ISOLATED SIGNALISED INTERSECTION OPTIMISATION UNDER MIXED TRAFFIC FLOW

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ISOLATED SIGNALISED INTERSECTION OPTIMISATION UNDER MIXED TRAFFIC FLOW

by

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LIST OF ABBREVIATIONS

CF	Continuous Flow Intersection
DLT	Displaced Left-Turn
GA	Genetic Algorithm
LTB	Left-Turn Bypass
NSGA II	Non-dominated Sorting Genetic Algorithm II
NSGA III	Non-dominated Sorting Genetic Algorithm III
SM	Superstreet Median Intersection
SUMO	Simulation of Urban Mobility
UAIDs	Unconventional Arterial Intersection Designs

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PENGOPTIMUMAN PERSIMPANGAN TERASING BERLAMPU ISYARAT BAGI ALIRAN TRAFIK BERCAMPUR

ABSTRAK

Kesesakan lalu lintas telah menjadi masalah kritikal. Banyak kajian telah memberi tumpuan kepada pengoptimuman prestasi persimpangan di bawah aliran trafik homogen yang merujuk kepada keadaan di jalan raya yang mana dimensi kenderaan tidak banyak berbeza antara satu sama lain, dan kenderaan berkelakuan sama dari segi kelajuan dan jarak mengikut. Walau bagaimanapun, hanya segelintir kajian yang mempertimbangkan aliran trafik bercampur. Aliran trafik bercampur sangat stokastik dan tidak linear dengan banyak komposisi trafik. Ini mengehadkan penggunaan kaedah terdahulu dalam skala besar. Oleh itu, kajian ini mengoptimumkan prestasi persimpangan di bawah aliran trafik bercampur daripada dua aspek: susun atur persimpangan dan pelan lampu isyarat. Untuk susun atur persimpangan, kajian ini mempertimbangkan suatu persimpangan dengan pintasan belok kiri satu lorong sedia ada. Untuk meningkatkan prestasi persimpangan, belok kiri dua lorong alternatif susun atur persimpangan pintasan dicadangkan. Kajian simulasi untuk membandingkan persimpangan yang dicadangkan dengan dua susun atur persimpangan lain di bawah aliran trafik campuran dijalankan. Keputusan menunjukkan bahawa prestasi persimpangan yang dicadangkan mengatasi dua susun atur lain. Bagi sistem lampu isyarat, kajian ini memfokuskan masalah pengoptimuman pelan lampu isyarat pelbagai objektif untuk persimpangan terpencil di bawah aliran trafik bercampur. Keputusan menunjukkan bahawa pelan lampu isyarat yang dihasilkan oleh kaedah yang dicadangkan mempunyai kelebihan yang lebih jelas dalam mengurangkan kesesakan berbanding dengan pelan isyarat lalu lintas sedia ada. Sumbangan utama kajian ini ialah pertimbangan aliran

trafik bercampur yang mengambil kira kenderaan beroda dua dalam model. Memodelkan tingkah laku seperti perkongsian lorong antara kenderaan beroda dua membawa kepada model yang lebih tepat mewakili dunia sebenar, terutamanya di negara-negara seperti Malaysia berbanding kajian terdahulu.

ISOLATED SIGNALISED INTERSECTION OPTIMISATION UNDER MIXED TRAFFIC FLOW

ABSTRACT

Traffic congestion has become a severe problem. Numerous studies have focused on optimising intersection performance under homogeneous traffic flow, which refers to a situation on a road where vehicle dimensions do not vary much from each other and vehicles behave similarly in terms of speed and following distance. However, few studies have considered mixed traffic flow. Mixed traffic flow is exceedingly stochastic and non-linear, with numerous traffic compositions which limit the large-scale application of previously proposed methods. Hence, the intersection performance under mixed traffic flow is optimised from two aspects: Intersection layout and signal timing. For intersection layout, this study considers an existing one-lane left-turn bypass intersection. To improve the intersection performance, an alternative two-lane left-turn bypass intersection layout is proposed. A simulation study to compare the proposed intersection with the two other intersection layouts under mixed traffic flow is conducted. The results show that the proposed intersection outperforms the two other layouts. For signal timing, this study considers the multi-objective signal timing optimisation problem for isolated intersection under mixed traffic flow. The findings demonstrate that traffic signal plans yielded by the proposed method have more advantages in reducing traffic congestion compared to the existing traffic signal plans. A main contribution of this study is the consideration of mixed traffic flow by including two-wheeled vehicles in the model. Capturing behaviours such as lane sharing between two-wheeled vehicles leads to a model that more accurately represents the real world, especially in countries such as Malaysia compared to prior studies.

