
  end
17   **if** $\theta_{actual} >= \theta_{end}$// Check if car has reached end **then**
18     $Reached_{End} = True$;
19     $\theta = -\theta$;
20   **if** $theta_{actual} <= \theta_{end}$// Check if car has reached end **then**
21       $Reached_{End} = True$
    end
  end
  // Compute amount of way driven;
22   **if** *Vehicle Reached End* **then**
23     $t_{AfterEndingCurve} = \theta_{actual} - \theta_{end}/360 * l_{circle}/s$ // Calculate the time at the end of the curve;
24     $s_{abs} = s_{current}$ // Absolute distance = current distance;
25     $\alpha = \theta_{actual}/180 * \pi$ // Calculate the current alpha;
26   **if** $\theta_{actual} == \theta_{end}$ // Check if this condition is true to confirm reach end **then**
27   return [True], $t_{AfterEndingCurve}$;
28   Else; return [False];
29   GOTO line no 12 // Go back to line number 12 and check if the vehicle has reached end of curve
    end
  end
end

The Movement Control Methods of the Car

This is the systematic way or manner of driving or moving a vehicle from one position to another as reflected in algorithm 8. The vehicle control process involves a guide by inputting the environmental information and potential estimation of minimal zero risks to enable the vehicle to change position at every instance of time.

$Next_Node$: This method feeds the next route node that should be traversed by the Car. It produces the next point on the road for the Car to move to like a conveyor belt as long as the Car has at least one more node to go to or the distance from it to the last node is above 37.5 metres (37.5m is the established optimal distance to begin decelerating based on its maximum speed.)

Algorithm 11: $Next_{Node}$ *Method* :

```
function NextNode : (Time step, road Node, Speed, direction, Distance, ReachNode, Acceleration,
  Deceleration) ;
output = next point on the road for the Car to move to, // (Update the Next Point for the car
  to move to);
for Every Time Step // (Update the next point on the road for the Car to move to);
 do
    Produces the next point on the road for the Car to move to like a conveyor belt as long as the Car
      has at least one more node to go to or the distance from it to the last node is above established
      optimal distance (of 37.5 metres) to begin decelerating based on its maximum speed;
    for Car distance from the current car position is > 37.5 if the number of Car is above 1.;
     do
        Confirm that this is a road node: // (Confirm that the car is currently occupying a
          road node);
        Get the speed and magnitude of the acceleration // Calculate the speed and magnitude
          from the velocity and acceleration for the subsequent calculations.;
        Get the direction // Get the direction that should guide this Car to the next node;
        Direction is calculated trigonometrically using the coordinates of the previous
          node and the next node.;
        Incline the velocity and acceleration with this direction.;
        for Car has reached the next node in the list using rounded values. do
            for the rounded up (or down) difference between this Car's position and the next node is 1
              (metre), make the Car reach the node. Without doing this, the cars will never register
              having reached a node as there is a high probability that the car's position will update with a
              lot of decimal places and not hit the node position do
                To reach the node, a method called each_node is invoked.;
            end
        end
    end
    for this is the last node and the distance from the position of this car is equal to or less than 37.5
      metres do

    end
    Set the acceleration condition property to False and begin decelerating the Car.
end
```

Reach $_{Node}$: This method copies the position of the next node on the list and assigns it to the Car's position. The reason for doing this is to ensure that the Car reaches the node otherwise, as there are infinite values between any 2 numbers, there is a high probability that the Car never reaches the node.

Algorithm 12: $Reach_{Node}Method$:

Data: Car count, position, time
Result: x_{safe}
for *The Car reaches the node* `// Check to make sure that the car has reached end` **do**
  copies the position of the next node on the list and assigns it to the Car's position. `// The reason for doing this is to ensure that the Car reaches the node otherwise, as there are infinite values between any 2 numbers, there is a high probability that the Car never reaches the node.`;
  Else: Record the count of how many cars have arrived at their destination.;
  if *Car has reached its destination* `// check if car has reached its destination` **then**
    Increment car counter
  end
  Else: preserve a copy of the current node in a member variable called $previous_{node}$ `// save the current node`
end
Unpack the first node in the route node list, making the next node list the current node. `// Update the route node list`

Move $_{Car}$: This method moves the Car while checking for traffic control protocols.

Route $_{cache}$ This is another route list introduced because the route list changes when the Car arrives at a route node. This *route* $_{cache}$ keeps the points of reference constant starting at the second node in the original route list.

Set $_{Environment}$: This is run at the instantiation of a new car object. First, set the running environment, using the Car's parent's method in $set_{environment}$.

$Behaviour_{Update}$: This is the way in which cars, actions, acts or conducts themselves in conjunction with the environment, especially towards others traffic. Other traffics, in this case, includes another vehicle, road system infrastructure, and obstacles. The car environment properties changes at every instance of time. It update the properties of the Car using the parent's method $Behaviour_{Update}$:.

$Physics_{Update}$: The car's physical forces properties control the acceleration or deceleration of the vehicle, including the car's speed. Lateral forces, which are caused by sideways friction on the wheels, allow the car to turn. Update the properties of the Car using the parent's method $Physics_{Update}$:.

Turning: The process of a vehicle turning takes place at road intersection or where a road branches off from another. This process obey the physics theory in calculating the direction and position of car.

$Apply_{Force}$: This method is responsible for applying engine force to move the Car. In addition this method requires another parameter called *magnitude* $around_{curve}$ which is used to curve the Car.

Algorithm 13: *Move* $_{Car}$:

```
Data: time, node, distance, braking, destination
Result: Car reaching its destination
for the node being approached is the last node // Check if this the last node do
    for the distance between the Car and that node is greater // Check if the distance between
     the Car and that node is greater than 37.5 metres, if so, do nothing. do
        Else: set certain properties;
    end
    Don't break the Car suddenly; bring the Car to reach and specify that this Car is reaching its
     destination. Else: grab the distance from which the condition above wasn't satisfied Store it in a
     member variable called initial_distance_before_rest.
    for this Car is not to be braked and not to be brought to rest // Check if the car should
     continue moving do
        Apply force to move the Car passing in the update time, moving force and if it is moving
         around an intersection or not.
    end
    for there are at least 2 nodes left for the Car to go to // you need at least 2 nodes to have an
     intersection. do
        Get the direction (in degrees) that would guide the Car in advance for the intersection using the
         next node and the node after that.
    end
    for the next 2 nodes don't form a straight line and the distance between the second node the Car will
     come across // check if the next 2 nodes forms a straight line do
        stored in route_cache // intersections in the experiment always involve the 2 middle
         nodes and there are 4 nodes in total, so that is why the second node is used as
         a reference point;
        for less than 10 metres do
            indicate that this Car is going around a curve using the curve method is_around_curve
        end
    end
end
```

Decelerate: This method is responsible for decelerating the Car.

The condition when the car is entering the curve

- If $\theta_{end} < \theta_{start}, \theta = -\theta$
- If $\theta_{end} > \theta_{start}, \theta = \theta$

Condition when the car reaches the end of the curve The time spent =

$$t_{end} = (\theta_{actual} - \theta_{end})/360 \cdot l_{circle(arc)}/v \tag{4.29}$$

$$\alpha = \theta_{actual} * \pi/180 \tag{4.30}$$

Algorithm 14: *Set* $_{Environment}$:

Data: car, time, environment, route
Result: environment
for *the route list is not empty (if its length is greater than 0)* // Check all the route status **do**
  Convert all the numbers in the list to actual route objects using the road system object in the environment. // Updating the current car environment;
  Else: Preserve copies of the first node in the list before unshifting;
  if *Unpack route list* // save the route list **then**
    Copy the remaining nodes into a new unchanging list called $route_cache$.
  end
  Else:;
  Make sure that the Car's position is the first node by copying the node position from the member variable called $first_{node_in_route}$. // update all node position
end
Call $first_{node_in_route}$ // update the record of all nodes in route

However, this scenario could be estimated by introducing a node of 30 meters from the bend, and the car begins to decelerate, taking into account the angle between the next two nodes to get an adequate vector velocity for its x and y-direction. 30 meters was chosen because the shortest distance between nodes (example: from node 2 to node 3, node 12 to node 8 or from node 4 to node 16)in the road layout is 35meters, so 30 meters will afford the moderate vehicle velocities, enough time to decelerate to a low enough velocity before the next node.

Alternatively, on leaving the bend, the car accelerates again till it reattains maximum velocity and sustains it until it is close enough to its destination when it begins to decelerate and stop.
Its total displacement, s_t can be given by:

$$s_t = a_1 \cdot t_1^2 + v_2 \cdot t_2 + d_3 \cdot t_3^2 + v_{x,y}4 \cdot t_4 + a_5 \cdot t_5^2 + v_6 \cdot t_6 + d_7 \cdot t_7^2, \tag{4.31}$$

where
$a = acceleration$
$d = deceleration$

$v_{(x,y)}$ = velocity changing with respect to direction
$t_1 ... t_n$ = divisions of time.

The simulation implementation started with the implementation subsystems that cover deliverable components from which the deliverable are produced. This process started with the mathematical design of the road system. Figure 4.7, represents a 2-dimensional vector x and y components, respectively, with the magnitude and applied angle of direction. This module defines lower-level operations for vector point arithmetic in two-dimensional space, such as getting the euclidean distance between two objects providing their given coordinates. It also abstracts away the necessary Physics computation, such as finding the magnitude of forces, velocities, and acceleration by considering their x and y components and scale them against some scalar quantity. Lastly, it provides methods that ensure that parameters do not exceed bounds, such as the maximum velocity.
In geometry, the Euclidean distance between two points in Euclidean space is the line segment's length between the two points. Cartesian coordinates of the points can be obtained using the Pythagorean theorem

Algorithm 15: $Behaviour_{Update}$:

Data: behaviour, time, $next_{node}$,turning method, $move_{car}$
Result: $Behaviour_{Update}$:
for *Every time step* **do**
  Update the properties of the Car using the parent's method behaviour update. // update the car environment Call $next_node$, method 1 described above. // refer to the status of the function $next_{node}$;
  Else: check if the car has more than one node to go;
  if *The Car still has one more node to go* // Calculate the direction from other method which keeps the direction updated at every moment in time **then**
    Call the turning method;
    Call the $move_{car}$
  end
  Else: Review the environment situation. // update the environment Keep track of how many cars are braked and how many compliments blending of flow at any moment in time. // Record the situation
end

used for the distance calculation. The coordinate system uses one or more numbers, or coordinates, to uniquely determine a vehicle's position or its reference location. Hence, the distance s between two point on a road =

$$s = \sqrt{(x_2 - x_1)^2 \ + \ (y_2 - y_1)^2} \tag{4.32}$$

Where x_1, x_2 *and* y_1, y_2 are the initial and final values of x *and* y coordinate respectively.

This method calculates and returns the Euclidean distance between two vectors on a plane in the simulation environment. This way, for example, two cars can tell how far away they are from each other. To return the scalar magnitude of a vector property such as position, velocity, force, and acceleration. It reuses the method above with a starting reference of [0, 0]. The vector's direction however is the inverse tangent of the component distances between this vector and the other vector in relative direction or the absolute distances from origin if no other vector is supplied. (Tan = Opposite / Adjacent). The simulator framework combines several vigorous aspects of state of the art architectures and improves them in several directions. The architecture comprised all the traffic components with a detailed description of its environments about the vehicle type contingency. The framework's objective is to use the traffic light, reservation nodes, cross collision point, and distance headway adjustment to optimise a traffic intersection's performance in a vehicle mixed environment. The proposal is for a framework that allocates traffic control actions on a platoons basis with a segment concept and utilises the reservation node and cross-collision control procedure to enhance safety and efficiency performance.
The traffic simulator is designed in Python with some modules containing reusable definitions such as functions and classes. The simulator development followed a systematic step from the road model to the vehicle model with all the associated features of a real-life road system.

Road Nodes and Edges in the context of the modelled intersection as represented in Figure 4.8:
A road node could be described as follow:

- Any point that defines the starting point or the ending point of a route, where a route is an established line of travel in the simulation.

Algorithm 16: $Physics_{Update}$:

```
Data: physics, time, safe_distance
Result: physics_update :
for Any instance in time of the Car // Update the properties of the Car using the parent's
  method physics update. do
    Assign the magnitude of acceleration to greater than 0.0 // To avoid division by zero errors;
    Else: apply physics_update :;
    if 'Car on motion' // Once we have a car on motion then
        Default reaction time value for non-Aggressive cars of 0.2;
    end
    Else: Aggressive cars and not at rest // Then it is an aggressive car  Derive the reaction
     time using the safe_distance and current speed, otherwise, set the reaction time to a default of 0.3.
     // apply the formula for calculating the reaction time;
     if 'Random factor is set to a random number between 1 and 3 ' // apply reaction time
     randomization approach for real behaviour then
        Scales the calculation result by a random number between 1 and 3.;
        Then proceed to find the safe distance and assign it to the member variable safe_distance.;
    end
end
```

- Any point where 2 or more edges cross.
- Any point of interest (with respect to vehicle activity, traffic control) to the researcher as you will see below.

A road edge is any line formed from the connection of 2 nodes. It is used to represent a route in the simulation. There are 2 types of nodes in the simulation:

- Road Nodes: They are found at the beginning and ending of each route.
- Reservation Nodes: They are found at the centre of the road system where the most vehicular concentration is found and are use to 'reserve' spots for vehicles on a basis of first come - first serve, ensuring collision prevention.

Intersection State: The intersection state I_t from the proposed model of 8 lanes defined as a column vector of all road lane delays. Looking at our 4-ways traffic model with vertices (road lanes) L_1 to L_8, and their corresponding connecting edges of 1 to 19, the traffic state at time t, is given by

$$I_t = [L_1(t), L_2(t), - - -L_{19}(t)]^T \tag{4.33}$$

Where $L_{i-j}(t)$ is the delay from L_i to L_j as a function of time representing the dynamic nature of the traffic flow.

Each vehicle has a defined route identifying all node-ID along its trajectory or path between the start node and the target node. Each node is analysed within each identified route following the metric assessment parameters by calculating a measured function value for each identified route. The task criteria may involve parameters associated with the system's road nodes and distance parameters of node-to-node, traffic movement rules, crossing time, straight, and curve movement.

Algorithm 17: Turning

Data: Direction, position, angle, $safe_{d}istance$ time
Result: Turning
for *Car is turning or branching off the road* // `when the car gets to a branch of the road to turn` **do**
  Keeps the right direction for the Car at all times // `Car maintains the road edges`;
  Else:;
  Continue moving;
  Using the previously visited node and the next target node.;
  Calculate the new direction with the car position observing the safe distance;
  Save the turning parameter into a file
end

Algorithm 18: $Apply_{force}$:

Data: Force, Mass, Acceleration Direction, safe distance time
Result: $Apply_{force}$:
for *The direction of movement of Car* // `check the direction of the car movement` **do**
  Using Newton's second law of motion (F = ma) // `the acceleration is derived and applied in the current direction of the Car. Values are rounded to 2 decimal places.`;
  Else:;
  Car is stationary;
  Specify that this Car is not decelerating.;
  Assign a copy of the acceleration vector calculated above to the Car's acceleration member variable.;
  store the calculated force
end

4.3.3 Car Following Model

The car-following model is a microscopic model that describes the behaviour of a driver when interacting with other vehicles in their proximity and maintains the behaviour pattern of the leading vehicle. The baseline theory is that each driver reacts to the stimulus received from other traffic. The characteristics pattern of the model analyses Figure 4.9 shows how a human being reacts in a traffic situation, represented in drivers' longitudinal behaviour following a leading vehicle and maintaining a safe gap in-between vehicle groups. The driving behaviour does not altogether depend on the leader in a car-following model, but it

depends on the immediate vehicle's optimal velocity in front. This model does not consider lane changing and overtaking scenarios as that will involve lateral behaviour. The car-following model behaviour could be described in details using the below three points:

- The leading vehicle is allowed to accelerate to its desired speed because there is no vehicle to influence its speed.
- The leading vehicle's speed primarily determines the following vehicle state because drivers try to maintain a reasonable interval of space or time.
- The braking process involves the use of varying degrees of braking force to avoid the collision

Algorithm 19: Decelerate Car process:

```
Data: Apply_force, Mass, magnitude, braking_force = 1200N, limit = 0m/s, Direction, Safe distance,
    time
Result: deceleration
for The direction is the same as the Car's direction. // Unless a different direction was
  specified in the method call do
    Using Newton's second law of motion (F = ma) // the acceleration is derived and applied
      in the current direction of the Car. Values are rounded to 2 decimal places.;
    Car is a child class of EnvironmentObject;
    Using Newton's second law of motion (F = ma),;
    The acceleration is derived and applied in the current direction of the Car. Values are rounded to 2
      decimal places.;
    Same as in apply_force above.;
    for Check the direction and if none : // check the direction of car movement do
        Calculate the acceleration_duetoforce;
        As long as the Car's speed is above the limit, keep setting is_decelerating to True and keep
          assigning a copy of the deceleration to the acceleration member variable.
    end
    Deceleration is negative acceleration, so values have been negated with the minus sign before
      assignment.
end
```

We propose a new mathematical model with aggressive factors and adjustable distance headway to describe the hybrid vehicle moving behaviour in which vehicle platoon used to balance the traffic flow. This model deals with the concept that a driver recognises and follows a lead vehicle at a lower speed. According to [Gip81, AR18, Mat09, ZZ18], the potential to follow and estimate the vehicle response to its predecessor's behaviour in a traffic stream is essential in evaluating what impact the changes to the driving condition will have on traffic flow. The car that follows the leader concept is dependent on the below two assumptions:

- The collision avoidance approach demands that a driver must maintain a safe distance from other vehicles on the road.
- The vehicle speed is directly proportional to the spacing between the vehicles.

Let δs^t_{n+1} represent the distance available for $(n+1)^{th}$ vehicle,
δx_{safe} represent the safe distance
v^t_{n+1} *and* v^t_n represents velocities

Therefore, the gap required for safety is given by

$$\delta s^t_{n+1} = \delta x_{safe} + T \cdot v^t_{n+1} \tag{4.34}$$

Where:
T = sensitivity coefficient.

