國立交通大學

資訊科學與工程研究所

碩士論文

考量大眾運輸優先之可適性都市交通號誌控制系統

An Adaptive Urban Traffic Signal Control System with Bus Priority

研 究 生：張慈麟

指導教授：簡榮宏 博士

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摘　　要

近年來，隨著經濟快速成長以及都市高度開發，交通壅塞已經成為各都市的主要問題，因此交通號誌控制一直是智慧型運輸系統(Intelligent Transportation System, ITS)中重要的一部分。巴士可搭載高乘客的特性使其成為非常適合都市環境的交通工具，因此巴士優先權也成為交通號誌控制系統中重要的一部分。巴士具有不同於一般車輛的特性:較多的乘客數量、巴士預計到站時間以及前後班次間隔等。先前有關巴士優先權的研究著重於減少平均等待時間，但他們並沒有同時考量到以上所提的種種巴士特性以及會對一般車輛所造成的影響。在此篇論文中，我們提出一可適性即時交通號誌控系統，藉由路邊的感測節點以及巴士上之車載機等方式收集即時交通資訊，計算出各時相所需的時間以及其所擁有的效益值和公車優先權，並依此控制交通號誌藉以減少乘客等待時間以及有效調整巴士的航班。實驗結果顯示我們的方法可以有效減少乘客等待時間以及有效改善巴士到站時間誤差以及前後班次間隔誤差。

An Adaptive Urban Traffic Signal Control System with Bus Priority

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Abstract

In recent years, with the economic development and urbanization, traffic congestion has become a serious problem in urban environments. So, traffic signal control plays a key role in Intelligent Transportation System (ITS). Particularly, bus system can carry a higher capacity of passengers, which help to relief traffic jam in cities. Thus, it is important to consider bus priority during traffic light control. However, different from ordinary vehicles, bus system has some unique features, including higher capacity of passengers, fixed routes and specific requirements on bus schedules and headways. In this thesis, we propose an adaptive traffic signal control system with bus priority. By collecting traffic information from roadside detectors and buses, we jointly consider how the above factors change buses priority and the impact to ordinary vehicles. Simulation results show that our system can significantly reduce total waiting time of both buses and ordinary vehicles and keep the schedule and headway on time.

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最後我要感謝我的家人以及眾多在這段時間中支持我走過研究生活的朋友們，感謝你們一路上的支持與鼓勵，讓我可以堅持到最後並完成人生重要的里程碑。在此，本文獻要獻給一路關懷勉勵我的家人以及朋友們。

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Chapter 1
Introduction

Intelligent Transportation System (ITS) is a system that incorporates advanced electronics technologies into transportation infrastructure and vehicles, in order to improve driving safety, transportation time, fuel consumption and services.

Traffic signal control systems [1-2] plays a key role in ITS. It improves the transportation efficiency by detecting real-time traffic information and choosing suitable strategies to adapt to different traffic scenarios. With the increasing motorization, urbanization, population growth and changes in population density, traffic congestion which increases travel time, air pollution and fuel consumption has become an important problem of the world today. An improper traffic signal control strategy may cause severe traffic jam, particular at road intersections.

The development of intelligent design in traffic light control depends on sensing techniques. In addition to traditional methods like inductive loop detectors and video vehicle detector [3], there are many advanced sensing techniques have been proposed. For instances, Wireless Sensor Networks (WSNs) [4] and Vehicular Ad hoc Networks (VANETs) [5] have been adopted in ITS in recent years which extend the sensing coverage and require less expensive cost. Furthermore, new techniques provide more detail information to achieve more sophisticated design of traffic signal control.

In recent decades, with the increasing attentions on environment protection, people have begun be aware of the importance of reducing air pollution. More and more passengers are willing to utilize public transport system instead of driving their own cars, in order to protect the environment as well as to avoid traffic congestion. Bus system is a major segment in public transport system of urban area. Bus system has several unique features different with ordinary vehicles. First, buses have higher capacity to carry more passengers (usually 20 to 35 persons) than ordinary vehicles (1 to 4 persons). It means that more people can be benefited from a waiting time decrement if we gave each bus a higher priority. Second, each bus has a fixed schedule which specifies the arriving time of the bus at each bus stop. People can save time if the bus arrived at bus stops on time. The third feature is that bus system has a specific requirement on the time interval between any two successive buses, i.e., the headway, in the same bus route. Keeping a regular headway would make the bus system more trustable and let people be more willing to take buses.