CHAPTER 1

INTRODUCTION

1.1 Introduction to Research Topic

Traffic congestion has become a serious social problem in major cities all over the world. With the rapid social development, the city's population and land area expanding continually. According to UN | Department of Economic and Social Affairs (2018), nearly 70% of the world's population is expected to live in urban city areas by 2050. With the rapid development of urbanisation, the original balance of supply and demand for urban transportation has been broken. Many urban cities face severe traffic congestion causing major negative effects on transportation, the environment, economy and social life. Each year traffic congestion results in billions of dollars in fuel costs (Wang et al., 2016). Transportation is a major contributor to world energy consumption, making up for 29% of global energy consumption and 24% of global CO_2 emissions (Chen et al., 2019). Urban transport problems not only damage the economy, but also cause many social problems that affect everyday life (Liu and Triantis, 2010). Managing and relieving traffic congestion is an urgent problem for cities. Nevertheless, with a shortage of available buildable area, the construction of new roads and the expansion of road metres is nearly impossible in some cities. Additionally, many existing transportation systems are not yet optimised. Therefore, optimising traffic management and control (Wang et al., 2018) is vital and could lead to cost effective solutions.

Intersections are critical in guaranteeing smooth traffic flow within a road network, and they have a significant impact on transportation system efficiency. There exist many studies that focus on optimising intersections to reduce traffic congestion at heavily congested signalised intersections. These studies mainly focus on traffic signal control optimisation and intersection layout optimisation mainly under homogenous traffic flow, which refers to a situation on a road where the dimensions of all vehicles do not vary much from each other, and vehicles behave similarly in terms of speed and following distance. Few studies consider mixed traffic flow. Mixed traffic flow in this study is defined as human-driven traffic consisting of four-wheeled vehicles such as cars, buses and lorries, and two-wheeled vehicles such as motorcycles. Mixed traffic flow is the dominant traffic flow in the real world, especially in Asian countries. Mixed traffic flow is extremely complex, random and nonlinear, which limits the world wide applicability of the methods proposed in studies that only consider homogenous traffic flow. Hence, this study aims to optimise intersection layout and traffic signal plan at isolated signalised intersections under mixed traffic flow.

1.2 Problem Statement

Rapid urban motorisation has resulted in worsening traffic congestion, and intersection optimisation has become the main bottleneck to alleviate traffic congestion. Although numerous studies have focused on optimising intersections with homogeneous traffic flow, little consider mixed traffic flow. Hence, this study considers intersection optimisation under mixed traffic flow problem from two aspects that are the intersection layout and the traffic signal plan.

(1) For the intersection layout optimisation: The rapid motorisation of cities in Malaysia has led to a dramatic increase in the number of vehicles. This has resulted in severe traffic congestion. One-lane left-turn bypass intersections are very popular

in Malaysia. An existing one-lane left-turn bypass intersection, which is located at the junction between Lebuhraya Thean Teik and Jalan Angsana, is selected as the location of our case study. This is because this intersection currently is facing severe traffic congestion, especially during the rush hours, which causes major negative effects on transportation, the environment, economy and social life. This study proposes a new layout that is an alternative two-lane left-turn bypass intersection layout. The study compares this new intersection layout with two other existing layouts under mixed traffic flow, using the traffic micro-simulation software SUMO (Simulation of Urban Mobility). The average delay, average travel time, average speed, and average number of stops are selected as the performance indicators to evaluate these three intersection layouts.

(2) For the traffic signal plan: Well-timed traffic signal plans are vital to ensure traffic smooth flow. Many studies have mainly focused on optimising traffic signal plan under homogeneous traffic flow, which refers to a situation on a road where vehicle dimensions do not vary much from each other, and vehicles behave similarly in terms of speed and following distance. However, real-world traffic flow is predominantly mixed traffic flow, limiting the widespread use of existing methods. Hence, the multi-objective signal plan optimisation problem at the isolated intersection under mixed traffic flow is considered. The objective is to acquire appropriate signal plan to enhance the intersection operational efficiency. This study proposes a hybrid approach which integrates non-dominated sorting genetic algorithm III (NSGA III) with simulation to solve this problem. NSGA-III has the advantage of producing many solutions in each iteration and is suited for solving problems that require the simultaneous optimisation of multiple objectives, unlike most traditional optimisation algorithms that only

update one solution at each iteration. The simulation software is an instrument that can precisely replicate real-world traffic conditions. In this study, SUMO (Simulation of Urban Mobility), a state-of-the-art micro-simulation software, is used to simulate and evaluate traffic signal plans. This is because that SUMO is an open source, microscopic, multi-modal traffic simulation, and it is also one of the most useful and economical tools to simulate, analyse and evaluate traffic systems. This study runs a simulation to compare the signal plan obtained from our proposed method and actual existing signal plan.

1.3 Objectives of Study

The objectives of this study include:

1. To simulate mixed traffic flow and portray vehicle characteristics (driver behaviors and interactions between different vehicles) at an isolated intersection under mixed traffic flow using SUMO.

2. To determine the effect of intersection layout design (one-lane left-turn bypass intersection, two-lane left-turn bypass intersection, and the intersection layout with no left-turn bypasses) on traffic congestion at a specifically chosen isolated intersection under mixed traffic flow using SUMO.

3. To propose a hybrid approach that integrates non-dominated sorting genetic algorithm III (NSGA III) with simulation to generate optimised signal plans at isolated intersections under mixed traffic flow to reduce traffic congestion.