However Equation (4.34) above could be expressed as:

$$x_n - x^t_{n+1} = \delta x_{safe} + T \cdot v^t_{n+1} \tag{4.35}$$

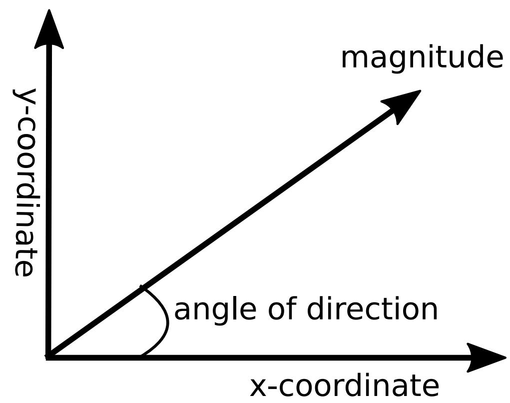


Figure 4.7: A 2-dimensional vector

When the above equation is differentiated with respect to time t:

$$v_n^t - v_{n+1}^t = T \cdot a_{n+1}^t \tag{4.36}$$

$$a_{n+1}^t = \frac{1}{T} \cdot [v_n^t - v_{n+1}^t] \tag{4.37}$$

From the model prototype, the chosen random values of (0.3 to 1.7) for the human drivers' safe distance based on the UK transport authority [ta20] According to the sensitivity coefficient term resulting from generations of models, we have

$$a_{n+1}^t = [\frac{\alpha_{l,s_e}(v_n^t)^m}{x_n^t - (x_{n+1}^t)^l}][v_n^t - v_{n+1}^t] \tag{4.38}$$

Where l = distance headway
s_e = speed exponent
α =sensitivity coefficient

Figure 4.10 is a background description of the vehicle safe distance as suggested by the UK Highway Code. The baseline of the method suggests that a human-driven vehicle moving at 30mph will take approximately 23 metres for the braking and stopping process. This is not the case with autonomous vehicle with about 0.1 seconds thinking distance. This stopping distance s is a component of the thinking distance (time it takes for a driver to activate brakes and time involved in covering distance before the applied) and from the time brake effect the car speed by initiating deceleration process. Also involved within the braking distance is the stopping time (time/distance it takes the car to come to a stop).

Based on this analysis, the traffic flow model with δT representing reaction time and δt to represent the updated time will give.

$$v_n^t = a_n^t - \delta t + a_n^t - \delta t \cdot x\delta T \tag{4.39}$$

From Newton's law of motion $v = u + at$, then the simulation version gives us:

$$x_n^t = a_n^t - \delta t + v_n^t - \delta t \cdot x\delta T + \frac{1}{2}[a_n^t - \delta t \cdot \delta t^2] \tag{4.40}$$

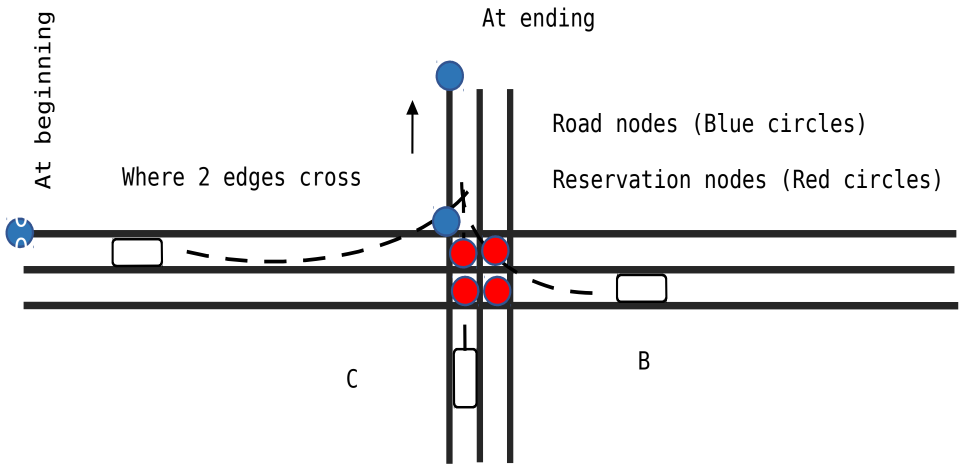


Figure 4.8: Road Nodes and Edges Description

This equation also is the simulation version of the Newton's law which states that $s = u \cdot t + \frac{1}{2} a \cdot t^2$

$$a_{n+1}^{t} = [\frac{\alpha_{l,m}(v_{n+1}^{t})^{m}}{x_{n}^{t} - x_{n+1}^{t})^{l}](v_{n}^{t})} - \Delta T - v_{n+1}^{t} - \delta T] \tag{4.41}$$

The safe distance will be updated based on the car's current speed at every time instance. The safe distance (x_{safe}) values for the HVs are randomised by setting the minimum and maximum values to reflect the actual behaviour of human drivers.
The algorithm 20 illustrates how the safe distance and reaction time methods are calculated and applied for AVs and HVs respectively.

Note: The vehicle's acceleration depends on the leading vehicle's relative velocity and the gap between the vehicles. The car-following model is extending to consider mixed traffic behaviour because the existing car-following model controls traffic only in a longitudinal direction and not in the lateral direction. The car-following model extension method addresses stabilising mix-traffic flow with the safe distance variation for autonomously driven vehicles. Inference from the prototype model the same proportion of AV and HV, shows that traffic flow stabilisation depends on the maximum velocities associated with the two-vehicle types, the average value of two safe distances, and the standard deviation of the maximum velocities among all vehicles. Traffic stability decreases with a decreasing flow efficiency when the average maximum velocity and safe distance increases. Besides, the direct test calibrated results are in good agreement with those of theoretical analysis. Moreover, investigating the relationship between the safe distance and the traffic density simulates the intersection capacity and vehicle occupancy. The car-following model scenario in the AVHV control does not affect the road capacity assuming a single-lane road system without any vehicles overtaking one another. The microscopic data model can be used for the validation of traffic data concerning volume

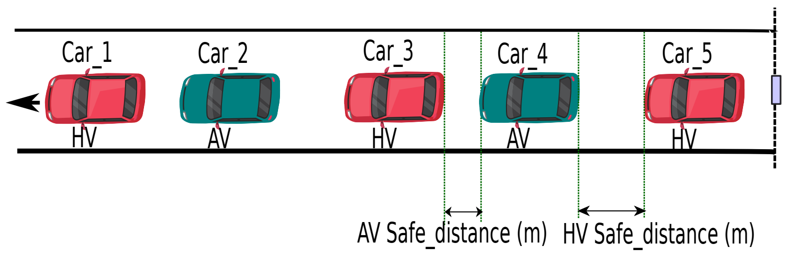


Figure 4.9: Car following model with safe distance

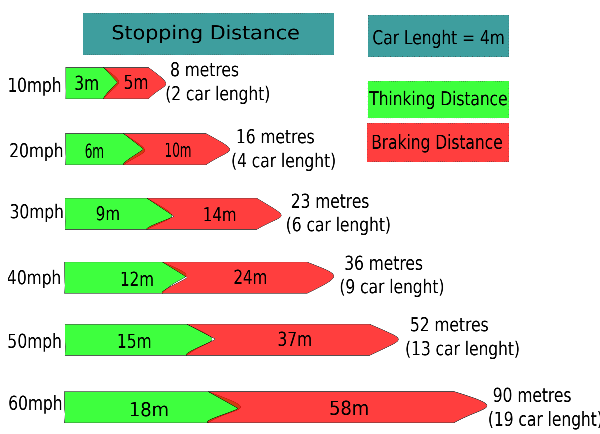


Figure 4.10: 2-Seconds Rule Safe Distance Description for HV

Algorithm 20: Safe Distance

```
Data: v_safe, time
Result: x_safe
for x_car < x_safe // when the car distance to another car is less than the safe distance
 do
    Car accelerate // Car continue moving;
    Else:;
    Apply safe_distance;
    if 'Aggressive Car' // Calculate random safe distance for HV then
        e.g0.5 + (0.1 − 0.5) <= 1.0 deceleration_force = 7500 + 500 * (0.5 + random.uniform(0.0, 0.5))
        Else:;
        Apply a constant safe distance of 0.1 for AV // Apply a constant safe distance of 0.1
    end
    x_safe = (F_deceleration/m) * t_reaction + sqrt((F_deceleration/m, *2)(t_reaction, 2)) * 2 * v_safe) // Calculate
     the safe distance for gentle car ;
    Goto line number 3
end
```

and speed. The car-following model formulae address the time and distance or spacing between vehicles, assuming that drivers will keep a safe distance from the vehicle ahead but will not lag unnecessarily behind. Once appropriately defined, the car-following rules models a bigger picture of the traffic flow model.

Cars trying to avoid hitting each other on separate lanes with no common nodes between them cannot always tell by their distance from each other if they are likely to collide with one another. They cannot also rely on the fact that they might eventually collide since they are heading towards the same destination. Gap acceptance is a vital component in this study because it involves modelling an agent-based system and implementing reflective drivers' behaviour at the microscopic simulation level. The usual problem is that it is hard to detect other vehicles coming from the other lane.The gap acceptance model is

$$s_r = v \cdot t \tag{4.42}$$

where v is the velocity and t is the time. For human driven vehicles, one have to build up the reaction time r_t

$$s_r = v \cdot (t + t_r) \tag{4.43}$$

Figure 4.11, is a model of a 3-way intersection traffic control approach. The development is in a vehicle queuing problem in a 3-way traffic intersection system that merges with a single stream of significant road traffic. Even more peculiar about this T-junction is that the non-priority road in Figure 4.11 feeds into the priority road at node 8, not at 90 degree's but 45 degrees, and this road itself is at a bend from the lane leading up to node 11–node–12. This approach aims to use the distance between each vehicle to judge how fast a car should go. It follows the safe distance model to keep each car at a safe distance away from the other. It also checks for nodes (which is where the Road-Vehicle Communication comes into play) on the roads and how far away each car is approaching. The first-in–first- out approach is used, while the car nearest to a node is given the right of way while observing the minimum acceptable gap. The length of the road is the addition of all route lengths specified in the main model Figure 2.3 are as shown below:
Therefore, $l_{road} = 2972.9m(approx,)$

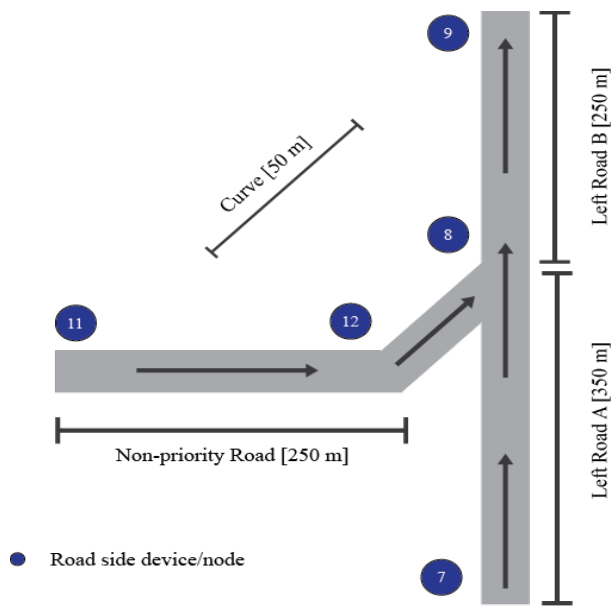


Figure 4.11: Schematic of a 3-way intersection to demostrate Gap Acceptance Model

Table 4.1: Calculation of Length of Road

Parameter	**Description**
Length of road(l_{road})	(1 - 2 - 4 - 5) + (11 - 12 - 14 - 15) + (7 - 6 - 8 - 9) + (17 - 16 - 18 - 19) + (12 - 8) + (2 - 18) + (16 - 4) + (6 - 14) + (12 - 16) + (2 - 6) + (8 - 4)
Computation of l_{road}	$600+600+600+600+49.5+106.1+49.5+106.1+106.1+49.5+106.1 = 2972.9m$(approximately,)
Length of car(l_{car})	4.5m (Average)
Number of cars on road(l_{car})	$l_{road}/(S + l_{car})$
Car velocity(v)	10m/s (Average)

where x_{safe}, S is 3m for AVs and 5m for HVs during platooning and, 2m after the reaction. Therefore, during platooning, the safe distance of 3m for AV, the vehicle capacity: $n_{cars} = 2972.9/(3+4.5)$
$= 396.3$ cars approximately (The Vehicle Capacity of 396.3" means the road system can house 396.3 cars at any time if the entire space is utilised and safe distances observed. Mathematically, the statement is correct, but it is not helpful because vehicles don't come in 1/3's, as they are non-fractional objects. The number 396.3 should be rounded down to an integer to make it worthwhile. This value should be an integer.) "The Vehicle Throughput Capacity of 396.3" is the number of cars (a rate quantity)that go through the road system, from starting point to destination, per unit time (e.g. per minute) could be fractional or an integer. In the simulator, vehicle Capacity (Volume) is concerned with things that can not be divided (cars). Rate, on the other hand, could be infractions and integers.

How it works From Figure 4.11, assuming that HVs are on Lane A and AVs, Lane B for simplicity. Lane A is a straight road, and the HVs proceed without making any turns or bends. Lane B meets Lane A midway after a curve and at an intersection. The AVs, approaching the curve, slows down considerably and, depending on how close they are to the intersection, gets a sense of how far the other car (HV) might be from the nearest RVC server or node. More importantly, the RVC server judges how far away both vehicles are from it. The RVC then uses this information to grant a car the right of way – it signals the AV to decelerate, keep moving or halt and displays a traffic signal for the human driver in the HV that prompts them to move or slowed down or halt as well. As a result, other cars behind the car that slow down while communicating with an RVC node or due to traffic or arriving at an intersection will also slow down to obey the safe-distance model by judging how far they are from the car ahead of them.
The decision-making protocol is to look for a "reasonably large" gap in the traffic to complete this manoeuvre without causing any accident or harmful interference with the direct traffic. This model explains the driver gap acceptance behaviour when a driver decides whether to change lanes at a merging section of the road. According to the merging decision rule, [Haw68], the idea of the model is that traffic from the major road is moving in a platoon with a probability density of "$b(x)$" with a gap duration of:

$$\lambda e^{\lambda(x)} \tag{4.44}$$

The vehicle's arrival from the minor road takes a random distribution process with an average rate of μ, with a probability distribution function K(z).

However, the vehicle merging process establishes a gap at a time t with a probability A_t or waiting for an established gap. The gap probability A_t based on the following conditions:

$$A_t = 1, t > T_{1+\delta} \tag{4.45}$$

Where $T - 1 > 0$ *and* $\delta >= 0$ are constants.
The following vehicle arrival process is designed to slow down the car time "M" and look for the next available gap. The idea here is that the vehicle use M time to look for the next available gap. $\delta >= M <= T - 1$. If the queue is empty at a time t_0, then t + M if t $< M + t_0$. For simplicity, $\delta <= M$

Dynamic Safe Distance

The dynamic safe distance is implemented to mimic the real behaviour of the human driver. A random factor is introduced, which is used as a multiplier in the safe distance equation, as shown below.

For AV, random factor is 1.0
For HV, random factor is a random number between 0.8 and 1.5
The dynamic safe distance of HVs is calculated thus:

$$x_{safe} = v \cdot t \cdot random_{factor} + \sqrt{v^2/b} \tag{4.46}$$

Where v is velocity, t is reaction time, b is deceleration and a clearing distance constant (in metres) is introduced to give better results. Additionally, the environment houses the property features of the model: such as cars, traffic lights, and intersection control scenarios.

4.4 Visualisation and Analysis of Component

The traffic management process trend has impacted how traffic control systems are designed and used in many applications. Visualisation and investigation of real-world dynamic traffic situation with as a high frequency of change based on real-time traffic events is considered realistic. Visualisation can be examined a consequence of various functional tasks, depending on the traffic parameters' record. However, from a scientific view point, visualisation functions are dependent on the traffic parameter data. Visualisation conveys relevant information to the recipient. A collision avoidance model (CAM), also known as a pre-crash model or collision mitigation model, is a car safety system designed to prevent or reduce the severity of a collision in a traffic flow system. Once an impending collision is detected, the model's responsibility is to ensure that the distance headway is enough for the braking of the car to prevent possible collision. The model aims to understand drivers' collision avoidance strategies, the tendency to break or steer is significant for the design and effectiveness of the simulator to examine the driver avoidance manoeuvre methods: braking only, steering only, and combined braking and steering to predict two or more cars moving together without collision at intersection.
The work of [TBM99] introduced a delay of T seconds before the following car braks in it's collision avoidance model. The perception-reaction time (PRT), is the time it takes the following driver to react upon seeing the brake light of the car in front. A good idea considered applying a 2-step deceleration model with an initial soft deceleration rate,a, and a final more sharp deceleration rate,$a*$. The implication of this is that the following vehicles mimic the behaviour of the drivers ahead. The following parameters describe cars that are following the AV. The first car following is denoted with i and the car following that by $i+1$

- a_i = Initial brake degree
- a_{i*} = Final brake degree
- Ti = Delayed time after the first brake with rate a_i and before braking harder
- V_i = Actual speed of the first car following AV.
- v_{i+1} = Actual speed of the car following the ith car
- $x_{i(t)}$ = Distance travelled by the first car following AV after t seconds since the start of braking by lead car
- $x_{i+1(t)}$ = Distance travelled by the follower to the first car following AV car after t seconds since the start of braking by lead car

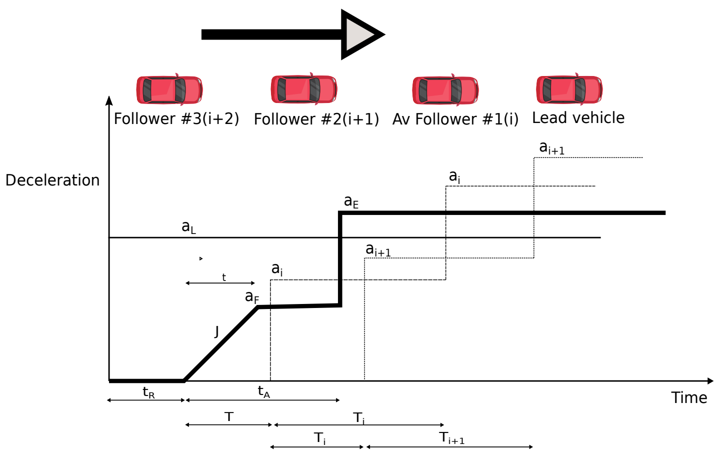


Figure 4.12: Collision avoidance model

Parameter Listing: These are the parameters used in the simulation.