A number of methods [18]-[22] have been proposed and adopted to benefit buses. However, most of them focus only on reducing the bus waiting time and pay little attention on the features of buses mentioned above. Besides, none of them consider the impact to ordinary cars, because allocating more passing time to buses could also scarify the passing time of other vehicles. Moreover, the previous works usually assume a fixed phase sequence, which however, has little flexibility to deal with the sudden traffic changing or an approaching bus.

In this thesis, we propose an adaptive traffic signal control system with bus priority, abbreviated as ATCB. The system is based on a non-fixed phase scheme to deal with the real-time traffic changing and approaching buses effectively. At each intersection, our system uses synergic information, including the predicted waiting time per passenger, schedule delay and headway deviation of buses, to select the most suitable signal. Simulation results show that ATCB can improve the waiting time of both buses and ordinary vehicles, keep bus schedules on time and regular bus headways.

The rest of the thesis is organized as follows. In Chapter 2, we review the review various traffic signal control strategies and related works with bus priority. Then, we give an system overview and system flow in Chapter 3. The detailed descriptions of ATCB are presented in Chapter 4. In Chapter 5, we evaluate the proposed system by simulation and compare it with other methods. Finally, conclusion and future works are given in the last chapter.

Chapter 2
Related Work

In this chapter, we review the previous studies and related works .In section 2.1, we introduce the existing traffic signal control systems. In section 2.2, we introduce some articles about bus priority.

2.1 Traffic Signal Control

There are a lot of traffic signal control systems have been implement worldwide, such as SCOOT [1] and SCATS [2]. These systems control the movement of vehicles by allocating time to the split of each phase in a cycle. Phase means a combination of green and red signals that vehicles in some specific directions can pass through the intersection at. In general, because the right-turning movement doesn't have conflict with other movement, it is included in straight-going movement. Split refers to the length of a phase in a cycle.

These traffic signal control method can be classify to two categories length of the defined plan. The systems of the first one [1], [2], [6]-[8]which make little changes on a predefined signal or choose a signal plan among a pre-specified set. The second category [9]-[15] decides to switch or not the traffic lights at each step. The first one usually focuses on long-term performance, but it can't respond well to dynamic changing like the second one.

And for the second category, it can be classified again by whether the phase sequence is fixed [9] or non-fixed [10]. Obviously, the fixed phase sequence scheme is more acceptable for drivers, because it is similar to the traditional methods we are familiar with.

A typical four-phase cycle at a four-direction intersection is shown in Figure 1, there are four phases: Phase1, Phase2, Phase3 and Phase4(straight-going in east-west, left-turning in east-west, straight-going in south-north, left-turning in south-north) to control the movement of all vehicles, and the split of each phase is 30 seconds, the total cycle time is 120 seconds.