4. To apply the proposed hybrid approach that integrates NSGA III with simulation to optimise signal plans at two intersections chosen in Pulau Pinang Malaysia,

implemented in Python and SUMO.

5. To compare the traffic signal plans generated by our proposed hybrid approach with existing traffic signal plans.

1.4 Significance of Study

This study focuses on optimising isolated intersection performance under mixed traffic flow, covering the intersection layout optimisation and the traffic signal optimisation.

This study is important both theoretically and practically. Theoretically this study proposes a new layout (two-lane left-turn bypass intersection layout) to relieve congestion, especially during rush hours. The study also proposes a hybrid method that integrates non-dominated sorting genetic algorithm III (NSGA III) with simulation to optimise multi-objective signal timing under mixed traffic flow. The proposed new intersection layout and the proposed multi-objective intersection optimisation method provide innovative ideas for layout optimisation and signal control under mixed traffic flow. Practically, the proposed intersection layout and signal plans obtained from our proposed hybrid method significantly reduces congestion, especially during peak hours. This study results not only provides a direct solution to alleviate urban traffic congestion, but also can serve as a useful reference for future work involving traffic planning and intersection design.

1.5 Assumptions

The assumptions for this study are:

1. The movement of pedestrians is not considered as there are no crosswalks in the intersection system.
2. Emergency vehicles such as ambulances and police vehicles are not considered.
3. The movement of motorcycles is taken into account.
4. Drivers obey all traffic rules.

1.6 Scope of Study

This study focuses on optimising isolated intersection performance under mixed traffic flow, covering the intersection layout optimisation and the traffic signal optimisation. Isolated intersection in this study refers to an intersection that is not directly coordinated with traffic signals or traffic flows of the surrounding traffic network. Traffic signal control and management at this type of intersection is focused on itself and does not take into account signal coordination at adjacent intersections.

For the intersection layout optimisation: an existing one-lane left-turn bypass intersection, which is located at the junction between Lebuhraya Thean Teik and Jalan Angsana, is selected as the location of our case study. For traffic signal optimisation: two existing left-turn bypass intersections in Pulau Pinang, Malaysia, are selected as case studies. Intersection-I is positioned at the junction of Jalan Tun Hamdan Sheikh Tahir road and Lebuh Dagangan 1 road, while Intersection-II is located at the junction of Jalan Tun Hamdan Sheikh Tahir road and Persiaran Dagangan road. The data for this study were obtained from a field survey in Penang, Malaysia.

The scope of study does not include assessing the cost effectiveness of implementing the proposed solutions. Future research could look into the financial implications to provide a more comprehensive evaluation for real-world applications.

1.7 Organization of Thesis

In Chapter 1, an overview of the research topic, problem statement, objectives and assumptions of this study is introduced.

In Chapter 2, the background of this study, basic definitions, and some related optimisation problems and some related results is introduced.

In Chapter 3, the intersection layout optimisation under mixed traffic flow problem is considered. This study first presents the most recent studies on intersection layout optimisation and corresponding results. Then the considered one-lane left-turn bypass intersection in Malaysia is described. In order to alleviate traffic congestion, this study proposes a new intersection layout, i.e., an alternative two-lane left-turn bypass intersection layout. In addition, these intersection layouts are constructed and the corresponding traffic volumes are input in SUMO.

In Chapter 4, in order to obtain reliable results, the simulation model is calibrated and validated. This study compares the proposed intersection layout with the existing the other two intersection layouts using performance indicators. The average delay, average waiting time, average speed, and average number of stop are selected as intersection layouts' performance metrics. The performance metric values are obtained through the simulation software SUMO.

In Chapter 5, the multi-objective signal plan optimisation problem for urban intersections under mixed traffic flow problem is considered. This study first constructs a multi-objective model of the optimising signal plan problem. Then it proposes a method which integrates non-dominated sorting genetic algorithm III (NSGA III) with simulation to solve the problem.

In Chapter 6, experiments to determine the appropriate mutation rate, population size and the number of iterations for each study intersection are carried out. Then using these determined suitable parameters, the experiments compare and analyse the traffic signal plans obtained from our proposed method with existing signal plans.

Finally, in Chapter 7, the conclusions of this study is presented, and then some new problems that deserve further study are proposed.