- $v_{max} = 10m/s$ (The average speed of a city road vehicle).
- $a_{max} = 6m/s^2$ (The acceleration)
- $m = 122.4Kg$(Car Mass,(1200N) from 1 Newton in Earth gravity is the equivalent weight of 1/9.80665 kg)
- $f_{moving} = 1200N$ (moving force)
- $f_{braking} = 1200N$(braking force)
- $l_c = 4m$ (car length)
- $w_c = 4m$ (Car width)

- $HVx_{safe} = 10$ (HV safe distance)
- $HVt_{reaction} = 0.1\ to\ 0.3s$ (HV Randomised reaction time)
- $AVx_{safe} = 5m$ (AV safe distance)
- $AVt_{reaction} = 0.1s$ (Av reaction time)
- $HVs_{spawning\ distance} = 10\ to\ 15m$ (distance headway from car spawner)
- $AVs_{spawning\ distance} = 10\ to\ 15m$ (distance headway from car spawner)
- $start_{Braking} = 30m\ beforex_{safe}$ (Distance to an object before braking)

4.5 Implementation of the Traffic Scheduling and Routing Process

Putting the suitable traffic scheduling and routing decision making is complex as it demands a build-test and rebuilds approach. The algorithmic implementation process involves a general methodology for designing integrated scheduling and routing traffic algorithms. The method used for analysing traffics based on fair queuing is treated purely as autonomous agents. The scheduling and routing algorithms are a vital part of the system that provides a broad range of 'Quality-of-Service(QoS)' assessments essential for managing a mixed traffic behaviour to support any feedback control and innovative strategy. The wide range of performance characteristics of scheduling and routing algorithms of traffic has been used to investigate several qualities of different traffic control methods [SV97]. All traffic scheduling and routing algorithms must meet the expectations of the three necessary attributes for use in a traffic management system: fairness properties, ease of implement and minimal delay in a heavy traffic density scenario. In many scheduling and routing algorithm strategies, implementation complexity is usually the essential criterion for selecting an algorithm for use in a real system.

4.5.1 Scheduling Process

Traffic lights scheduler have been utilised since 1868 [Lea06] to control traffics at a road intersection and improve throughput. The queuing and scheduling practice of directing vehicles to obey traffic code rules determines how the reservation node resources are allocated. The road intersection reservation nodes are shared by vehicles arriving from different road segments to join another segment, which leads to its destination. The presence of congestion at the intersection typically controls the requirement for queuing and scheduling because if RN scheme is adequate and there is no conflict for it, then queuing protocol is not necessary. The queuing and scheduling method at the intersection allows traffic to be treated individually as an agent, which the scheduler can decide which type of treatment the traffic inside each queue receives. If the traffic mapped to each queue belongs to the road system's specific route, the scheduler can apply platoon service for optimal performance.

The traffic routing algorithm involves a set of step-by-step operations used to direct vehicles efficiently from start to target node. When a vehicle leaves its source node, it can take many different paths to its destination or target. The proposed algorithm considers the real-time traffic flow's behavioural characteristics that tend to cross the road intersection while scheduling each traffic light's time phases. The proposed scheduling algorithm for creating time-evolving point objects is modelled with a two-dimensional moving point over time as a line in three-dimensional space for generating sets of mobile points or rectangular data that accompany an enlarged set of distributions. Each vehicle within the ICR periodically broadcast their necessary travelling intelligence (speed, target, position/location, and direction). Vehicles obtain the necessary traffic information of their environment. From the received information, the controller checks vehicle trajectories with common reservation nodes and arrival time then assigns reservation nodes and updates the vehicle. In each traffic flow process, the vehicle whose position is closest to the reservation node is allocated access. The traffic scheduling algorithm is designed to synchronise autonomous and human-driven vehicle behaviours at the road intersection. The traffic scheduler decides the type of treatment to be given to each traffic or queue of traffic as they arrive at the intersection. This protocol is based on the measurement of a service's overall performance (Quality of Service). The scheduler's primary consideration is based on the flow of hybrid vehicle occupation time at the intersection. When traffic is available, the scheduler maps it to the appropriate queue.

The moving vehicle identified with ID is a time-evolving spatial object with parameters that control the spatial vehicle evolution. The introduced new parameters created more realistic vehicle movement and permitted the modelling of traffic paths originating from a vehicle travelling along an obstructed environment (rerouting). However, this idea has been by these three authors [PT03, TVM02], but they did not consider a road intersection as the basis of their simulation; instead, they used airplane. Other researchers like [Li13]considered their model in road networks but not in traffic mixed environment. The traffic control scheduling algorithm checks the distance between each car and intersection nodes and the distance between each car and the next car in front of it before deciding to slow down to avoid a collision.

Managing conflicting vehicles at road intersections is the primary aim of any road traffic intersection manager. While in this case, managing conflicting autonomous vehicles and the human-driven vehicle is the main contentious issue because of the two-vehicle behaviour and communication media differences. This variation in vehicle behaviour places severe constraints on the efficiency of each vehicle category. Besides, this established variance in the vehicle behaviour decreases the road intersection's safety, efficiency, and capacity compared with managing a homogeneous vehicle behaviour. The variation in vehicle behaviour in a mixed-setting will negatively impact the advantages of autonomous vehicles. The adjustment of inter vehicle-space could prevent a collision in a mixed vehicle environment. This method could only be possible for AVs and not for HVs because human drivers' speed cannot be accurately predicted. After vehicle merging, a long distance for the reaction time is required with a higher braking force harmonise HVs braking pattern with AVs as vehicle speed is expected to increase after ward.

The AV decelerates to 1 second less the vehicle's speed ahead of it, while the HV decelerates randomly between 1 to 6 seconds. Note that 's' from 4.47 is speed, not the velocity, while 'S' is used in this document to refer to distance. Velocity is used to decide this effect because it is relatively easier to perform scalar operations and make comparisons with scalars than with vectors.

$$s_{Car-behind} + -a \cdot t = s_{Car-front} - 1 \tag{4.47}$$

The velocity control process ensures the vehicle behind has lower velocity (and speed) than the vehicle in front of it and hence less likely to run into it. The scheduling algorithm checks the distance between each car and the intersection nodes, the distance between each car and the next car in front of it before deciding to slow to avoid a collision.

4.5.2 Routing Process

The process of selecting traffic trajectories in the proposed road intersection uses the road node system to transit vehicles from start to target nodes. The designed traffic routing system efficiently maps the vehicle's movement and goal from the start node, connecting all joining nodes and the destination. The routing process is dependent on the road intersection type or configuration and the traffic rule in place.

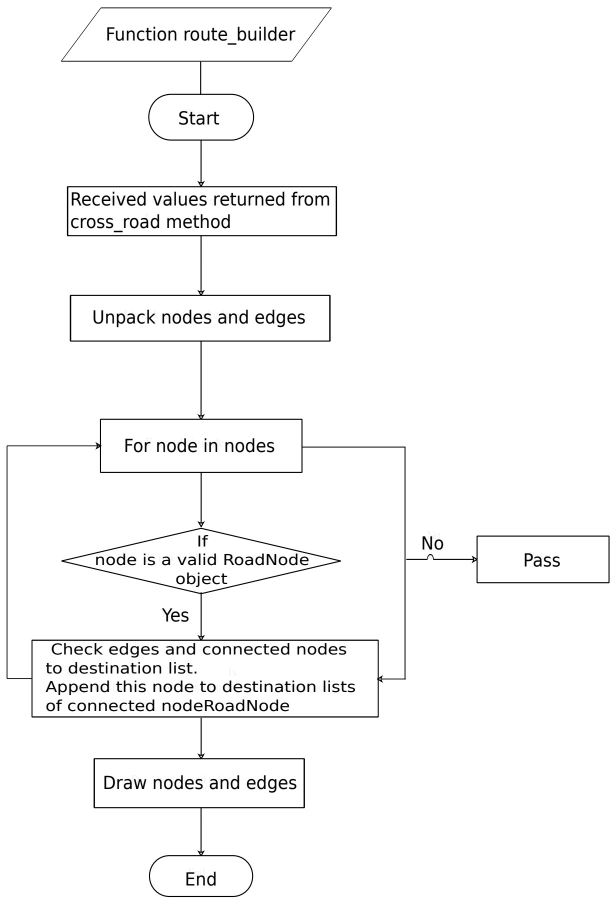


Figure 4.13: Scheduling algorithm

Table 4.2: Road Layout Table

RN id	Node Route	RN id	Node Route
1:	[11, 12, 14, 15]	7:	[5, 4, 2, 1]
2:	[11, 12, 8, 9]	8:	[5, 4, 8, 9]
3:	[11, 12, 16, 17]	9:	[5, 4, 16, 17]
4:	[7, 6, 8, 9]	10:	[19, 18, 16, 17]
5:	[7, 6, 2, 1]	11:	[19, 18, 14, 15]
6:	[7, 6, 14, 15]	12:	[19, 18, 2, 1]

The nodes represent the road lane, while the edges represent the vehicle trajectory where the reservation nodes are located. The routing algorithm directs the vehicle path from its source to the destination node. Table 4.2, represents the routing process flowchart where the routing algorithm starts updating the nodes of the intersection configuration from the road node catalogue to compute the node routing requirement for each vehicle trajectory. A suitable routing algorithm is employed to allow vehicles to move from start to target in a real-life traffic situation using the UK traffic rule. The intersection-based routing protocols designed for the vehicular communications process of selecting a traffic path are designed using the road nodes system.

Road Node Layout List: This defines the road edges that list all the possible route connections to be made from start to target node for a given trajectory as reflected in Table 4.2. The related Layout List and Road System modules draw out the road schematic in the simulation by connecting lines between the nodes. The layout list defines all the central nodes in the road schematic and their corresponding coordinates.
In this case, a routing catalogue is used to capture the routing pattern based on the road configuration and traffic rules. For this study, we considered the vehicle routing scenario as shown in Figure 4.14 using a cross intersection based on routing traffic delay estimation to guide the routing pattern mechanism, in directing each vehicle from the start to the target node. The intersection control unit (ICU) uses the reservation nodes (RN) to calculate the following parameters: vehicle position to the RN, speed, and delays associated with each vehicles and then assign the use of reservation accordingly.

Intersection Control Unit uses its road layout to calculate individual and total delays and compute the vehicles' routes in the simulation. The same is true for anywhere else on the road in the simulation. These parameters are calculated thus:

To calculate Position: The ICU selects the current environment where the simulation is taking place - this is the current location of the road system. The environment then focuses on an environment object which is any of the vehicles on the road and asks the car to calculate its new position. The object then updates its psychical parameters, namely acceleration (using applied engine force), velocity, and displaced position in that order. It does this every time interval t, where t can be as small as 0.1 secs.

1. ICU -> selects Environment
2. Environment -> Environment object
3. Environment object -> Physics Updates:
4. -> Update Acceleration
5. -> Update Velocity

6. -> Update Position

7. Repeat every t interval (t can be as small as 0.1 secs).

Mathematical approach to the calculation of traffic parameters: Velocity, displacement, and acceleration are vectors, whose direction of effect specified in x and y coordinates. By decomposing the mass m, force F into x and y components using cosine and sine of direction angle θ, and time interval t we drive the acceleration a thus:

$$a[x, y] = [\frac{F}{m} \cdot \cos\theta, \frac{F}{m} \cdot \sin\theta] \tag{4.48}$$

The displacement s:

$$s[x, y]_{new} = s[x, y]_{old} + v[x, y] \cdot t \tag{4.49}$$

The distance travelled d:

$$d = \sqrt{([s[x]_{new} - s[x]_{old}]^2 + [s[y]_{new} \check{} s[y]_{old}]^2)} \tag{4.50}$$

The velocity v:

$$v[x, y]_{new} = v[x, y]_{old} + a[x, y] \cdot t \tag{4.51}$$

Where F - engine force, m – mass of vehicle, θ – direction angle of car, t – time interval (can be as small as 0.1 secs), a – acceleration/deceleration,v – velocity,s – displacement, and d – distance travelled.

For example, if a vehicle of mass 1200 kg, an engine force of 2000N inclined parallel to the x axis, (0 degrees) starts from position [1, 1], with an acceleration of [2, 0], and initial velocity of [0, 0], after 1 second:
Its acceleration will be

$$[2000/1200 \cdot cos(0), 2000/1200 \cdot sin(0)] = [2, 0] \tag{4.52}$$

Its velocity will be:

$$[0, 0] + [2, 0] \cdot 1 = [2, 0] \tag{4.53}$$

Its new position will be:

$$[1, 1] + [2, 0] \cdot 1 = [3, 1] \tag{4.54}$$

It's travelled distance will be:

$$\sqrt{[3 \check{} 1]2 + [1 \check{} 1]2 = 2} \tag{4.55}$$

The implementation of of how the Intersection Control Unit uses its traffic map (or road layout) in calculating the traffic performance parameters

- Parameters calculations within the environment method
  - The Simulator tells the environment method to update all its objects at every time interval ($\delta_t ime$)
  - The environment method goes through each object contained in itself updating their Physics properties.
  - The environment method apply Equation (4.48), the vector2 method makes F/m a vector, while the redirect method decomposes the force into x and y components as a vector.

  - The environment method apply Equation (4.51). This method updates the velocity of the vehicle while keeping it below maximum velocity. The "scale" method does the multiplication of acceleration and time interval, t.
  - Apply the update physics function which updates object's acceleration, velocity and position.
  - Apply Equation (4.49)

- Calculate Individual and Total delays of Vehicles at Each Lane giving minimum gap/safe distance. If the traffic is at 50% capacity, run the first half of it, otherwise run the second half.

  - Individual Delay:

$$Safe\ distance = v * rt + rf + \sqrt{(v^2 + a)} + rt \tag{4.56}$$

    Where rt is reaction time, rf is random factor (adds randomness for HVs. For AVs, rf is 1, meaning no randomness.), v is velocity and a is acceleration.
    This keeps the minimum gap/safe distance between vehicles on an individual level.
  - Total Delay: This is carried out by the Intersection Control Unit/Vehicle Group Controller/Central Collision Avoidance System/Reservation Node Algorithm. This process is repeated every time interval, t (where t = 0.1 secs).
    * Take inventory of all cars in the simulation.
    * Prevents collisions of cars by applying reservation nodes.
    * At every time instance loop through all cars velocity and position to update the reservation nodes.

- Compute Route: This process takes care of the computed routes for vehicles, and it is repeated every time interval, t (where t = 0.1 secs).

  - Import lists of all possible valid routes (route groups) from each start to destination position.
  - Define the route for each spawner (car group). The number of cars in each route and the total number of cars in the simulation are determined randomly.
  - The $choose_{r}atioed$ function spawns the AVs and HVs by a specified ratio

- Route Navigation: This shows how the route is navigated by a vehicle, it is repeated every time interval, t (where t = 0.1 secs).

  - $reach_{n}ode$ If this is the last node in the route, i.e only one route node left, increment the total number of vehicles that have reached their destination for that type for reporting purposes.

Upon the computation of the vehicle control parameters, the RN also compute the expected vehicle arrival time at each of the RN and use this information to assign vehicle to RN without collisions. Each vehicle defines its trajectory from start to target. Intersection state I_t is defined as a column vector of all road lane delays. Looking at our 4-ways traffic model in Figure 5.1 with vertices (road lanes) L_1, toL_8, and their corresponding connecting edges 'e' of 1 to 19, the traffic state at t time t:

$$I_t = [e_1(t), e_2(t), - - -e_{19}(t)]^T \tag{4.57}$$

Where:
$L_{i-j}(t)$ = Delay from $L_i\ to\ L_j$ function representing dynamic nature of the traffic flow. However, Looking ahead on how the cars will decide on their movement to the target, each vehicle has a defined route identifying all node -ID along its trajectory or path. The ID is between the start and target node, analysing each node

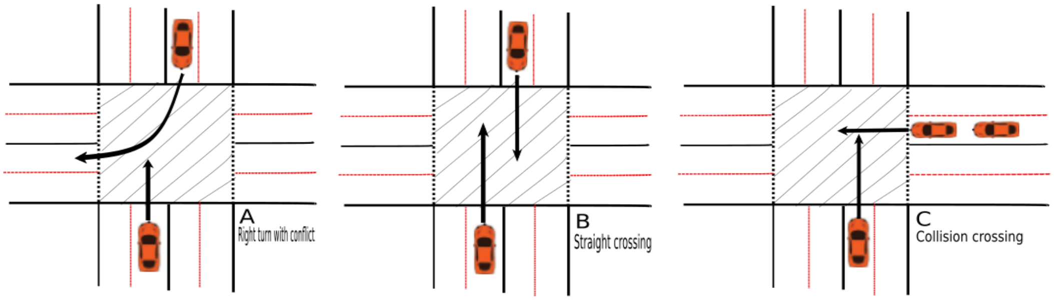


Figure 4.14: Different scenarios of intersection crossing (A,B,C)

along route according to a metric function calculated for each recognised route. The parametric function may include road nodes associated parameters, including a distance between nodes, traffic movement rules, crossing time, straight, and curve movement. According to [EAAI19, Fu01, GMS01], the following main types of traffic routing algorithm strategies exist:

1. Origin to Destination Routing: In this case, the vehicle routes are specified from start to destination with a list of nodes involved from start to target node along its trajectory. The vehicle does not change its routes along the way until it gets to its' destination. Though this is currently being implemented because of its predictability and enables the routing algorithm to compute the routing table in advance. The path a vehicle takes between the start node and destination node is always known precisely and controlled precisely.