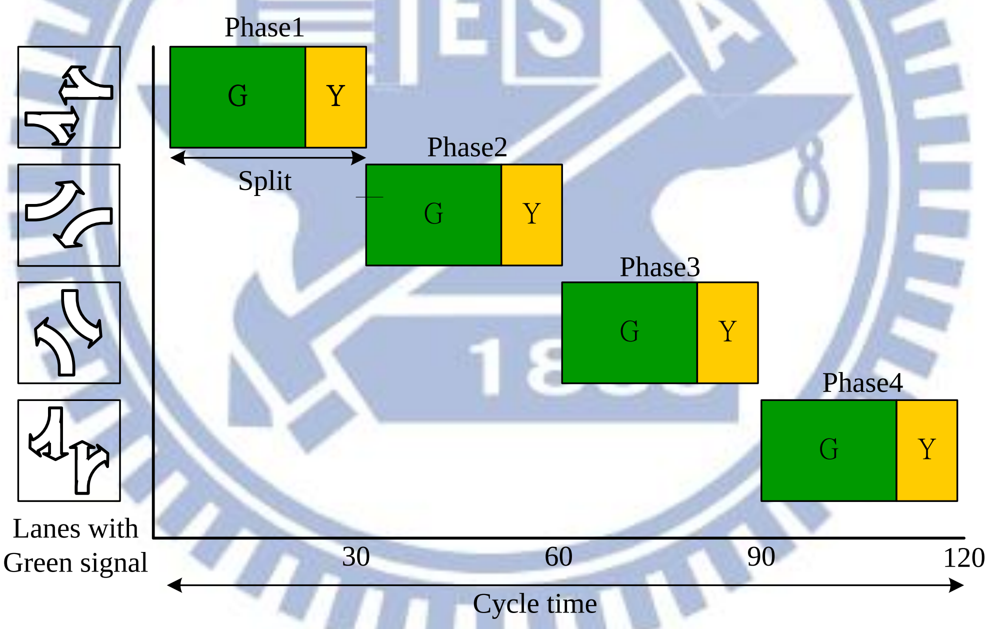

Figure 1. A typical four-phase cycle at a four-direction intersection

2.2 Bus Priority

In[18], it first summarizes how bus priority at traffic signals works within iBUS(an automatic vehicle location system): When a bus is detected on the approach of a signal, the bus send its GPS location information to the signal, so that the signal can predict the arriving time of the bus and decide whether to extend current phase for the bus. This paper then explores the effects of GPS locational errors on bus priority benefits, and we can know the impotence of accurately predicting.

In [19],this work also decides whether to extend the current phase after receiving the request of the incoming bus. But it has considered the situation of buses to design a headway-based strategy or a schedule-based strategy. So if two or more buses request the signal different phases, the signal will meet the request with the highest priority (this not considered in [18]).

Unlike [18] and [19], some works[20] adopts a fixed cycle-time plan, it allocates time to split of each phase at the start of the cycle, and it will change its plan after receive request of bus. This method can meet multiple requirements by modifying its original plan, it can not only extend the phase, but also can make the required phase occur more early. If there are two or more requests from different buses conflict, it uses a headway-schedule bus priority to decide what changing should be taken.

In [21], it changes the signal not only based on information of buses but also information of roads and ordinary vehicles. It considers several elements: First, the remaining time until the traveling bus in the current green signal phase arrives at the stop line. Second, the waiting time duration that buses in the next green signal phase stay on red signal. Third, the ratio of the effective green signal time duration to the green signal time duration, where effective green signal time duration means the duration between vehicles arriving the stop line and pass through the stop line. Fourth, the number of vehicles in the link between the intersection and the adjacent downstream intersection, if the high number refers the downstream intersection will be possible to congest. Then it uses a fuzzy method to compare these factors and decide whether to extend the current phase.

Some researches focuses on reducing passengers' waiting time for buses arriving at bus stops instead of passengers' waiting time for signals on buses. [22] shows that greater regularity benefits could be achieved through a strategy where priority for a bus is based not only on its own headway but also the headway of the bus behind.

However, these works about bus priority have some drawbacks. First, they mostly focus on reducing bus waiting time and can't concern about features of buses in the same time. Second, they may not consider the impact to ordinary vehicles by control signals for buses. Third, these works usually control signal with a fixed phase sequence which have little flexibility to change to the phase has highest priority due to the more vehicles or delay buses.

Chapter 3
Adaptive Traffic Signal Control System

In this chapter, we introduce out adaptive traffic signal control system .In section 3.1, we propose our system architecture. In section 3.2 we introduce assumptions of the system.

3.1 System Overview

As shown in figure 2, intersections collect information includes the location and speed of vehicles, headway deviation and schedule delay of buses at the intersection. In order to deal with the real-time changing of traffic flow, we adopted a non-fixed phase sequence [10] at each intersection. For each intersection, when the current phase is over, we will use the information mentioned above to calculate the passenger waiting time per unit of time in the phase, bus schedule delay ratio and bus headway deviation ratio of each phase. And we use a phase demand function to calculate the phase demand value of each phase, and then we will choose the phase with the highest phase demand value and allocate enough time to the phase. When the remaining time of the phase is over, we do the above action again.