CHAPTER 2

BACKGROUND OF STUDY

2.1 Types of Conventional Intersections

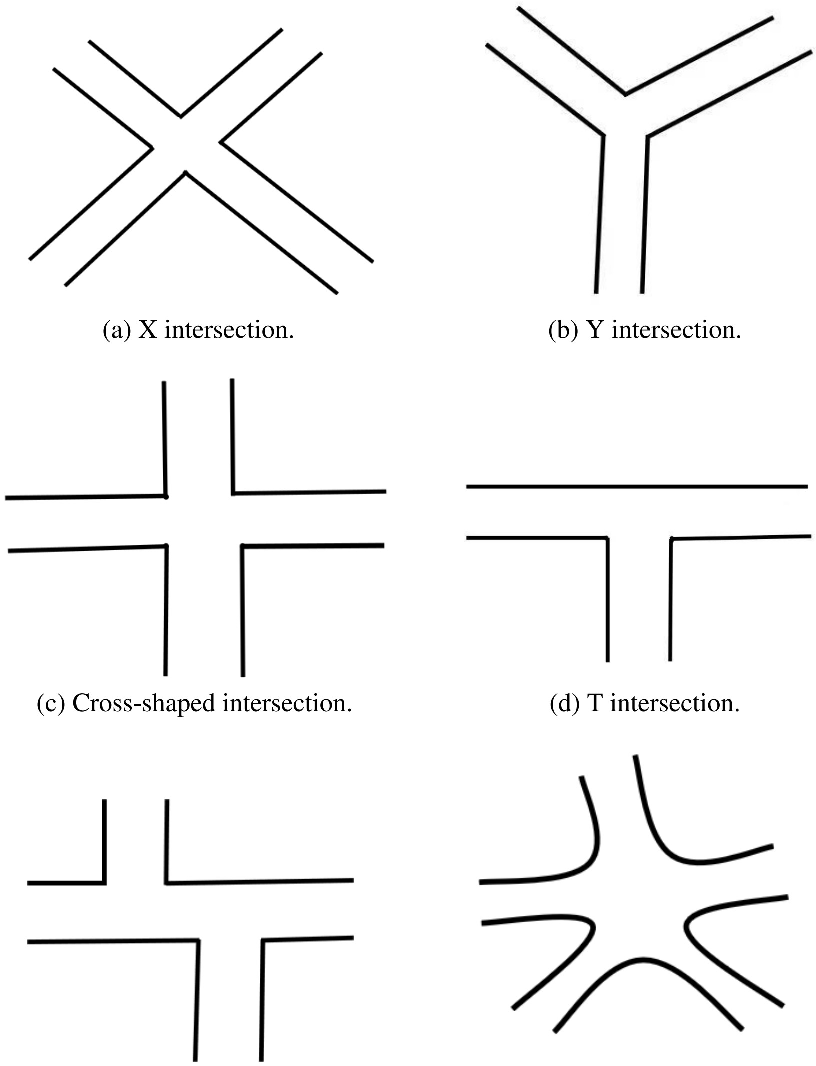
An intersection is referred to a location at which two or more roads meet. Road intersections are complex in structure, diverse in form and size, and adjacent intersections may be close to each other (Wan et al., 2019). Intersections are the foundation and core element of the road network, and play an important role in connecting roads and carrying turns (Li et al., 2018). Intersection controlling is an essential component of the transportation system, and plays a vital role in enhancing the effectiveness of the transportation system as a whole. The intersections are roughly classified into two categories: the traditional intersection and the unconventional arterial intersection.

2.1.1 Traditional intersections

The main types of traditional traffic intersections are X intersections (as shown in Figure 2.1a), Y intersections (as shown in Figure 2.1b), the cross-shaped intersections (as shown in Figure 2.1c), T intersections (as shown in Figure 2.1d), the staggered intersections (as shown in Figure 2.1e), and the multi-way intersections of five roads or more than five road intersections (as shown in Figure 2.1f).

2.1.2 Unconventional arterial intersection designs

With urbanisation continuing and economical development, the demand for vehicles is increasing and traffic congestion is becoming serious. In order to alleviate the worsening traffic congestion, unconventional arterial intersection designs (UAIDs) were proposed as a novel method. By directing left turns away from the main intersec-



(a) X intersection. (b) Y intersection. (c) Cross-shaped intersection. (d) T intersection. (e) Staggered intersection. (f) Multi-way intersection.

Figure 2.1: Traditional intersection types.

tion, unconventional arterial intersection designs aim to shorten travel times and delays at the intersection (Jagannathan and Bared, 2004). UAIDs mainly include the super-street median intersection (SM), the displaced left-turn intersection (DLT) (Dhatrak et al., 2010), and the left-turn bypass intersection (LTB), described as follows:

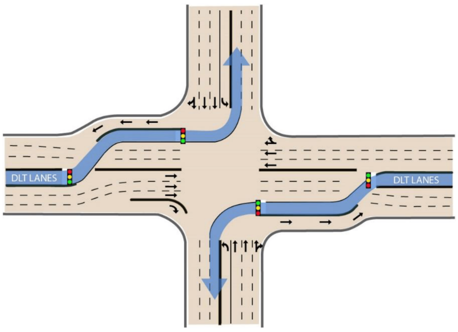
- Displaced left-turn intersection (DLT): DLT is also known as the continuous flow intersection (CF) (Jagannathan and Bared, 2004; Shokry et al., 2020). The DLT is a two-phase intersection system which comprises one main intersection and four subordinate intersections. One of the most significant innovations of DLT is that it allows for simultaneous movement of through traffic and traffic turning left at the main intersection (Reid and Hummer, 2001). The layout of DLT is shown in Figure 2.2a.