2. Dynamic Routing: Unlike static routing, all vehicles can be rerouted periodically in this case. When a vehicle arrives at the intersection control zone at time t, it is rerouted based on the real-time traffic event (the vehicle queue length and the vehicle with the highest waiting time are to be considered for priority on routing). This dynamic routing technique comes with many advantages ranging from managing the dynamic configurations, which can be easily achieved, and if a link fails, the dynamic route can easily be rerouted.

3. Dynamic Routing with traffic prediction: In this case, the routing is based on the predicted or forecasted. In this case, there are always error margins because of the variation between the real traffic situation and the predicated one.

4. Real-Time traffic situation: This method manages traffic based on the real-time traffic event process. This technique's main drawback is its limited knowledge of the future because it can only utilise real-time traffic history. This method appears to be the most reliable, but it is expensive to implement.

Using Figure 4.11 as a guide, the routing table defined how the car can move from the start node to the target node, on Table 3.3, 1 represents collision-free or compatible lanes with the reference traffic flow lane while 0 represents possible collision lane. The intersection was defined using a dictionary of traffic nodes and position nodes, as shown in the below table.

Algorithm 21: Routing algorithm

```
1  Data: Road Node, Road Edge
2  Result: Route Builder
3  for Road Node do
       // Create the road layout;
4      Create road nodes from the number list;
5      Create road edges to connect road nodes;
6      Store all nodes and edges in dictionary;
   end
7  Return dictionary to caller line number 3;
   // Check the function route_builder;
8  for Node in Route do
       // Add up all the nodes involved in the vehicle trajectory;
9      if Node is a valid RoadNode from the route-list then
           Check edges and add connected nodes to destination list;
10         Add this node to destination lists of connected node in vehicle trajectory;
       end
11     for Number of node in route-list do
           number = corresponding to the scheduled car trajectory to destination;
           // Check if the above condition is true, Create the road layout;
12         Destination is reached;
       end
13     Else: Shift-to-next-node();
       // Check the type of route:  straight or curve;
14     for angle between route-list[0] and route-list[1] is equal to 0.0 or 90.0 or - 90.0 or 180.0 or -180.0
        do
15         Calculate the centripetal force and move the car // Calculate and apply the centripetal
            force
       end
16     for distance of current car position to route-list[0] <= 10 do
           Decelerate the car and apply the safe distance.
       end
       // Check distance to the next node;
17     Accelerate car to maximum-velocity;
18     Else;
19     for Distance of current position to route-list[0] > 50 do
20         Accelerate car to maximum-velocity;
       end
21     Else:;
22     Decelerate car to 0 velocity;
23     Goto line number 8;
   end
```

Chapter 5

Model Validation and Simulator Test Procedures

This section presents the simulator testing procedure conducted using different traffic scenarios and reviews their output. The developed model satisfies the criterion that the model parameters should correspond to realistic characteristics of the driver-less and human-driven vehicle. The testing of traffic theories when reasonable values are assigned to the parameters to show that the model is able to mimic the behaviour of real AV and HV is conducted. The advanced traffic simulator measures the distinct delays related to supervising traffic through an intersection and using other defined performance assessment metrics for each strategy. According to [DS04], with autonomous vehicle features like cruise control, autonomous steering, and GPS-based route planning, the mixed-traffic coordination in a multi-agent behaviour and mechanism will increase the performance of human-driven vehicles. The process of executing the test and validation involved using small experiments to demonstrate that the mathematical model is well approximated and the resulting car behaviour matches our expectations. The simulation process testing made use of different traffic intersection scenarios.

- Testing scenario1: straight(lateral) movement.
- Testing scenario2: straight-curve-straight movement of vehicles.
- Testing with the 3-way intersection system.

5.1 Scenario 1: Straight Car Movement (with Traffic Light)

In this scenario Table 5.1, the car takes a straight route. A route is determined to be straight if each successive two (2) nodes in the route have an angle of 0, 180, or -180 degrees between them. It begins from rest, accelerating till it attains maximum velocity and sustains it till it is close to its destination. 50 metres to its destination, it begins to decelerate until it comes to rest at its destination node. Because the car is moving in a straight line, its velocity will displace it in one direction. Hence, either *x or y* value of the velocity vector will = 0, subject to the car moving in a vertical or horizontal direction.

The displacement has direction as well as sizes(or magnitude); therefore, the total displacement, s_t is given as:

$$s_t = (\frac{v_i + v_f}{2}) \cdot t \tag{5.1}$$

where
v_i = Initial velocity
v_f = Final velocity
t = time
This scenario involves vehicle moving on a straight road with green traffic light or there is no traffic light at all. The car passes the traffic light at the intersection without stopping or decelerating, as represented in Figure 5.1. The scenario's overall description was defined by the basic 4-way intersection layout, basic infrastructure design, key features, and the scenario's key assumptions relevant for determining the specific tasks involved and how the scenario works. This scenario also represented the general regions associated with each behaviour and was divided into segments with the segment's relationship characteristics. The primary basis for traffic parsing through this scenario on each segment is that each segment had a different overall driving goal Table 2.2. It is observed that the speed of the vehicle does not vary significantly in between. Figure 5.1 shows the speed graph for this scenario, emphasising the 3-segments involved. This scenario is based on the following segments and actions specific for car behaviours:

1. Approach or acceleration: This segment involves the car accelerating with a speed of 50 to 60mph and maintain a constant velocity at high speed. In this case, we consider that there is no intersection traffic light, and the approaching vehicle has the right of way, or there is no intersection as applicable to a straight road.

2. Intersection area: This segment can be integrated into the approach of segment 1 in Figure 5.1 because of its aim of maintaining a constant velocity as the car pass through the intersection area at the same high speed. It involves entering the intersection with the same high speed from the approach segment.

3. Exit intersection: As the car exit the intersection, it will increase its acceleration at a maximum speed of 70mph, maintain it and continue its journey. The car moves with a maximum speed of 70mph, or that might be prescribed, and then maintains a steady velocity out of the intersection area to its destination.

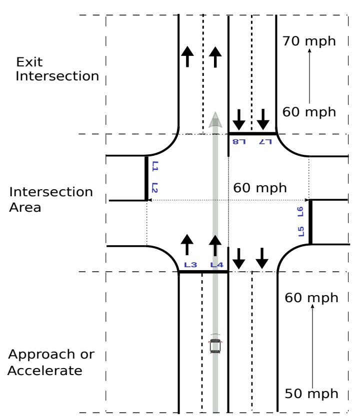


Figure 5.1: Straight movement scenario

Table 5.1: Scenario 1: straight movement driving with varying speed at each segment

Segment	Objective of Driving	Speed Characteristics
Approach or accelerate	Car start accelerating from between 50 -70mph	Travelling at full speed
Intersection Entry	Maintain the same speed of 60mph in crossing the intersection	Maintain Constant velocity
Exit Intersection	Continue accelerating from 60mph	Accelerate to speed max of 70mph.

The assumption for this scenario

In this scenario, the following assumptions are made:

1. There is a traffic light, and the HVs are expected to slow down a bit to observe the traffic light condition.
2. The traffic light is green
3. The car has the right of way and does not have to consider any potentially crossing car.
4. The car maintains high speed within the intersection and decelerates to a stop at the end of the intersection.

Expectations: It is expected that vehicle maintains a realistic behaviour concerning its movement, as stated in this scenario. Looking at the speed graph in Figure 5.2, the vehicle enters the intersection at the same speed. This behaviour of the car appears to reflect what was stated in the scenario. Critically looking at the graph, the car accelerates from rest to 30m in 60 seconds and maintains a constant velocity across the intersection. For vehicles moving in a straight road Figure 5.1, the vehicle enters the intersection zone at a speed of 50mph and accelerates to the high speed of 60mph, enters the intersection area with the same speed, and accelerate to a maximum of 70mph upon exiting the intersection. The straight movement schematic, its model graph, and also the simulated speed graph are represented in Figures 5.4, 5.10 and 5.11 simulated simulation.

5.1.1 Straight Movement – No Traffic Lights, No Braking:

The car drives through its destination or target in a straight route beginning from rest as stated in the above scenario, accelerates to a high speed, maintains constant velocity, and exits the intersection with a maximum speed without decelerating to stop.

The Assumption for Scenario

1. There is no traffic light.
2. The car has the right of way and does not have to consider any potentially crossing car.

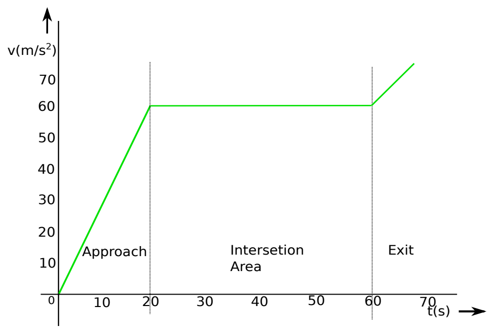


Figure 5.2: Straight movement model

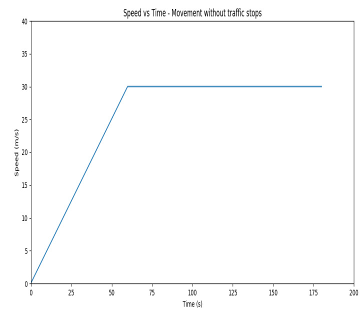


Figure 5.3: Straight movement simulation output

3. The car maintains a high speed within the intersection and increases its speed once it exits the intersection because it does not brake or stop at any point.

Like in the case of Straight Movement – No Traffic scenario, so there is no deceleration midway. Its total displacement, s_t can be given by:

$$s_t = a \cdot t_1^2 + v_2 \cdot t_2 \tag{5.2}$$

5.2 Scenarios 2: With More Than One Car

Considered adding a safe distance model involving more than one car in a row in these scenario, each following the other. Below is a list of scenarios implemented to explain this situation:

5.2.1 Sub-Scenario 1.1: Two Cars Straight Movement – No Traffic Lights

Two (2) cars start from the same position as the start node, but the second car starts a bit later after 10 seconds with a higher engine force. The second car now has higher acceleration and velocity. The second car eventually catches up with the first car just as they arrive at the destination. The movement direction is straight, as in the case of Straight Movement – No Traffic Lights. Their total displacements, st and s_{t2} can be given by:

$$s_t = a_1 \cdot t_1^2 + v_2 \cdot t_2 + d_3 \cdot t_3^2 + v_{x,y}4 \cdot t_4 + a_5 \cdot t_5^2 + v_6 \cdot t_6 + d_7 \cdot t_7^2, \tag{5.3}$$

$$s_{t2} = a_1 \cdot t_1^2 + v_2 \cdot t_2 + d_3 \cdot t_3^2 + v_{x,y}4 \cdot t_4 + a_5 \cdot t_5^2 + v_6 \cdot t_6 + d_7 \cdot t_7^2, \tag{5.4}$$

where a = acceleration
d = deceleration

$v_{(x,y)}$ = velocity changing with respect to direction
$t_1 ... t_n$ = divisions of time.

The assumption for the scenario

- Considering a situation where two cars move along in the same direction from start to target.
- The first is being followed by the second after 10 seconds from the start of the movement.
- The second is moving at a faster speed than the first. Figure 5.4 represents the speed graph for this scenario. This scenario can be extended with the following assumptions.
- The second car that accelerates at high speed will decelerate and maintain a safe distance from the 1st before the two cars finally arrive at the same destination.
- There are no overtaking, cars maintain a single lane .
- The two cars are not stopping within the intersection area, as they are maintaining the high speed away.

5.2.2 Sub-scenario 1.1.2: Two cars moving along but stop at the target node

When the two cars apply braking at the destination node, this scenario is the same as in (Figure 5.4), but the only difference is the deceleration and stopping at the destination node upon the exit of the intersection Figure 5.5. There is a speed adjustment applied to this scenario.

5.3 Scenario 3: Curved car movement (Straight-curve-straight car movement-no traffic lights)

In this scenario, as reflected in Table 5.2, the car takes a curved route. A route is determined to be curved if any two (2) nodes in the route have an angle of + or - 180 degrees.
It begins from rest accelerating till it attains maximum velocity and sustains it until it approaches a bend or curve.

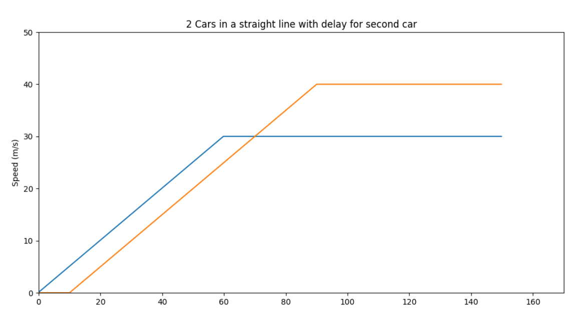


Figure 5.4: Two cars straight movement model

Table 5.2: Scenario 2: straight-curve-straight movement

Segment	Objective of driving	Speed characteristics
Approach	Car accelerating with high speed	moving at 60mph
Deceleration toward the intersection	Slow down to turn at the curve	Maintain a reduced speed
Exit the intersection	Upon exiting the intersection accelerate	apply maximum-acceleration

This scenario (Figure 5.8) involves a car in motion identifying the intersection at the turn right location, then decelerating before turning. As the decelerating vehicle nears the intersection, the car maintains a safe speed before turning to avoid over-shooting off the road, maintain a constant velocity, and then start accelerating again upon exiting the curve. With no leading traffic and with the vehicle close enough to the intersection, the vehicle enters the intersection after determining that it is safe to do so with traffic light signals and proceeds with the turn with a minimum speed.

In this scenario, as reflected in Figure 5.8, the following assumptions were made:

1. There is no traffic light.
2. The car has the right of way
3. There is no other car approaching, or crossing
4. There is no car following.

However, this traffic scenario was divided into 4 sections:

1. Acceleration or approach
2. Deceleration/reduce the speed
3. Enter the curve with safe speed to avoid over-shooting
4. Exit the intersect and accelerate with speed max

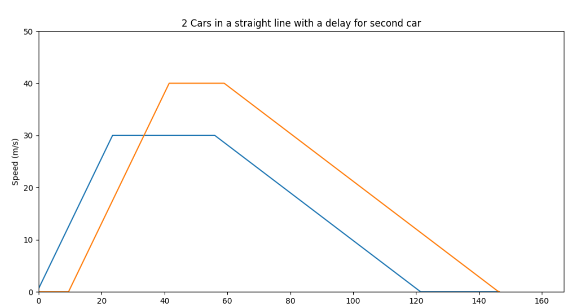


Figure 5.5: Two cars straight movement model with braking

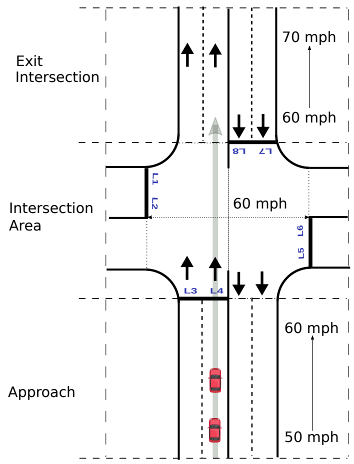


Figure 5.6: Two cars straight movement Scenario

Note However, a peculiar situation associated with this scenario is that in more than two-thirds of cars' real-life scenarios turning movement, the vehicle is in motion before turning (rather than stopping first). This situation is likely to reflect that less time is available to judge whether it is safe to turn before doing so, Figure 5.8 is a typical representation of this scenario. The essence of capturing the safe to turn decision section is for safety and to reflect reality.

The basic assumption for the straight-curve-straight: For this scenario, the following assumptions were made:

1. The lead car is not following any other car, but other cars can follow it.
2. The turn in the intersection is familiar to the car drivers.

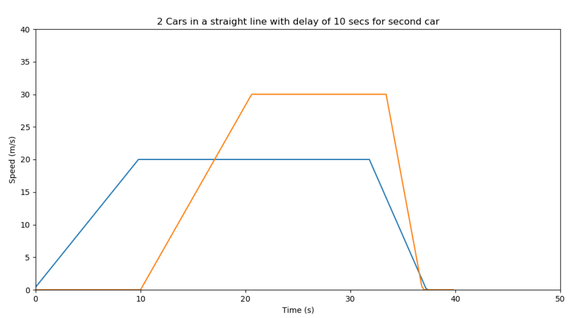


Figure 5.7: Two cars straight movement with 10 secs delay for the second car with braking

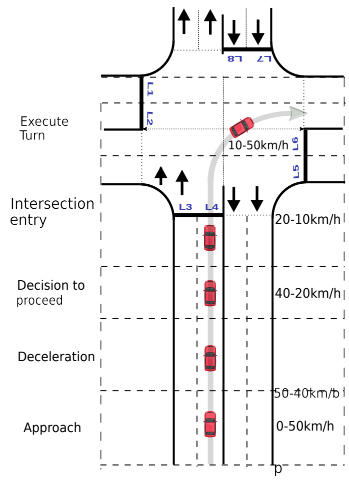


Figure 5.8: Curved Movement Model

3. The signal light is green upon the car approaching the intersection, or there is no traffic light.
4. No lane changing is required to get into the turning lane.
5. There is enough visibility of oncoming vehicles.

Straight – Curved – Straight Movement – No Traffic Lights, No Braking

In this scenario, the car also takes a curved route but begins from rest, accelerating till it attains maximum velocity and sustains it until it approaches a bend. Unlike the Curved Movement – No Traffic Lights scenario, the car does not brake on approaching its destination but connects through it and moves on with a controlled speed around the curve.
The total displacement, s_t can be given by:

$$s_t = a_1 \cdot t_1^2 + v_2 \cdot t_2 + d_3 \cdot t_3^2 + v_{x,y}4 \cdot t_4 + a_5 \cdot t_5^2 + v_6 \cdot t_6 \quad (5.5)$$

where
a = acceleration
d = deceleration
$v_{(x,y})$ = velocity changing with respect to direction
$t_1 ... t_n$ = divisions of time.