- Left-turn bypass intersection (LTB): LTB has four left-turn bypasses which allow vehicles to turn left for every direction (Chow et al., 2021). A bypass is a traffic road constructed at an intersection so as to enable vehicles to turn left without entering the intersection. Thus, these left-turn vehicles are not under the control of traffic signals. The layout of LTB is shown in Figure 2.2b.

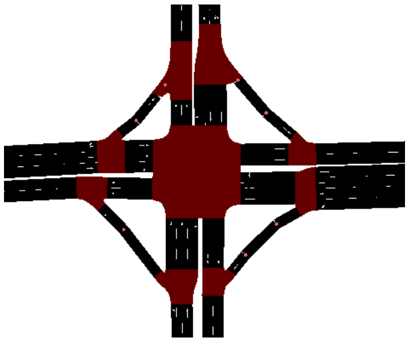
- Superstreet median intersection (SM): SM is also known as restricted crossing U-Turn intersection (RCUTI). The main characteristic of SM provides a additional break which permits traffic signals on opposite directions of the arterial to work separately (Jagannathan and Bared, 2004; Shokry et al., 2020). The layout of SM is shown in Figure 2.2c.

2.2 Traffic Signal Control Systems

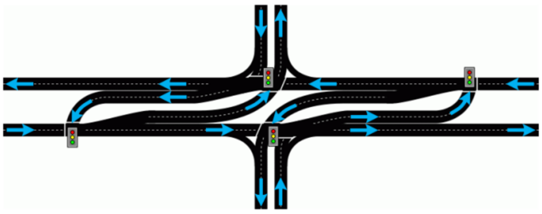
The traffic signal control system plays an important role to reduce traffic congestion in transportation systems. The signal control systems can be divided into three types: pre-timed (fixed time) signal control system, actuated signal control system, and adaptive signal control system. Most signalised intersections in developing countries and developed countries (Chen et al., 2016) are equipped with fixed-time controller and actuated controllers.



(a) Displaced left-turn intersection layout (Qu et al., 2020).



(b) Left-turn bypass intersection layout.



(c) Superstreet median intersection layout (Superstreet Median Intersection, 2021).

Figure 2.2: Unconventional arterial intersection designs.

- Pre-timed (fixed time) control system (Allsop, 1971) : Pre-timed signal control systems use historical traffic low data to calculate the suitable time for traffic signal plans. All of the control parameters (phase green duration, offsets, cycle length and phase sequence) in a pre-timed control system are determined based on previous traffic data (Araghi et al., 2015). A pre-timed signal control system is not able to react to fluctuations in traffic flow. This means that it cannot cope with unexpected traffic conditions. Pre-time signal control is widely employed in practice (Köhler and Strehler, 2015). In this study, the problem of the intersection optimisation with pre-timed signal control is considered.

- Actuated signal control system (Shirvani Shiri and Maleki, 2017; Zhang and Wang, 2010): With the looming availability of sensors and computer technology, these optimizations laid the foundation for traffic-actuated signal control systems. In traffic-actuated control systems, signal control parameters like phase green durations, offsets, cycle length and phase sequence are dynamically changed to adjust for changing real-time traffic conditions reported by detectors (Grether, 2014). However these changes are still limited by many preset control parameters (e.g., maximum green split and minimum green split, etc.), which do not respond to changing traffic conditions. Actuated control has been widely employed, due to its flexibility in adjusting phase green durations, offsets, cycle length and phase sequence to accommodate traffic change (Zhang and Wang, 2010). However, traffic actuated signal system may become unstable at the network level and thus perform much worse than fixed time control in some situation, if they do not obey some mathematical constraints (Lämmer and Helbing, 2010).

- Adaptive signal control system (Zhu et al., 2019): This system is designed to sense real-time changes in traffic flow based on vehicle detectors on the road, and provides an adaptive timing plan. The adaptive signal control system can change the signal control parameters (phase green splits, offsets, cycle length and phase sequence) in response to fluctuation in real-time traffic flow (Wang et al., 2018), which can improve intersection operation efficiency. Compared to non-adaptive traffic signal control systems, the adaptive traffic signal control system is superior in relieving traffic congestion. However they require a substantial long-term investment due to their high implementation and maintenance costs, making them unfeasible for widespread adoption in developing countries (Zhu et al., 2019). More than 20 self-adaptive traffic control systems have been created by transportation research institutes and businesses throughout the world, but fewer than half of these systems have been implemented (Stevanovic, 2010).

2.3 Mixed Traffic Flow

2.3.1 Mixed traffic flow definition

To the best of our knowledge, there are very few studies that have provided a definition of mixed traffic flow. Mixed traffic flow was defined by Qi et al. (2020), Yu et al. (2019), and Zhu and Zhang (2018) as traffic which consists of human-driven and autonomous vehicles. In addition, mixed traffic flow was defined by Yu and Zhou (2019) as human-driven traffic consisting of motor vehicles, non-motorized vehicles, and pedestrians. Mixed traffic flow in this study is defined as human-driven traffic consisting of four-wheeled vehicles such as cars, buses and lorries, and two-wheeled vehicles such as motorcycles.