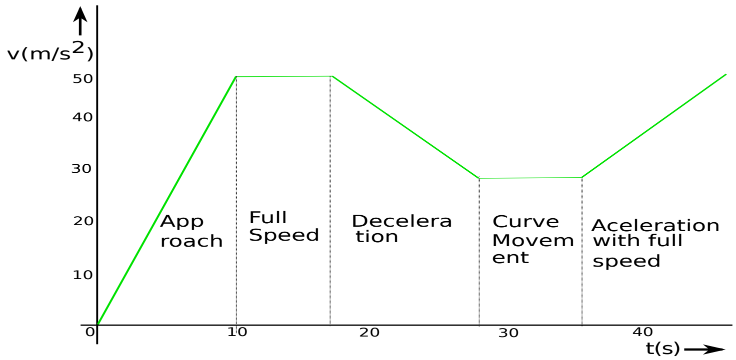


Figure 5.9: Velocity model of curved movement

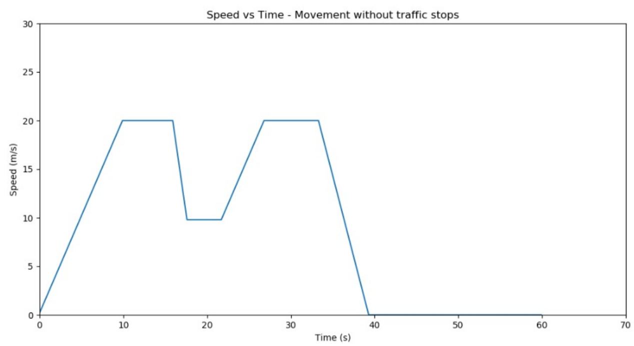


Figure 5.10: Curved movement speed graph

Sub-scenario 1.1: Two Cars, Straight Movement – No Traffic Lights

Just as in the case of Two Cars, Straight Movement – No Traffic Lights, the two cars start from the same position but, the second car starts after a delay of 10 seconds. This second car has a higher engine force applied, giving it a higher acceleration and a higher velocity. This car eventually catches up with the first car just as they arrive at the destination. The movement direction is straight, as in the case of Straight Movement – No Traffic Lights.

The total displacements, s_t *and* s_{t2} can be given by:

$$s_t = a_1 \cdot t_1^2 + v_2 \cdot t_2 + d_3 \cdot t_3^2 + v_{x,y}4 \cdot t_4 + a_5 \cdot t_5^2 + v_6 \cdot t_6 \tag{5.6}$$

$$s_{t2} = a_1 \cdot t_1^2 + v_2 \cdot t_2 + d_3 \cdot t_3^2 + v_{x,y}4 \cdot t_4 + a_5 \cdot t_5^2 + v_6 \cdot t_6 \tag{5.7}$$

where a = acceleration
d = deceleration
$v_{(x,y}$ = velocity changing with respect to direction
$t_1 ... t_n$ = divisions of time.

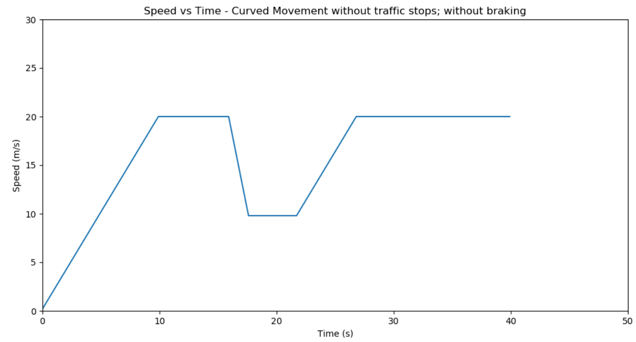


Figure 5.11: Curved movement speed graph without traffic light and no stopping

5.4 Summary

In summary, this chapter described the Simulator design's fundamental comprising the road system design for the car model based on physics principle. Existing traffic microscopic and macroscopic traffic simulation models are adopted to model a hybrid traffic flow behaviour with details of the individual vehicle types response based on the AV and HV unique characteristics. Explained in detail are the step-wise mathematical modelling, and high-level abstractions procedure for creating and implementing the prototype simulator. Described above is the implementing process of the simulator architecture with its essential components using mathematical abstraction. The design is used in developing its numerical description, visualisation, and analysis component involving the drawing outlook and function or workings of the road system and intersections details. Also described above is the validation of calibrated traffic data from the various traffic scenarios conducted using traffic scheduling and routing in a 4-way road intersection. The validation results generated supports the prototype simulator in demonstrating that the mathematical model is well approximated, and the resulting car behaviour matches the expectations for a realistic city traffic performance. A new method of reserving intersection node for vehicles entering the intersection is presented as part of the mixed traffic integration scheme. This reservation node method proves to be more efficient than the state-of-the-art mixed traffic control method.

Chapter 6

Experimental Results and Discussions

Chapter Overview

This chapter presents the conducted experiments that estimate the benefits and drawbacks of the research hypothesis. Section 6.1 presents an overview of the different road intersection management scenarios with an introduction to traffic controls and road parameters. In Section 6.2, the model performance assessment benchmark is described using qualitative and quantitative assessment criteria to evaluate the alternative traffic management strategies. Section 6.3 presents the conducted experiments and results generated from different mixed-traffic management strategies. And finally, the overarching conclusions drawn from all experimental results are presented.

6.1 Overview of the Conducted Experiments

This scientific procedure investigates the different mixed traffic (AVs and HVs) management strategies at a road intersection and proposes an alternative control scheme with safe and efficient traffic movement. This investigation process involving reviewing the current state-of-the-art mixed traffic management strategy. City road traffic system's performance primarily dependent on the intersections' control strategy, capacities, and the traffic signals in use. Traffic management method application is subject to traffic users and control signals involved in a road system. Many traffic control media exist, ranging from traffic light signals, roadside traffic signs, wireless communication, and road markings. Traffic management requires efficient communication between the road users (traffics) and the road system. The proposal is made to apply intersection node reservation to mixed traffic management on the prototype simulator and review their performance with state-of-the-art. The performance impact of the control strategies on traffic parameters' performance is used to evaluate each control method. The model road intersection prototype involves the crossing over of two perpendiculars to each other streets or roads. The road segments maintain the same crossing angle with traffic from the right by default have priority to go first when two or more cars pull up to a four-way stop simultaneously. The model shares the traffic light signal control with the wireless vehicle to vehicle and vehicle to infrastructure communication control. The experiments are conducted using the following traffic intersection control strategies: Traffic Light, Collision Avoidance, and Node Reservation.

To better understand the features upon which each traffic control strategy is based, it is essential to describe the procedure used to define the traffic control strategy and road intersection scenarios. A prototype road intersection scenario is described to understand better the future upon which each traffic control strategy is based. The same type of road intersections may vary significantly in traffic control methods, control devices, and other features. Parameters that vary are the HV/AV mix ratio, intersection capacity utilisation (50%

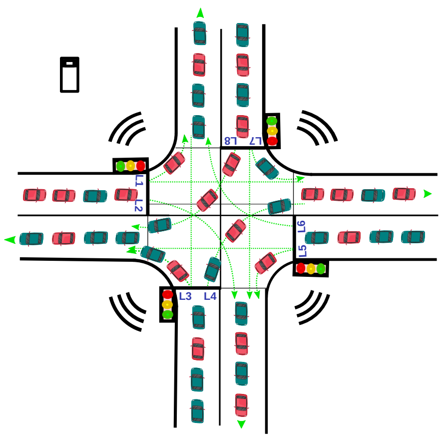


Figure 6.1: AVHVControl with Traffic Light

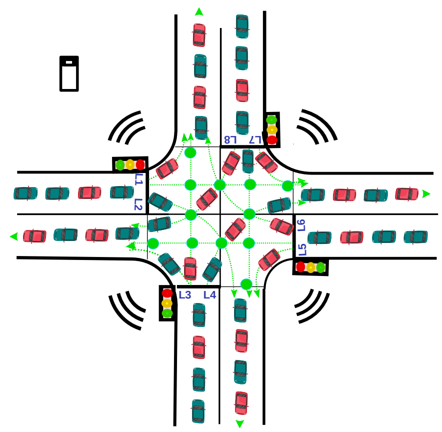


Figure 6.2: AVHVControl with CCP

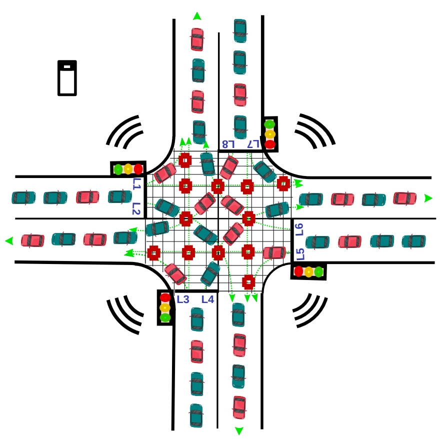


Figure 6.3: AVHVControl with Reservation Nodes

and 100%), HV safe distance, HV reaction time, vehicle route (start to destination), time, and speed. The research criteria utilised the traffic control framework and method to assess the efficiency and safety of the following traffic control strategies.

6.1.1 Traffic Lights (TL) Control Method

The traffic light control technique, as described in Figure 6.1, is the conventional traffic control method designed to use a static cycle timing system to control traffic flow through the road intersections. The signal timing is designed to rotate at a constant time among all the phase or traffic routes. The traffic light control system is a roadside indicator that uses the light colour variable's status per cycle to direct human-driven vehicles across the road section. Though the traffic light is designed for human-driven vehicles, its operations are synchronized with the autonomous vehicles' wireless communication control protocols. The traffic lights system assigns the specified amount of time to each vehicle trajectory sequentially. For optimal performance, the modern traffic light system is integrated with infrared sensors, which senses the optimal density of traffic signal control following the constantly changing road traffic situation, and provides valuable traffic information for the control process. The historical traffic statistic or information from TL is used to predict future traffic flow performance.

6.1.2 Collision Avoidance with Save Distance (CAwSD) Control Method

The collision avoidance techniques described in Figure 6.2, the interaction between traffics and the road system is represented as a chain of conflict points. There is no requirement for a phase assignment or cycle time compared with the traffic light control method. At each instance of time, traffic arriving the intersection check to know if there is another traffic sharing the collision points along its trajectory. The vehicle arriving parameters of position, speed, time are used to calculate which vehicle would be given way to the collision point in a real traffic situation. On arrival at the intersection, conflicting vehicles cannot enter the intersection simultaneously when they share the same collision point but can move concurrently on intersection as it provides that they do not share the same collision point simultaneously. This method takes an analytical approach by calculating the probability of traffics arriving at a conflict point simultaneously and the subsequent delay. When vehicles are sharing the same collision point from a different route, they might eventually collide. Naturally, the major problem will arise from human-controlled vehicles as their behaviour is stochastic, and they are more prone to errors in prediction. Consideration is based on two types of vehicles which varies in their maximum velocities; slow (V_s) and fast (V_f) which denotes the fraction of the slow and fast vehicles, respectively.

6.1.3 Reservation Nodes (RN) Control Method

This RN technique described in Figure 6.3, is a reservation-based algorithm that schedules the vehicles' entrances into the intersection space by reserving a collision node to one particular vehicle every instance. The process of using the intersection collision point is based on a request, and reservations are made based on a predefined protocol before vehicles can pass. This efficient schedule is formulated to calculate the vehicle's relative speed to the reservation node and assign the node a vehicle sequence. Car's distances to other cars before it is calculated and the minimum distance to the reservation node is found. After this, the environment's central collision avoidance system signals the car to brake, decelerate, and, if not, to keep going. The safe vehicle distance, reaction time, and relative distance model are proposed to maximise the delay and reduce the probability of accidents at cross collision points. This traffic management strategy is a decentralised strategy where drivers and vehicles communicate and negotiate for access to the cross collision point based on their relative distance and access priority to the intersection.

Table 6.1: Simulation conditions and parameter Values

S/N	Parameter Description	Value
1	Simulation time	between 600 to 10800 sec
2	Intersection capacity utilisation	50% and 100%
3	Intersection zone dimension	36 m^2
4	Vehicle origin to destination node	Random
5	Maximum Velocity	10 m/s
6	Max Acceleration / Deceleration	$10m/s^2$ / $-10m/s^2$
7	Braking Force	1200 N
8	AV Safe Distance	10 - 15 m
8	HV Safe Distance	15 - 20 m
9	Reaction Time (HV)	0.3 - 1.2 secs

6.1.4 Simulation Parameters

The parameter values for the experiment are predicated upon a series of calibration and guidance with the real-traffic parameter values support the research hypothesis. The mixed traffic flow experimental investigation provides the vehicle flows qualitative and quantitative data for a more general picture to account for the heterogeneous nature of the traffic flow characteristics. Table 6.1 contains a list of parameters forming one of a set of conditions that defines the AVHVControl simulator's operation, including the physics for car operation. The model is applied to a 3-way and 4-way single lane road intersection, and the propagation of traffic flow overtime is evaluated with the generated measurement data from the developed three traffic control strategies.

6.2 Model Performance Measures

Research in traffic management has dramatically helped describe traffic parameters and measurements that could be used to investigate traffic flow behaviour. Since vehicles rarely travel alone, the performance parameters guiding the interaction between vehicles are one of the bases for this investigation. Road traffic flow parameters are the measurable factors forming a set that defines traffic performance at a road intersection or sets its operational conditions. Traffic flow behaviour could be investigated using a variety of parameters and quantifiable metrics. A thorough investigation of the mixed traffic flow management strategies is carried out to assess its performance with the alternative. The model's effectiveness is derived from addressing vehicle behavioural objectives using the intersection collision points' operation. The performance assessment of the proposed mixed traffic flow strategy involves a comprehensive and systematic process for investigating traffic flow problems at intersections. It also involves measures relating to high throughput and identifying measures to deal with the anticipated drawbacks and safety issues. Consideration is based on processing, compiling, and analysing each qualitative and quantitative traffic parameter's effect on the traffic flow's performance. The chosen model parameter values are based on the specification of UK highway code. [COD93, THM11] which served as a guide in choosing values that are realistic to a city traffic system. The characteristic of traffic flow parameters drives this investigation. Measures of parameters could include lateral and longitudinal inter-vehicle performance, usually related to vehicle motion, but this will be part of the subsequent research direction. Besides, this investigation looks at drivers and vehicle characteristics such as mitigating collision risk, optimal utilisation of the intersection space, stable reaction time, and safe distance distribution.

6.2.1 Quantitative Assessment Variables

Upon solving the problems of determining the optimal, safe distance and reaction time values for human-driven vehicles, the intersection performance parameters need quantitative evaluation. The quantitative assessment methodology comprises the model parameters to assess the various intersection control strategies implemented with a 3-way and 4-way traffic intersection system. The parameters to be evaluated on its performance on different strategies include:

- Time it takes for cars from start to destination (for the specified distance covered)

$$t = \frac{d}{v} \tag{6.1}$$

  Where d is the distance, while v is the velocity. Looking at the performance of the control strategies to time in Table 6.3, while the number of vehicle 100 is kept constant and at an optimal mix of 50% AV and 50% HV, the RN, CAWSD, and TL takes 199.4 minutes, 203.7 minutes, 205.1 minutes, respectively. Table 6.3, present the measurements from the Simulator in analysing the time metric of the different traffic control strategies. The generated CSV file results are based on the time it takes the different proportions of HV and AV ratio mix to access the intersection. In this scenario, 21 different mix ratio of AV and HV is simulated, and the time it takes to complete the simulation process is recorded. This table gives us a picture of the expected impact of AV on traffic considering different traffic control strategies.

- The intersection capacity: This refers to the no of vehicles that access the intersection at a given period for the different control strategies. Equation (2.11), Equation (2.12), and Equation (2.14) describe the capacity equations for HV, Av and Mix traffic respectively.

This method evaluates the overall effects of the traffic intersection control strategies and the relative volume significance. This parameter evaluates each traffic control strategy's overall outcomes and the impact AVs and HV's have on each other's performance. The evaluation of the traffic performance is based on the proportion of each vehicle type. The corresponding distributions for the different traffic management strategies are shown in section 6.1.

6.2.2 Qualitative Assessment Variables

The quality assessment parameters looked at those that take care of the traffic flow performance and are not easily quantified. Involves utilising the intersection to guarantee an efficient flow of traffic. They include:

- Scalability - The AVHVcontrol accomplishes this by providing its compatibility with different intersection sizes. The different handling of traffic and node reservation allocation to specific traffic flows in the intersection are also included.

- Traffic stability: It is common knowledge that a steady, continuous flow is efficient than the stop-and-go approach. From the simulation, the traffic stability analysis generated/simulated from the number of brakes cars experience for each traffic control method. It is assumed that the less the number of brakes observed by vehicles, the more stable the traffic flow is.

- Error management: Its ability to run high-priority traffic control calls under limited intersection capacity dependably. The intersection efficiency is measured with specific metrics which detail the characteristics of vehicles.

The qualitative parameters that could affect the quality of service of the traffic flow control process are as discussed below.