2.3.2 Mixed traffic flow characteristics

Mixed traffic flow is complex, random and nonlinear in real life. There are many static and dynamic characteristics in mixed traffic flow. Therefore, simulating mixed traffic flow is very difficult and challenging. Along with four-wheeled vehicles, there are also a lot of two-wheeled vehicles (motorcycles) in mixed traffic flow. This is a typical feature in metropolitan areas, especially throughout Southeast Asia. Small-sized vehicles such as motorcycles have unique characteristics, due to their high degree of maneuverability and compact size. Sometimes these vehicles do not obey the same physical traffic rules as other large vehicles. Small-sized vehicles may accelerate and decelerate more quickly, maneuver between lanes or in a shared lane, move to adjacent lanes, and even cause intense traffic on a road when halted at red lights (Izadi et al., 2021; Maini and Khan, 2000).

2.3.3 Previous studies on mixed traffic flow at isolated signalised intersection

Studies involving both isolated intersections and mixed traffic flow have gradually increased in recent years. Ingale et al. (2020) assessed driver decision behaviour at an isolated signalised intersection under mixed traffic flow using questionnaire survey in India. Investigation has shown that the ways drivers behave at intersections are impacted by demographic variables such as age, gender, education level, driving experience, frequency, and income. Yu and Zhou (2019) studied traffic features of non-motorized vehicle, pedestrian and right-turning vehicle without any disturbance at an isolated signalised intersection under mixed traffic flow. The conclusions can serve as a good reference for optimising intersection design and traffic signal timing to improve the safety at the intersection under mixed traffic flow. Biswas et al. (2018) presented a model for calculating saturation flow at an isolated signalised intersection under mixed traffic flow. It has been proved that the proposed approach outperforms traditional regression techniques. Saha et al. (2017) proposed an improved delay model for an isolated signalised intersection under mixed traffic flow. It was found that the proposed model outperforms existing methods for mixed traffic flow as well as homogeneous traffic. The existence of these studies show that there is interest in expanding the field of an isolated signalised intersection under mixed traffic flow.

There have been few studies that optimise signal plans at an isolated intersection under mixed traffic flow. Wei et al. (2022) developed an adaptive traffic signal control to optimise the operational and safety performance at an isolated intersection under mixed traffic flow. The simulation showed that the developed signal control substantially decreased the average delay and conflict rate, compared to pre-time and traffic actuated control. A novel extended ant colony labour division model for traffic signal timing under mixed traffic flow was proposed by Jiang et al. (2020). The results showed that based on current road conditions and suitable traffic signal timing, the proposed model can significantly enhance road traffic capacity. In Van et al. (2020), a fuzzy traffic signal control system was developed for an isolated intersection under mixed traffic flow. It was found that the developed method significantly decreased the average delay compared to the existing control system. In order to alleviate traffic congestion at an isolated intersection under mixed traffic flow in Vietnam, Vuong et al. (2019) proposed an optimum cycle model. The results showed that the proposed model remarkably decreased average delay by 23.9%. Lan and Chang (2014) proposed an optimisation model for optimising traffic signal plans at isolated intersections under mixed traffic flow. The results showed that the proposed model is effective in relieving traffic congestion.

2.4 Traffic Simulation

Traffic simulation is an important technical method for designing, analyzing, and evaluating intersection operation efficiency. Traffic simulation is the process of using modern computer technology to construct a computational model to replicate a real traffic system. A low-cost and practical tool for studying traffic flows, traffic simulation softwares are a crucial tool for researchers (Bieker-Walz et al., 2017). Conducting traffic congestion experiments manually in real life would be incredibly challenging, costly, and potentially dangerous. Simulation is largely regarded as one of the most effective tools for assessing traffic flow. As micro-simulation models are cost-effective and time-efficient, they have been widely utilised to test and evaluate innovative intersection geometric designs and new traffic control choices before to field deployments (Autey et al., 2013).

2.4.1 Application of SUMO in traffic simulation

SUMO (Simulation of Urban Mobility), a state-of-the-art micro-simulation software, is used to simulate, evaluate and analyse intersection layouts and traffic signal control system. SUMO is an open source, microscopic, multi-modal traffic simulation. SUMO makes it feasible to model traffic systems including cars, public transportation, and pedestrians. The SUMO interface is showed in Figure 2.3. Due to its

Figure 2.3: SUMO simulation software interface.

advantages, SUMO is becoming more and more popular for modelling and simulating traffic. To the best of our knowledge, Bouktif et al. (2021) proposed an approach in adapting a hybrid deep reinforcement learning which used SUMO to simulate traffic flow. The simulation results showed that the proposed approach significantly reduced queue length and travel time, compared with intelligent traffic signal control system based on deep reinforcement learning. Mahmood et al. (2019) developed a two-stage fuzzy logic system minimize the average waiting time and utilised SUMO to simulate traffic. The simulation results revealed that the average vehicle waiting time reduced by nearly 20 seconds, implying that the proposed method was superior to the fixed time control system. Other applications of SUMO can be found in Chow et al. (2021), Celtek et al. (2020), and Liu and Zuo (2020).