6.3 Performance Investigations and Result on Mixed-Traffic Management Strategies

Traffic flow could be analysed or measured analogously to fluid mechanics, influenced by the applied traffic control devices and strategies. The proposed traffic control methods are evaluated using the basic diagrams (Speed/ Flow/ Density) to demonstrate their efficiency. All conducted experiments used the simulation variables described in Table 6.1. This investigation is sifted through and in detail to identify causes, key factors, and results to support the findings of the thesis. An investigation of the performance of different mixed traffic management strategies is carried out using traffic parameters and measurements. Selected Model Performance Metrics was used in investigating the characteristics of the traffic flow variables for analysing the different traffic control methods' performance and understanding the systems' behaviour. These control variables are collected from traffic performance theories , whose variables are generated from the calibrated simulation results. Below is carefully chosen traffic performance parameter metrics for the assessment of control strategy performance:

6.3.1 Intersection Capacity Utilisation - Car(s)Min:

This deals with the average number of cars that pass through an intersection or observation point at a specified time interval. The intersection capacity analysis table in 6.2 indicate the performance of the 3 different traffic control strategy studied, recorded over 3600 seconds. Looking at the table section for 50:50% mix scenario, the RN control method performed better with a capacity of 397.3 cars per hour against 261 and 147.2 for CAWS and TL, respectively.
The perspective of the intersection efficiency utilisation that needs to be investigated are subdivided into two: the mixed proportion of the cars scenario performance and the time it takes for the vehicles to pass through the intersection using the different control strategies. Intersection capacity is the main determining factor for measuring performance efficiency, which could be evaluated based on intersection size and the number of vehicles. The degree of saturation can be used to express the relationship between a performance metric and capacity (demand volume- capacity ratio). Also considered are the performance of the different control strategies in 50% and 100% intersection capacity utilisation. The relationship between the traffic density p and vehicle speed s describes the intersection capacity c. Table 6.6 show the low and high-end capacity metrics with the occupation ratio and time with an intersection capacity of 300 cars (300 cars was chosen after a repeated calibration with different number of vehicle and consideration of the time taken for the simulation). The data in Tables 6.7 and 6.8 presents a 19 times repeated simulation to generate enough dataset for 1-minute average traffic flows, speeds, and densities for the three control methods used in the comparison. In analysing the performance of each traffic control strategy using intersection capacity, the ratio of different vehicle type ratios are compared with the time of passing the intersection as represented in Table 6.4.

$$c = p \cdot s \tag{6.2}$$

Where p is density and s is vehicle speed.

Table 6.2: Intersection Capacity Analysis F

Vehicle Type Mix Ratio	Control strategy	Average Car Speed (Mph)	Capacity (Veh/hr)
$50\%AV : 50\%HV$	RN	18.4	397.3
	CAWSD	11.02	261
	TL	7.24	147.2
$100\%AV : 0\%HV$	RN	22.59	526.2
	CAWSD	Not applicable	Not applicable
	TL	Not applicable	Not applicable
$0\%AV : 100\%HV$	RN	Not applicable	Not applicable
	CAWSD	Not applicable	Not applicable
	TL	16.12	353.15

Note: The capacity value does not have to be an integer, because it is a rate quantity which can be fractional or an integer.

The calibrated capacity values are used to investigate the three traffic control methods' performance. The simulation time is used as a deciding factor in analysing the impact of different traffic management strategies while keeping the vehicle's count constant. Figure 6.4, describe the effect the vehicle mixed-proportion has on traffic performance considering the different traffic control strategies and the behavioural features. A basic assumption is made for AVs and HVs to ignore traffic light and vehicle-to-vehicle communications, respectively, and run concurrently. The vehicle occupation time is analysed for the two-vehicle types (AV and HV), with different vehicle movement scenarios. The vehicle occupancy time is analysed for the two vehicle types (AV and HV) at road intersections with different vehicle movement scenarios.

From the Figure 6.4, it is clear that the intersection capacity increases with an increase in the proportion of AV's. This is as expected because of its smart behaviour comprising of short reaction time and safe distance. The intersection capacity utilisation describes the number of vehicles that can pass through the intersection within an observation period. Figures 6.5 and 6.6 represent a 100% and 50% intersection capacity, which shows the optimised number of vehicles accessible with each traffic control strategy under certain traffic conditions. As could be observed from the statistics, the RN has the highest capacity. The histogram in Figures 6.5 and 6.6 indicates a varying 50% and 100% intersection capacity recorded over a 3600 seconds simulation period. Overall, the traffic flow performance for 50% and 100% capacity witness an upward trend for the RN, followed by the TL and lastly by the CAWSD. While the RN maintains 350 cars per hr for both 50% and 100% capacity, the TL varies from 300 cars per hr to 250 cars per hr for the 50% and 100% capacity, respectively. The details of the flow performance for the CAWSD show that the intersection capacity increases from 125 cars per hr to 175 cars per hr, respectively for 50% and 100% capacity, respectively.

6.3.2 Time:

Time has many components which describe the position of individual vehicles in time and space, and it helps to understand traffic flow's behaviour. This parameter is used to analyse the travel time, traffic delay, and queue lengths of the traffic system. Another component of the time is an occupation which is the length

Table 6.3: Vehicle ratio occupancy metrics

S/n0	% of AV:HV	TL Occupancy Time(s)	CAwSD Occupancy Time(s)	RN Occupancy Time(s)
1	100 : 0	195.2	193.1	188.0
2	95 : 5	196.1	194.1	190.2
3	90 : 10	197.1	195.1	191.0
4	85: 15	198.3	196.1	191.9
5	80 : 20	199.3	197.1	193.2
6	75 : 25	200.2	198.1	194.0
7	70 : 30	202.5	199.1	195.2
8	65 : 35	201.9	200.1	196.4
9	60 : 40	203.0	201.7	197.0
10	55 : 45	205.0	202.1	198.5
11	50 : 50	205.1	203.7	199.4
12	45 : 55	206.1	204.5	200.8
13	40 : 60	208.0	206.0	202.1
14	35 : 65	209.2	207.5	203.0
15	30 : 70	211.1	209.0	205.0
16	25 : 75	212.6	210.5	206.2
17	20 : 80	213.2	211.0	207.1
18	15 : 85	214.4	212.5	208.3
19	10 : 90	216.2	214.1	210.0
20	05 : 95	218.1	216.6	212.1
21	0 : 100	219.2	217.6	213.1

of time a car or car group moves from start to target. The delay at intersection is generated/simulated from Equation (4.33). This equation is used to quantify the total delay vehicles experience in waiting for access at the intersection. The time associated with traffic could be expressed in different ways:

- Delay: This is the leading performance metric for intersection efficiency because it gives one the cumulative effect of an intersection over travel time. In improving traffic efficiency, we make sure that it does not negatively impact other traffic parameters. Considering an N vehicle passing through the intersection at a time t, and an alone vehicle c_i is passing through the same intersection to complete its goal from start to destination at time t_i. Assuming that the vehicle is moving at a maximum speed in this case because there is no other vehicle on the road. However, due to the presence of other vehicles sharing the intersection simultaneously, the vehicle arrives instead at its destination at time t_f. Then we define the mean delay (MD) of a traffic intersection to be:

$$MD = \frac{1}{|N|} \sum_{c_i} t_f - t_i \tag{6.3}$$

  This research shows that modelling delays for homogeneous traffic show a linear relationship with the same type of vehicle. This may be caused by uniformity in vehicle behaviours. However, such a linear models will not be appropriate for mixed-traffic co-existence and non-uniform car behaviour, which leads to a traffic collision.

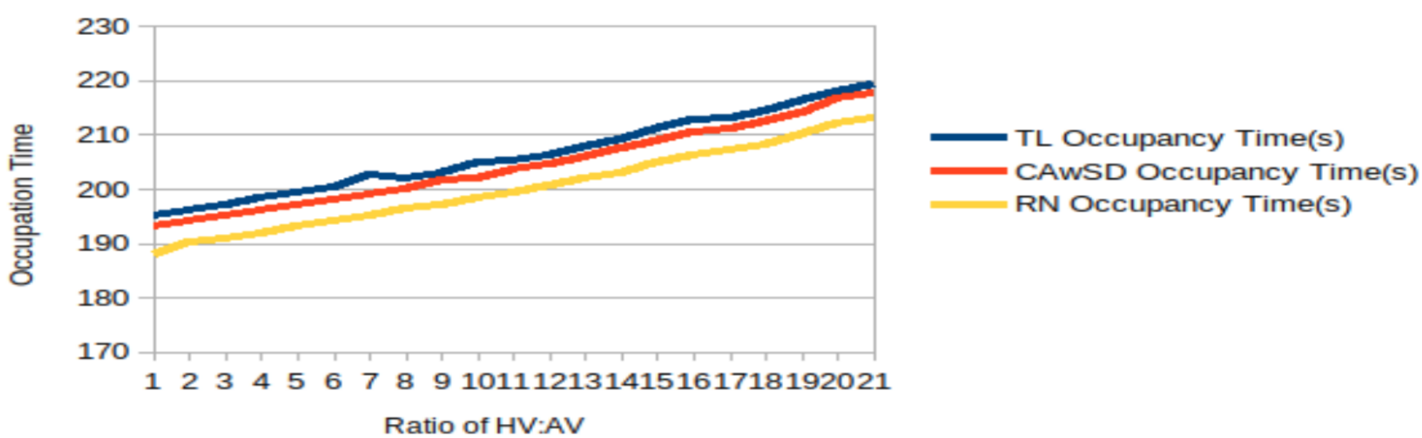


Figure 6.4: Vehicle Occupancy metrics AV:HV

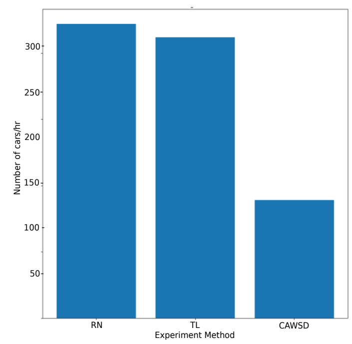


Figure 6.5: 50% Capacity

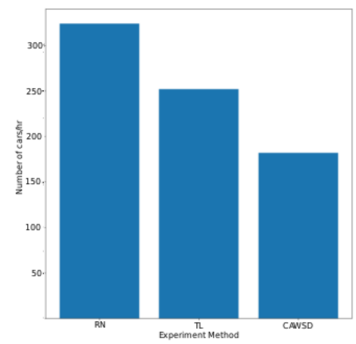


Figure 6.6: 100% Capacity

- Maximum delay: This is the worst case of traffic delay

$$Max_{c(i)}t_i - t_0(i) \tag{6.4}$$

- Delay due to the car is waiting for signal clearance to pass.
- Delay due to driver's observation of the vehicle at the intersection based on traffic rules.

However, the above list of traffic delays is hard to measure because it depends on the traffic signal characteristics. The focus was on accessing delay estimation associated with cars waiting at the intersection for clearance to pass the intersection. The delay estimation on lane $L1_{ij}$ on a road intersection I is defined as:

$$L1_{ij} = D_{ij}/v_{ij} \tag{6.5}$$

Where D_{ij} is the length of queue on Li which is the distance from n_i vehicle to n
The subscripts $_{ij}$ represent no of vehicle on the lane
V_{ij} is the velocity of vehicle

6.3.3 Vehicle Queue

Queue estimates the time vehicle spent waiting for another vehicle to access the intersection first before having the right of way. The queue length generated/simulated using Equation (3.9), which functions/equations are calculated for various control method. Depending on the intersection-specific conditions and at the city's discretion, it is queuing analyses for transportation system plan, transportation planning rule (TPR) may be required for operational analysis. Traffic congestion is often associated with stop-and-go traffic, slower speeds, longer travel times, and increased vehicular queuing as characteristics. This can be quantified by the number of vehicles waiting for vehicles around any intersection. It is the cumulative effect of an intersection over travel time. The vehicle delay time analysed for the three intersection control strategies using the time difference between the average vehicle occupancy.

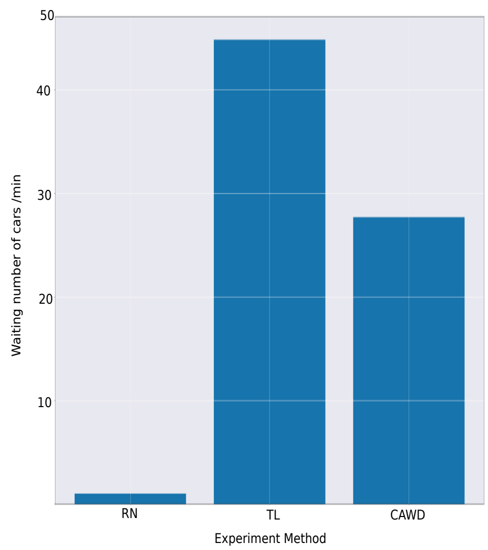


Figure 6.7: Travel time delay

6.3.4 Stability:

In the contest of this thesis, traffic flow stability as represented in Figure 6.8 is analysed with the number of traffic braking in response to the volume for the different control methods under the same condition. The traffic flow efficiency at road intersections depends partly on traffic flow stability which is analysed with the number of braking associated with a control method. The traffic stability could be accessed from the uniformity of the flow speed. It is a state where all cars move with an identical safe distance and optimal velocity. A speed fluctuation impacts the vehicle flow stability when in motion. It is observed that the different traffic control methods are associated with different stability levels. The vehicle safe distance process involves deceleration and acceleration, which causes a perturbation in the stability of the overall flow.

6.3.5 Safe distance

The spread of the safe distance over a range of human-driven vehicles counts on traffic flow performance. The afe distance is generated/simulated from Section 3.3.2 with a random value assigned. The distribution of the safe distance varies based on individual drivers. The safe distance design corresponds to the distance covered by the vehicles in at least 2 seconds, irrespective of its current speed. While the safe distance of the autonomous vehicle is constant, that of the human drivers follows a normal distribution. This distance could also be described as the elapsed time between two successive vehicles merging at a road intersection within a considered distance frame in an intersection. Figure 6.9 shows the corresponding distribution for safe distance-time distributions for different traffic conditions. The corresponding safe distance is calculated based on time concerning the actual distance due to varying vehicle speeds. Vehicle safe distance distribution is directly proportional to the vehicle because while vehicle density increases, the speed is reduced with a reduction in a safe distance; this is from the theory of 2 seconds rule. Looking at Figure 6.9, RN maintains an average safe distance of 19.59m, TL has 18.39m, while the CAWSD has 12.74m.

The decision between different safe distance distributions of vehicle control methods has direct consequences for assessing traffic efficiency because of the variation in individual human drivers. Consideration is on the safe distance distribution that performs optimally for many vehicles, and from there, one can make reliable average predictions of traffics. The generated results in Figure 6.9 underscore the need to carefully judge the effect of choosing a specific distribution and thus choose an optimal distribution that fits the analysis data. The choice of traffic control method to be applied impacts the policy decision in traffic management research. The equations obtained are used to evaluate the critical safe distance and reaction time for an aggressive driver (HV) to improve traffic efficiency. The safe distance is calculated using incorporating the reaction time components and the method of behaviour clearing. The safe distance distribution appears realistic when the reaction time and the aggressive behaviour of drivers are integrated into the model.

6.3.6 Reaction time:

The human drivers' reaction time varies based on human psychology and many other un-quantifiable factors like age, sex, experience, and many others. The time in most cases is influenced by many factors, which lead to variations in its value. The reaction time entails some degrees of freedom because of their skewed distribution nature, which counts for different drivers. In investigating the group reaction time spatial correspondence effects, some unique properties of the mean and standard deviation are used. The analysis data for the reaction time is from the state of the vehicle's deceleration, stopping, and a car-following scenario. The reaction times is generated/simulated from Equation (3.2) with a random value assigned. The reaction time is sampled from a normal distribution of N(0.3, 1.5) milliseconds. The distribution of the reaction time varies based on individual drivers' psychology. Looking at Figure 6.11, the details safe

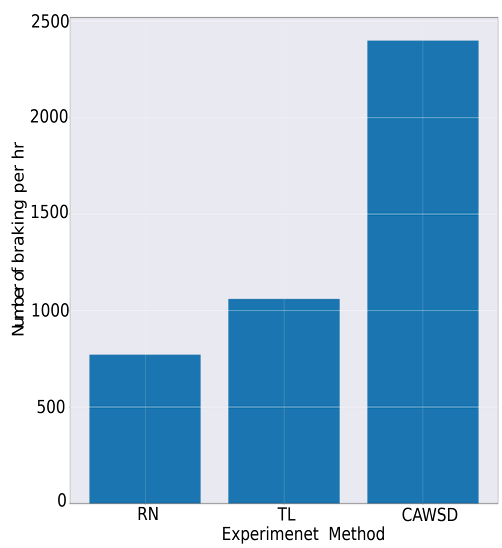
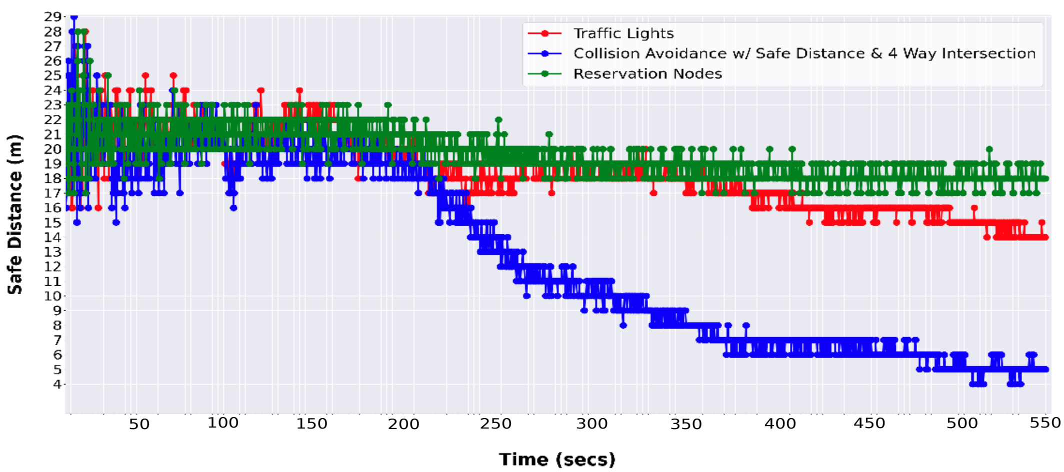
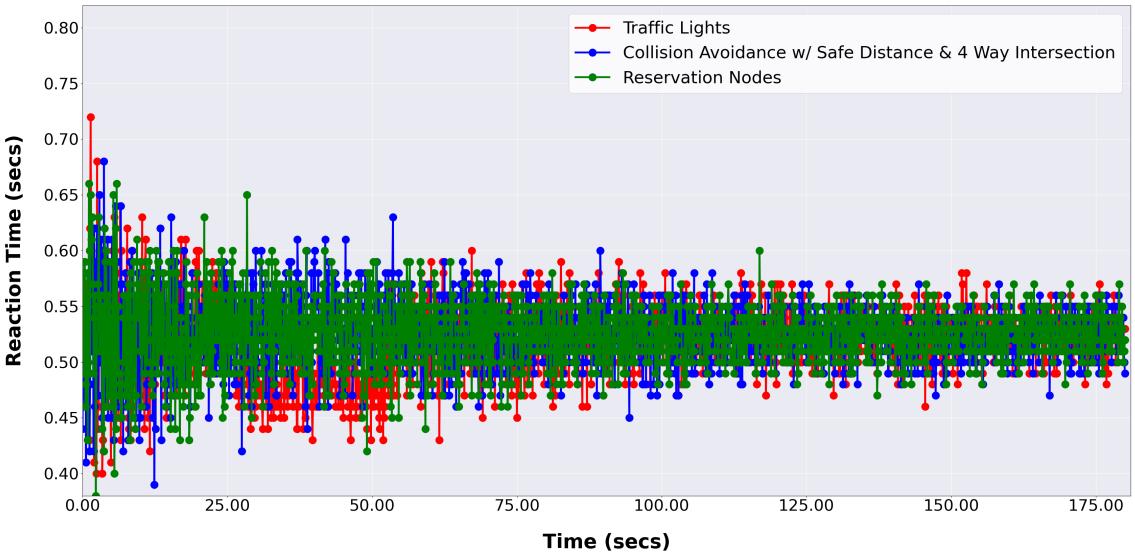


Figure 6.8: The Number of Braking Occurred



t = 3.0 min(s)	Min. SafeDist.	Max. SafeDist.	Avg. SafeDist.
TL	14	28	18.39
CAwSD4WI	4	29	12.74
RN	17	28	19.59

Figure 6.9: Distribution of Safe Distance



t = 3.0 min(s)	**Min.**	**Max.**	**Avg.**
TL	0.4	0.72	0.52
CAwSD4WI	0.39	0.68	0.53
RN	0.38	0.66	0.53

Figure 6.10: HV Reaction Time Distribution

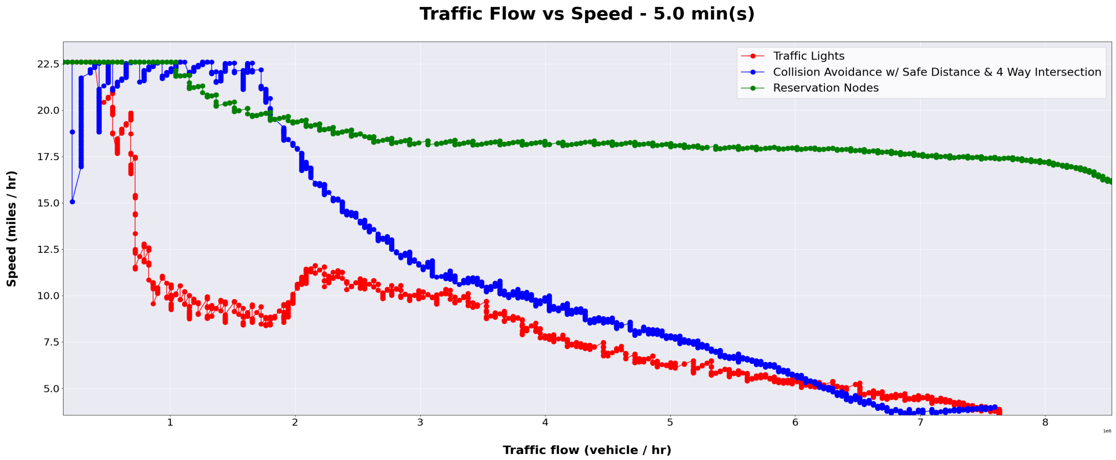
distance distribution maintained the value of a relatively stable mean distribution bearing the exact value of 0.53seconds seconds for both RN and CAWSD, while the TL method has 0.52 seconds. This shows that the model reasonably mimics the real-life behaviour of the vehicles irrespective of the control strategy in place.

The reaction time distribution is a psychological experiment because it is driven from two normal random variables' quotient. The driver's reaction times are not normally distributed, but there is little consensus about how they are distributed, though a typical reaction time has a fitted model that will predict that more than 5% of the reaction times will be faster than the fastest RT ever recorded. For every instance of stimuli, the distribution of reaction time were made. The result appears symmetric and is skewed positively for HV. The reaction time distribution results have some implications in modelling the human driver's behaviour date as represented in Figure 6.10 for a 50% and 100%capacity utilisation.

6.3.7 Volume

This is the number of vehicles that pass a through an observation at a specified time period. The traffic flow rate (q) at which vehicles passed through an observation point could be derived from volume by converting the volume to the vehicle per hour. This parameter is used to access the intersection capacity utilisation of the different control methods when other factors are kept constant. Traffic flow rate at the intersection could be described as:

$$q = \frac{n \cdot 3600}{t} \tag{6.6}$$



t = 5.0 min(s)	Min. Flow	Max. Flow	Avg. Flow	Min. Speed	Max. Speed	Avg. Speed	Reached Dest. AV : HV
TL	144000.0	7632000.0	4950660.0	3.56	22.59	7.24	0:0
CAwSD4WI	144000.0	7596000.0	4109602.13	3.58	22.59	11.02	0:0
RN	144000.0	7596000.0	4109602.13	16.12	22.59	18.4	74:88

Total AV: 121 **Total HV**: 127

Note that speed is in **miles/hr.**
Flow is the number of vehicles at each instance of time(t) (0.1secs for 5 minutes period).

Figure 6.11: 50%Capacity Flow-Speed Curve

where:
3600 is a constant (The area of the intersection)
q = Traffic volume (vehicles/hr)
n =Number of vehicle count. It is a variable generated through a counter within the observation point at a specified time (t sec)
t = Time length: This is the simulation time(sec) for the scenario. This is set to be constant for each scenario and could be varied for different vehicle densities. The speed-flow relationship states that speed will be maximum when the number of vehicles is minimum, while at a free-flow speed, the density is maximum, while the speed will be zero. Looking at the details of the speed/flow graph above, with all vehicle starting at a high speed, the speed is 0 at a flow rate of 7v/h for the CAWSD, 7.5v/h for TL, while maintaining a speed of 17.5m/h at a flow rate of 8.5v/h.

The proportion of volume-over-capacity(V/C) is the crucial measuring parameter of traffic flow effectiveness for investigating the operational performance of an intersection. The ratio of V/C for cross-junctions can be calculated based on the entry demand and capacity for the single lane's most critical approach (i.e., approach with the highest v/c ratio) at the intersection.

6.3.8 Speed

This denotes how quickly a vehicle moves or the rate at which a vehicle travels. Equation (2.1) and Equation (2.17) are used in calculating the vehicle speed from the simulation. When a vehicle's speed remains relatively identical or the same over a distance, it shows that the flow is stable and can easily be predicted. The speed is calculated for both single cars and cars or mean speed over an observation period. The speed performance Table 6.4 is used to assess the traffic flow efficiency when other factors are kept constant. Traffic speed is inversely proportional to the density, which means that as density increases, the speed decreases. The vehicle density approaches' 0' at a free-flow speed.

$$v = \frac{d}{t} \tag{6.7}$$

where:
v = Vehicle speed (distance over time)
d = Travel distance (Generated from the displacement between the start and destination position ($X_f - X_i$).
t = Time (sec), the elapsed time for the flow

From the analysis of the different traffic control strategies mean speed Table 6.4, the node reservation method is beneficial in a 100% intersection utilisation because the average speed of the vehicle is higher when compared with the 50% capacity. Speed–Volume diagrams in Figure 6.11 are used to determine the speed at which the optimum traffic flow occurs. In this diagram, we have two different speed values of observation: the minimum speed at the maximum density and the maximum speed at a minimum density. In a free-flow traffic condition, vehicles travel at the maximum allowed speed. Traffic flow grows nearly linearly with the density until a critical density value at which the flow rate takes its maximum(road capacity). At critical density value, vehicles travel closer to one another at a reduced speed. The speed-density curve helps predict the road intersection capacity of different traffic control methods in place. The effect of the traffic control strategies on the vehicle speed is investigated for a 50% and 100% intersection occupancy. The speed-time graph describes the vehicle movement behaviour within an observation time. It helps us

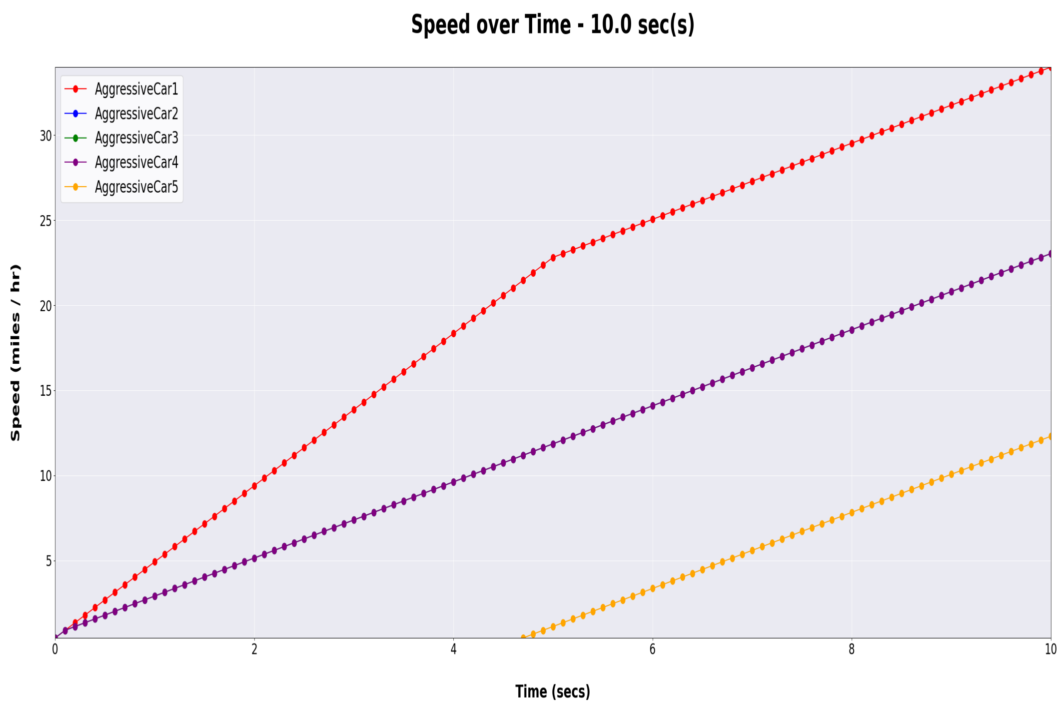


Figure 6.12: Speed time graph

determine the distance traveled by a vehicle and how fast it moves, considering the other control methods. Travel cost and traffic delay are like the queue are estimated using the speed-time graph Figure 6.12. It is essential to appropriately evaluate the lost time in traffic because it affects traffic performance.

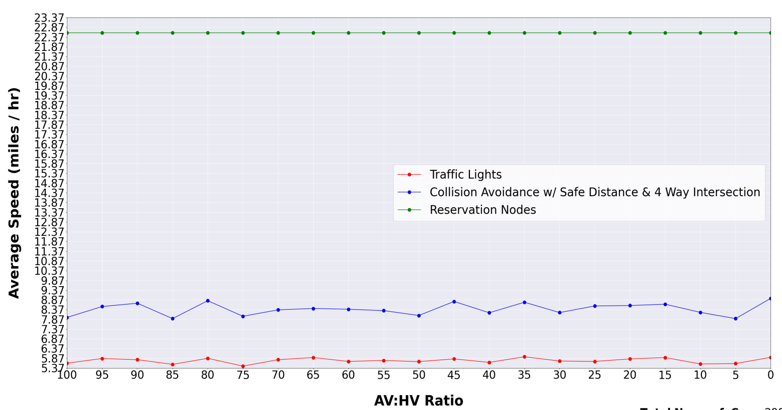
6.3.9 Density

This is the % of the road space occupied on a relevant road section. The distances between vehicles determine traffic density, and this distance is based on a reaction time and the safe distance. The density, the concentration of vehicles, measures the number of vehicles on the road segment per unit length. Traffic density can be expressed as:

$$k = \frac{n \cdot 2.5m}{l}(We\ assume\ an\ average\ length\ of\ 2.5m\ per\ vehicle.) \tag{6.8}$$

where:
k = Vehicle density (in % of the road length)
n =Number of vehicle count. It is a variable generated through a counter within the observation point at a specified time (t sec) 2.5m = constant - the assumed average length of vehicle.
l = The length of the road section being observed (in meters).

The volume-density relationship defines the traffic condition of an intersection. Analysing volume-density describes the relationship between the traffic volume and the amount of road space available as a function of the number of vehicles per unit length. Analytically, the traffic volume rate decreases with an increase in density. The volume-density curve determines the traffic state, implying that the higher the density on the congested intersection, the lower the flow experiences. The intersection of free-flow and congested traffic flow vectors is the curve's apex and is considered the intersection capacity.



t = 3.0 min(s)	Min.	Max.	Avg.
TL	5.47	5.95	5.75
CAwSD4WI	7.91	8.95	8.4
RN	22.59	22.59	22.59

Figure 6.13: Speed Performance Analysis

Table 6.4: Vehicle Mean Speed Analysis for 50% (300-vehicles)

S/n0	% of AV:HV	TL Mean Speed(m/s)	CAwSD Occupancy Time(s)	RN Occupancy Time(s)
1	100 : 0	17.1	11.2	22.9
2	95 : 5	16.9	11.0	22.9
3	90 : 10	16.8	10.8	22.8
4	85: 15	16.7	10.7	22.8
5	80 : 20	16.7	10.5	22.7
6	75 : 25	16.6	10.3	22.7
7	70 : 30	16.5	10.1	22.7
8	65 : 35	16.2	9.8	22.7
9	60 : 40	16.0	9.4	22.6
10	55 : 45	15.9	9.2	22.6
11	50 : 50	15.6	9.5	22.6
12	45 : 55	15.3	9.2	21.0
13	40 : 60	15.1	9.0	20..5
14	35 : 65	14.5	8.6	18.3
15	30 : 70	14.1	8.2	17.9
16	25 : 75	13.4	7.8	17.0
17	20 : 80	12.9	7.4	16.7
18	15 : 85	12.5	7.4	16.3
19	10 : 90	12.2	6.9	15.5
20	05 : 95	11.7	6.5	15.1
21	0 : 100	10.2	6.1	14.7

Table 6.5: Vehicle Mean Speed Analysis for 100% (600-vehicles)

S/n0	% of AV:HV	TL Mean Speed(m/s)	CAwSD Occupancy Time(s)	RN Occupancy Time(s)
1	100 : 0	8.3.1	11.1	22.9
2	95 : 5	8.2	11.0	22.9
3	90 : 10	8.0	10.8	22.8
4	85: 15	7.7	10.7	22.8
5	80 : 20	7.2	10.5	22.7
6	75 : 25	6.9	10.3	22.7
7	70 : 30	6.8	10.1	22.7
8	65 : 35	6.2	9.3	22.7
9	60 : 40	5.9	8.9	22.6
10	55 : 45	5.8	8.6	22.6
11	50 : 50	5.8	8.4	22.6
12	45 : 55	15.3	9.2	21.0
13	40 : 60	15.1	9.0	20..5
14	35 : 65	14.5	8.6	18.3
15	30 : 70	14.1	8.2	17.9
16	25 : 75	13.4	7.8	17.0
17	20 : 80	12.9	7.4	16.7
18	15 : 85	12.5	7.4	16.3
19	10 : 90	12.2	6.9	15.5
20	05 : 95	11.7	6.5	15.1
21	0 : 100	10.2	6.1	14.7

6.3.10 Max-Road-Density

This is the % of road occupied by vehicles according to the optimal safe distance. Hence, a value of 100% means that the safe distance of all cars is satisfied, but there is no extra space where any more cars could be placed. In that sense, it removes the impact of speed from the density metrics.

$$\frac{1}{l} \cdot \sum_{car} \text{save\_distance(car)} \tag{6.9}$$

where:
l = The length of the road section (in meters)
save_distance(car) = The optimal save distance as computed by physics – it matches the AV save distance, but human-driven cars may have a higher or lower value according to their aggressiveness.

6.4 Discussion

The proposed methodology for analysing the impact of mixing AVs and HVs will help determine the integration pattern of an autonomous vehicle for the mixed vehicle transition period. In addition, traffic engineers can use the models developed in this study to estimate the capacity of a road intersection in a mixed-traffic environment. This investigation discovered that autonomous vehicles are much safer, time-efficient, and help de-congest roads. Two examples were presented that exploit the reservation node protocol to prioritise mixed vehicles at a road intersection, increasing the total vehicle delay compared with the alternative collision avoidance strategy. It is evident from Table 6.3 that intersection efficiency increases with an increase in the ratio of an autonomous vehicle. This is because AVs combine and interpret their surroundings' sensory data to identify appropriate navigation paths, obstacles, and appropriate signage. The measure of intersection efficiency is conducted using traffic parameters performance metrics relating to throughput and delay. The Performance for different traffic control strategies is analysed using different parameter values based on simulations to see the effect of their values on the system's throughput performance. In addition, the developed AVHV model behaviour appears to be able to reasonably mimic the behaviour of mixed traffic with parameters consistent in the behaviour of the mixed traffic and simulated flow. The combined behaviour of the traffic is mainly controlled by the distribution of the harmonised speed, safe distance distribution, and the number of braking. In contrast, the reaction time distribution controls the individual vehicle behaviour, and the vehicle length. The experimental results show a well-harmonised vehicle group speed at every instance of time.