2.4.2 Application of other simulation software in traffic simulation

Other than SUMO (Simulation of Urban MObility), there are many other simulation software that have been successfully applied in the field of transportation. Shokry et al. (2020) compared the displaced left-turn (DLT) intersection and superstreet median (SSM) intersection with existing conventional signalised intersections. VISSIM, a microsimulation software, was utilized to accomplish this study objective. The simulation results showed that the performances of the proposed DLT intersection and SSM intersection were better than their conventional counterparts. Guo et al. (2019) proposed a model for optimising area-wide traffic signal timing under user equilibrium traffic, and GA is used to determine the model solution. PARAMICS, a simulation software, was utilised in this study. The results showed that applying the proposed model for area-wide signal timing optimisation reduced through and turning movement delays. Li et al. (2017) employed an improved GA to handle the issues of multi-intersection signal optimisation in real time. DISCO traffic simulation software was used for numerical simulation experiment. The results showed that the improved GA required 38% less search time and 1/3 fewer iterations compared to the standard GA.

In this study, SUMO is chosen to conduct our simulation experiment, as SUMO is an open-source and free tool.

2.5 Genetic Algorithm

2.5.1 Definition of genetic algorithm

The genetic algorithm (GA), is a heuristic search tool that was motivated by the process of biological evolution. GA were first introduced by Holland (1992). The basic idea of GA is to draw on the law of biological evolution to achieve superiority, so that the problem approaches the optimal solution step by step. Unlike the majority of conventional optimisation algorithms, which only update a single solution at each iteration of the process, genetic optimisation processes have the advantage of generating many solutions in a single iteration based on a population approach. GA is mainly used to solve optimisation problems that are difficult to solve using traditional methods.

2.5.2 Integration of GA and simulation in optimising signal plan

The integration of GA and simulation methods has been successfully applied to address traffic signal timing problems. The relevant studies in recent years are given, mainly from two aspects: isolated intersections and multi-intersections.

- For isolated intersection: Chow et al. (2021) used a method which integrates GA with SUMO to optimise traffic signal plans considering different traffic volumes (low, medium, and high traffic volume) at an isolated intersection. The results showed that compared with the traditional method based on Webster's formula, the proposed method had more advantages, especially in high traffic volume. Liu and Zuo (2020) proposed a fuzzy control method for optimise traffic signals at an isolated intersection, which was implemented by using GA to optimise the fuzzy control system. In this study, SUMO was used to simulation. The results showed that the proposed fuzzy control was able to effectively reduce the average delay time of vehicles and improve the capacity of the intersection. Park et al. (1999) proposed a method, based on GA and mesoscopic traffic simulator, to optimise the traffic signal plan at an isolated intersection under oversaturated conditions. The results indicated that traffic signal plans obtained by the proposed method have obvious advantages in terms of queue time, compared to signal plans obtained by the TRNASYT 7F, a traffic simulation software.

- For multi-intersection: Guo et al. (2019) provided a model for optimising area-wide traffic signal timing under user equilibrium traffic, and GA is used to figure out the model solution. PARAMICS, a simulation software, was utilised in this study. The results showed that applying the proposed model for area-wide signal timing optimisation can reduce through and turning movement delays. Li et al. (2017) employed an improved GA to handle the issues of multi-intersection signal optimisation in real time. DISCO traffic simulation software was used for numerical simulation experiment. The results showed that the improved GA required 38% less search time and 1/3 fewer iterations compared to the standard GA.

The integration of other meta-heuristic algorithms and simulation methods also has been successfully applied to address some traffic signal timing problems. Celtek et al. (2020) used the particle swarm optimisation algorithm to optimise traffic signal plans at an isolated intersection. SUMO was used to evaluate and test traffic signal plans obtained from proposed method. The results showed that the particle swarm optimisation algorithm was successful in optimising traffic signals. Mihăiţă et al. (2018) used 3D mesoscopic simulation and evolutionary algorithms to optimise multi-objective traffic signal plans at isolated intersection to minimise average travel time. The proposed optimisation approach significantly decreased average travel time by 21 seconds.

2.6 Optimising traffic signal plans at isolated intersections

Optimising traffic signal plans can significantly improve operational performance at signalised intersections. This study focuses on isolated intersections in this study because that is the traffic signal system commonly used in Pulau Pinang. Isolated intersection in this study refers to an intersection that is not directly coordinated with traffic signals or traffic flows of the surrounding traffic network. Traffic signal control and management at this type of intersection is focused on itself and does not take into account signal coordination at adjacent intersections. Studies involving both isolated intersections and traffic signal optimisation have gradually increased in recent years (Jamal et al., 2020; Mao et al., 2019; Wei et al., 2022). In this study, the problem of optimising traffic signal plan with pre-timed signal control system at an isolated intersection is considered.