This thesis looked at an in-dept investigation of the parameters of the Gipps' model in a mixed-traffic setting with the objective of providing insight on the dynamics of the model. Furthermore, the investigation consisted of traffic control strategies to optimise the flow of traffic at a road intersection. The inherent properties of the model were investigated and values of the vehicle mixed ratio were increased in every simulation to establish the impact of the ration variation to guide the integration pattern. The performance of different ratio cases is analysed and compared under the three traffic control methods. This trend makes the HV benefit inefficiency from the AV in a co-existence scenario. Traffic speed Figure 6.13 describes the AVHvcontrol traffic flow pattern in the model. In this experiment, the point of interest is on the measurement values of some physical quantity as represented in Table 6.1, analysing these calibrated values on the above table, it is established that all are not the same, somewhat varies over some range of benefits. The test results for the parameter values were conducted to investigate the impact of autonomous vehicles on traffic, using different traffic control methods, the metrics of the performance of the parameters extracted, and used for our investigation.

Table 6.6: Full and half vehicle capacity metrics

Safe Distance (S_D) Margin	Capacity	No of Cars Mix				Total cars	Time(s)	No of Cars/minute
Low End	Full	Av S_D = 5m	59	HV S_D = 7m	50	109	200	33
		AV S_D = 5m	59	HV S_D = 5m	61	120	200	36
	Half	Av S_D = 5m	15	HV S_D = 7m	15	30	97.9	18
		AV S_D = 5m	15	HV S_D = 5m	15	30	95.6	19
High End	Full	Av S_D = 10m	41	HV S_D = 14m	36	77	200	23
		AV S_D = 10m	41	HV S_D = 10m	43	84	200	25
	Half	Av S_D = 10m	15	HV S_D = 14m	15	30	111.9	16
		AV S_D = 10m	15	HV S_D = 10m	15	30	108.6	17

6.5 Scientific knowledge derived from the AVHV simulator and its experimental results

Reviewing the performance and the experimental results, the following piece of knowledge could be extracted from the AVHV model behaviour:

- The investigation of the simple properties of the mix-traffic model (speed, acceleration, deceleration, reaction time, safe distance) and their dynamics.
- Developed a model that describe the relationship between vehicle type properties of acceleration/deceleration, desired speed.
- Vehicle speed harmonisation technique for mixed traffic.
- The safest hypothesis that could be made to determine whether the reservation node is actively utilised to reduce delays of vehicles is to check if the reservation node's idle time is more than the vehicle's safe distance.
- In-depth investigation of the Gipps model sensitivity with a varying human drivers' reaction time in a mixed traffic to identify the stable and unstable regions.
- This research work further analyses the Gips car-following model, which shows that Gipp's model is inconsistent with the Mix-traffic experimental simulation results because of the heterogeneous vehicle behaviours. Hence the AHCV car-following model is proposed for a mix of human-driven and driverless vehicles.

Table 6.7: Lower end S_D vehicle ratio occupancy metrics

AV $S_D = 5$ with Del. Force = 2500N, HV $S_D = 7$ with Del. Force = 3500N

Serial number	% of AV:HV	Occupancy Time (s)	No of Cars/minutes
1	100 : 0	176.1	34
2	95 : 5	177.1	43
3	90 : 10	178.1	34
4	85 : 15	179.1	34
5	80 : 20	180.1	33
6	75 : 25	181.1	33
7	70 : 30	182.3	33
8	65 : 35	183.8	33
9	60 : 40	185.3	32
10	55 : 45	185.8	32
11	50 : 50	188.3	32
12	45 : 55	189.8	32
13	40 : 60	191.3	31
14	35 : 65	192.8	31
15	30 : 70	194.3	31
16	25 : 75	195.8	31
17	20 : 80	197.0	30
18	15 : 85	198.8	30
19	10 : 90	200.3	30

Table 6.8: Higher end S_D vehicle occupancy ratio metrics

AV $S_D = 10$ with Del. Force = 2500N, HV $S_D = 14$ with Del. Force = 3500N

Serial number	% of AV : HV	Occupancy Time(s)	No of Cars/minutes
1	100 : 0	224.1	27
2	95 : 5	225.3	27
3	90 : 10	226.5	26
4	85 : 15	227.7	26
5	80 : 20	228.9	26
6	75 : 25	230.1	26
7	70 : 30	231.3	26
8	65 : 35	234.9	26
9	60 : 40	236.7	25
10	55 : 45	238.2	25
11	50 : 50	239.4	25
12	45 : 55	240.6	25
13	40 : 60	241.8	25
14	35 : 65	243.0	25
15	30 : 70	244.2	25
16	25 : 75	245.4	24
17	20 : 80	246.6	24
18	15 : 85	247.8	24
19	10 : 90	249	24

Chapter 7

Summary and Conclusion

Chapter Overview

This chapter presents the thesis summary in Section 7.1. Section 7.3 addresses the direction of the future work. The all-embracing conclusion of the thesis is presented in Section 7.2.

7.1 Summary

The emergence of autonomous vehicles has attracted researchers to develop many related technologies to support autonomous vehicle integration process. This thesis aims to investigate the different traffic control strategies for integrating of human-driven and autonomous vehicles. A hybrid traffic control strategy of node reservation for mixed vehicles co-existence is proposed. The simulation model combines the strength of human-driven vehicles to benefit autonomous vehicle performance. However, considering the limitations and significant shortcomings of human-driven traffic signal control systems and relying on a wealth of high-level degree of refinement, precision, and intelligence of autonomous traffic control is the objective need and development direction of traffic control technology. The first chapter provided a detailed background and narrative of the traffic management research, including details on the history, characteristics, behaviour, and understanding of mix-traffic flow phenomena. The research question, hypothesis, and structure of the thesis are presented along with a description of the investigation conducted in traffic management strategies with the alternative. The second chapter provides an introductory theoretical background of road traffic systems and a state-of-the-art mix-traffic management review with relevant traffic terms and concepts. A classification matrix is used to explain in detail the various traffic flow models, parameters, and theories used in managing intelligent transportation and road traffic intersections and the details of different modelling approaches. Chapter 3 presents the framework for the mixed-traffic management research design methods of node reservation strategy for the investigation to support the research hypothesis with the research background idea. The research design procedure, methodology, and fundamental assumptions of the proposed model are all covered in this chapter. A detailed model abstraction of the traffic flow model and implementation assumptions with performance validation are also treated in this chapter 3. Chapter 4 presents the proposed traffic simulator architecture, its essential visualisation, analysis components, and a detailed description of how the prototype simulator was conceived and implemented based on the mathematical model and high-level abstractions. This chapter also discusses the simulator's actual implementation, testing procedures, validation process, and some experiments conducted. The details of the experiments that estimate the benefits and drawbacks of the research hypothesis using different traffic scenarios and assessment benchmarks are presented in chapter 5.

The new research direction looks at the autonomous vehicle integration process and how to address the attendant mixed traffic problems. In a conceptual framework, the different car behavioural pattern is defined, and an integration the framework was presented that addresses the unique characteristics of each vehicle type. Very few studies investigated the traffic parameter responsible for the longitudinal and lateral vehicle behaviour in a car-following model to accurately model the real behaviour of a mix of human and autonomous vehicles. The existing microscopic car-following and lane-changing models used two separate models to simulated the lateral and longitudinal vehicular interaction. Besides, a mixed vehicle scenario involves human drivers tending to make aggressive and unpredictable movements. A single model that effectively describes all driving behavioural parameters is not available, though some effort has been made. Generally, the road intersection region is considered a significant traffic congestion source because traffic from different routes converges to share the intersection space before joining another road segment to their destination. An efficient strategy to control and optimise mixed-traffic flow behaviour at road intersections is essential as a baseline for the autonomous vehicle integration process. The results obtained are based on the investigation of the performance of the three traffic control strategies using an intersection capacity utilisation of 50% and 100%. It is observed that an increase in the ratios of autonomous vehicles is directly proportional to the traffic flow performance, and this supports the research hypothesis.

Following this detailed investigation in mixed traffic performance, listed below is a summary of the findings:

- This macroscopic traffic flow investigation shows that it is theoretically possible that a significant increase in the performance of human-driven vehicles is expected with an increase in the proportion of autonomous vehicle ratio. Along with the expected increase in traffic flow quality, the intersection capacity efficiency increases with an increase in autonomous vehicle ratio.
- Motivated by the fact that AVs react faster, the road intersection capacity has increased when compared to maintaining the same safe distance for both vehicle categories.
- It is assumed that the vehicle's safe distance of HV represents a random parameter distribution, and there is no exact value where traffic flow stops being stable and breaks down if this value is exceeded. However, the investigation shows that the following factors: vehicle characteristics, human reaction time, safe distance, and traffic stability, are responsible for the intersection capacity throughput:
  - Shortening the distance headway of AV's. With a reduced gap between AVs and the preceding vehicles, driving comfort is maintained because of the precision driving features of AVs.
  - Intersection capacity is increased with an increase in traffic stability which is described with the reduction in the number of brakes experienced
- The traffic flow stability describes by the average braking, mean reaction time and average speed associated with each traffic control method describes how stable the traffic flow is.

7.2 Conclusion

Status of the Research The mix-traffic flow experience comprises of a vast scope of complex activities, ranging from vehicle behaviour: travel speed, time, volume, density, and principles underlying intersection crossing, gap acceptance, acceleration, and deceleration. By observing the vehicle's movement in a traffic stream, collecting traffic data, and synthesising the traffic flow characteristic through the developed mathematical model, one would understand mixed traffic flow behaviour phenomena. The developed traffic model prototype appears to be realistic in testing traffic theories conducted with the generated data. The model's performance in different traffic conditions and scenarios has been conducted, with the results analysed. The model has been calibrated with real traffic parameters to improve its efficiency and optimal performance with good suggestion for future work direction.

Presentation from this research

- 3rd November 2021: Ph.D. Workshop - Presented my research work on " Node Reservation Intersection Control Management - A Strategy for Autonomous and Human-Driven Cars Integration."
- 19th June 2019: Three Minute Thesis Competition 2020 @ Doctoral Research Conference
- 5th April 2019: OpenSource AI Ph.D. Workshop (presentation title: Integration of Autonomous and Human-Driven Cars).

Publication from this research

Conference Papers- UK Computing Conference, March 2022 (Awaiting Decision)

- Speed Harmonisation Strategy for Human-driven and Autonomous Vehicles Co-existence.
- Node Reservation Intersection Control Management - A Strategy for Autonomous and Human-Driven Cars Integration.

Journal Papers (Making corrections on reviewers feedback - IEE and Hindawi)

- Road Intersection Coordination Scheme for Mixed Traffic (Human Driven and Driver-less Vehicles) -A Systematic Review
- The Effect of Autonomous Vehicles on traffics.

This investigation would contribute to an improved understanding of the mix-traffic flow system and compare the state-of-the-art control strategies with its alternative. Node reservation method for a mixed traffic integration is proposed. Implementing the human drivers' aggressive behaviour is challenging to describe, and challenging to have a clear definition for aggressive driving because of two factors: circumstance, and scenarios, which can lead to aggressive driving. The characteristics of mix-traffic flow depend on on-road features, vehicle performance characteristics, and road user behaviour. However, the background and narrative of the research area have been presented with this thesis structure. With the developed model characteristics, one can understand the mix-traffic flow phenomena and use an alternative control strategy to reduce the problem commonly met within road traffic intersections. AV and HV flow pattern performance with mix-traffic control strategies at a road intersection has been investigated. Failure to effectively model the drivers' behaviour is a significant constraint of the macroscopic and microscopic traffic flow modelling.

The intersection capacity analysis table in 6.2 indicate the performance of the 3 different traffic control strategy studied, recorded over 3600 seconds. Looking at the table section for 50:50mix scenario, the RN control method performed better with a capacity of 397.3 cars per hour against 261 and 147.2 for CAWS and TL, respectively. Suggestion for this behaviour might be that the benefit of the vehicle platooning system appears more advantages for heavy traffic. In this thesis, a traffic scheduling algorithm which synchronises the behaviour of autonomous and human-driven vehicles at road intersection is developed. It is established that increasing the ratio of the autonomous vehicle intersection efficiency increases by an and by the varying the safe distance. This study presents the effect of driverless cars on human-driven vehicles at a road intersection using distance headway. The vehicle occupation time is observed as a mathematical relation relating the different mixed vehicle occupation time. From our findings, a vehicle ratio occupancy pattern is developed as a useful evaluation tool in the integration process of autonomous vehicles. Efficiency and reliability are critical when developing systems in the current world. The simulation results from this study show that from mixing AVs and HVs, the road capacity could be increased. Also, vehicles forming a platoon improved the stability and efficiency of the traffic flow. The mixed-traffic management strategy aims to use the RN and distance headway to judge vehicle position and predict its movement with the intersection zone. This strategy follows the safe distance model to keep each car safe from the other (the safe distance depends on car type). The potential impact of integrating autonomous vehicles to co-exist with human-driven vehicles on the road is examined. The assessment is carried out under parameters that align with the realistic operating environment of the city traffic flow system. The feasibility of a hybrid mixed-traffic model has been demonstrated in this thesis.

The novelty of the node reservation method is that it tackles vehicle collision by assigning individual vehicles sequentially to the intersection reservation nodes. Secondly, by addressing a 2-dimensional traffic flow problem in heterogeneous traffic using an existing 1-dimensional car-following model and compensating for unexpected changes in human-driven vehicles. The algorithm controls the mix-traffic variable speed bottleneck to smooth the traffic flow effectively. This proposed model entails interpolating human-driven and autonomous vehicles' behaviour with distance headway adjustment using the acceptance safe distance model. The above strategy has been implemented on the developed model and calibrated with realistic parameters, vehicle distribution, and vehicle ratio mixes. The concept of the node reservation method appears to be efficient as it centrally synchronises both AH and HV parameters simultaneously. Developing related traffic technologies to support the autonomous vehicle integration process is essential for the effective utilization of autonomous vehicles' benefits. As an alternative to traffic problems, autonomous vehicles can share car movement parameters in real-time and improve HV performance. The feature of real-time traffic parameter sharing in AV makes predicting vehicle velocities in managing traffic possible. This thesis provides scientific support for the integration plan of autonomous vehicles and a mixed traffic control system. It will improve mixed-traffic efficiency, mitigate traffic congestion at road intersections, and provide technical support for future research in traffic control systems. A mix of human-driven and automated vehicles is gradually becoming the norm around the world. The large-scale advancement and application of new technologies in vehicle and traffic management will greatly promote urban traffic control systems.

In conclusion, the work done so far represents steps towards a system of safe and efficient mixed traffic management schemes to aid the autonomous vehicle integration process. It is a fundamental goal as reliance on these autonomous vehicles is ever increasing. This project's objectives have been identified with node reservation among the feasible solution to AVs integration. Autonomous vehicles have come to stay and co-exist with human-driven vehicles inevitable. Towards this end, the node reservation system is a promising method of managing traffic mix. The experimental results generated from the proposed mixed traffic simulator show some promise to produce a traffic schedule that will outperform the state-of-the-art mixed traffic environment management. The traffic speed performance under the different traffic condition suggests that the reservation node method outperform the other two methods with an average of 22.59mph. The minimum and maximum, and average speed is shown in Table 6.3, where the traffic light control has 5.75mph, and the RN has 22.59mph with a total vehicle of 298 used for the observation. There is a significant throughput improvement in a mixed traffic environment when the distance headway of autonomous vehicles is adjusted in supporting the research hypothesis. This hypothesis was reasonable, given the small distance headway associated with autonomous vehicles and its expected improvement in a mixed environment's human-driven vehicles' performance.

7.3 Future Work

Node reservation intersection control appears to be an efficient and cost-effective method to improve mix-traffic performance for autonomous vehicle emergence. The following significant categories are the areas that need some research improvement from future researchers:

Drivers Models

- This work could be extended to incorporate the drivers' decision to accept or reject an already assigned reservation node before committing the vehicular manoeuvre.
- Mixed traffic fundamental models such as drivers' behavior and social force models could be integrated with car-following and lane-changing models to efficiently address the behavioural challenges of human and autonomous vehicle co-existence.
- The mixed traffic situations necessitate a re-look into the factors that influence the safe distance behaviour at a road intersection.

Vehicle Models

- Consideration of varying vehicle lengths to reflect the actual city traffic situation is essential for feature research direction.
- Current research work maintained a fixed lateral distance headway of the vehicle, which is not realistic, but for accuracy, the model should simultaneously describe different vehicle types' lateral and longitudinal behaviours.
- Autonomous Vehicle can be made to communicate with other objects in their environment and determine how far away a car or an object might be from it.
- Human Vehicles operated by humans can also tap into this approach by engaging the sense of sight and looking out for traffic control mechanisms though at a less precise value than autonomous cars.

Road Intersection Model

- To obtain more efficient and all-encompassing simulation results, researchers should consider using a multi-lane multi intersection road network. More complex utility functions, such as the number of stops, mean speed on a route, and multiple intersections, can be implemented in the future.
- The road capacity could be increased substantially by increasing the cooperation level between vehicles when their behaviours are homogeneous.

Traffic Flow Model

- The vehicle deceleration produced produced by the simulator could be bigger than the set parameters, indicating that a constant need to be set to address the relationship between speed and acceleration.
- The combined effect of all safe distance and reaction time distribution issues make it tough to estimate the critical distance headway in a mixed environment.
- Applying Machine Learning to control car traffic and provide more real-life physics and mistakes or realism to the cars and other objects to enable researchers to mimic real-life scenarios better.

- A drawback to the node reservation strategy approach is the non-compliance to an emergency, how the system mitigates against such a situation.
- Because of the combined effect of all safe distance and reaction time distribution issues, determining the critical and efficient safe distance in a mixed environment is challenging and needs to investigate on.

The emergence of autonomous vehicles has opened the door to much research in mixed traffic control systems. There are still further development possibilities to facilitate the integration regime. The heterogeneous behaviour of mixed traffic makes the study of its co-existence complex considering the underlining difference in the behaviour of the two cars category of vehicles.

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