2.6.1 Mathematical approaches

Many mathematical approaches have been successfully applied to solve traffic signal optimisation at isolated intersections. An early study by Yulianto (2003) applied fuzzy logic to solve a traffic signal control problem at an isolated intersection under mixed traffic flow in Indonesia. Lan and Chang (2014) proposed an optimisation model for optimising traffic signal plans at isolated intersections under mixed traffic flow. Vuong et al. (2019) proposed an optimum cycle model to alleviate traffic congestion at an isolated intersection under mixed traffic flow in Vietnam. Van et al. (2020) developed a fuzzy traffic signal control system for an isolated intersection under mixed traffic flow. Jiang et al. (2020) proposed a novel extended ant colony labour division model for optimising traffic signal plans at an isolated intersection under mixed traffic flow. Wei et al. (2022) developed an adaptive traffic signal control to optimise the operational and safety performance at an isolated intersection under mixed traffic flow. The existence of these studies shows that there is interest in the field involving traffic signal optimisation and mixed traffic flow.

Other approaches also include meta-heuristic methods combined with simulation tools which have been successfully applied to solve traffic signal optimisation problems. Gökçe et al. (2015) employed particle swarm optimization algorithm combined with a micro-simulation tool to optimise traffic signal plans with the objective of minimise travel time through the roundabout. Dabiri and Abbas (2016) and Panovski and Zaharia (2016) also utilised particle swarm Optimization algorithm combined with a micro-simulation tool to optimising traffic signal plans at intersections. Jintamuttha et al. (2016) utilised bat algorithm combined with SUMO (a micro-simulation tool) for optimising traffic signal plans at a crowded intersection in Bangkok. There also exists a study that utilised distributed ant colony algorithm combined with micro-simulation tool for optimising traffic signal plans (Elgarej et al., 2016). All of the aforementioned studies demonstrate the effectiveness of the combination of simulation and meta-heuristics for traffic signal optimisation. However, these studies that optimise traffic signal plans have not considered mixed traffic flow. In recent years, evolutionary algorithms like the genetic algorithm (GA) have become popular in solving traffic signal optimisation. This is because unlike most optimisation approaches that only generate one solution at each iteration (Deb, 2011; Konak et al., 2006), evolutionary algorithms which run on population method can generate multiple solutions in a single iteration.

2.6.2 Genetic algorithm

Due to it's efficiency, genetic algorithm (GA) has become popular in solving optimisation problems. GA has been successfully applied to solve traffic signal optimisation problems. Tan et al. (2016) used GA to optimise traffic signal plans to reduce the average delay at a cross intersection under oversaturated conditions. Li et al. (2018) used a GA-based approach to solve their intersection control optimisation problems. Mao et al. (2019) used GA to optimise traffic signal plans at an intersection under non-recurrent traffic incidents. All results showed that the traffic signal plans obtained from GA or GA-based approachs have obvious advantages.

The above studies have focused on homogenous traffic flow, which refers to the situation where dimensions of the vehicles do not vary much from each other, and vehicles behave similarly in terms of speed and following distance. Few studies have considered using GA to optimise traffic signal plans at an isolated intersection under mixed traffic flow. Recent years, Jamal et al. (2020) utilised GA and differential evolution algorithm to optimise the signal plans at isolated signalised intersections under mixed traffic flow. This study only considered optimising over a single objective.

Our proposed study considers optimising over multiple objectives.

Optimising traffic signal plans often requires taking into account multiple objectives such as travel time, speed, delay, number of stops, capacity, queue length, and exhaust emission. Non-dominated sorting genetic algorithm II (NSGA II) (Deb et al., 2002) and non-dominated sorting genetic algorithm III (NSGA III) (Deb and Jain, 2013) have become popular tools for addressing multi-objective optimisation problems due to their effectiveness. Li et al. (2013) utilised NSGA II to optimise traffic signal plans at over-saturated intersections, with the objective of maximising throughput and minimising average queue ratio. Sun et al. (2016) utilised NSGA II to optimise traffic signal control at intersections, with objectives of maximising saturation and minimising delay. Zhang et al. (2022) developed an approach which hybrids constrained strategy and NSGA III to optimise multi-objective traffic signal plans, with the objective of maximising traffic capacity and minimising exhaust emission at an isolated intersection. However, these studies focus on optimising multi-objective traffic signal plans at intersections under homogeneous traffic flow, and not mixed traffic flow, which limits the widespread application of these proposed approachs. Mixed traffic flow is the prevailing traffic composition in Asian countries, like Malaysia. Thus, the multi-objective signal plan optimisation problem for the isolated intersection under mixed traffic flow is considered. This study proposes a hybrid approach which integrates non-dominated sorting genetic algorithm III (NSGA III) with simulation to solve this problem. Unlike most traditional optimisation algorithms that only update one solution at each iteration, NSGA-III has the advantage of producing many solutions in each iteration and is suited for solving problems that require the simultaneous optimisation of multiple objectives.