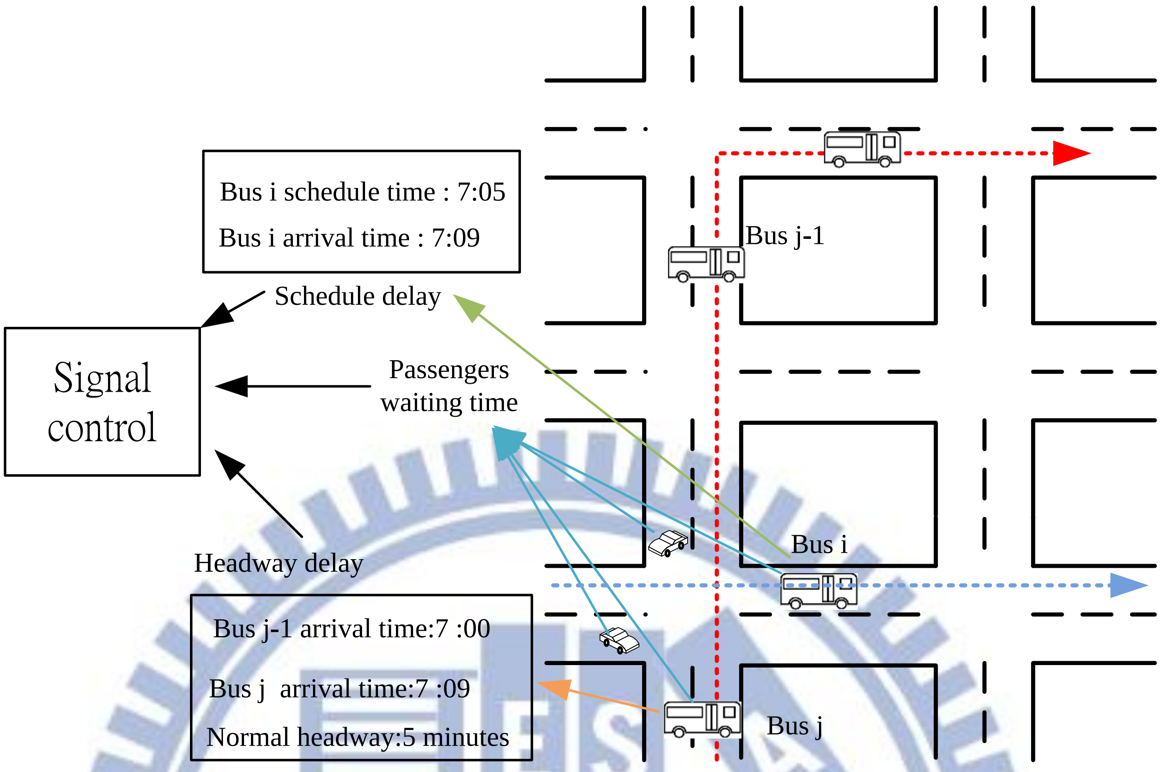

Figure 2. System architecture

The intersection model is shown in Figure 3. Each intersection has four lanes at each direction (west, east, north and south), two are approaching lanes, and two are leaving lanes. The inside lane is for left-turning vehicles, and the outside lane is for right-turning and straight-going vehicles. We install three detectors such as on each approaching lane, and they are placing in the start, middle and end of roads to detect number and speed of waiting vehicles, leaving vehicles and approaching vehicles. And we divide one lane into two areas: waiting area and forwarding area. We use the vehicles in the waiting area to determine phase length. Then we calculate passenger waiting time will be caused by vehicles has been in the waiting area and vehicles in forwarding area will arrive at waiting area then wait for the red signal. Then we calculate the bus headway deviation ration and bus headway ration of buses in the waiting area. Finally, we can determine phase demand value of each phase.

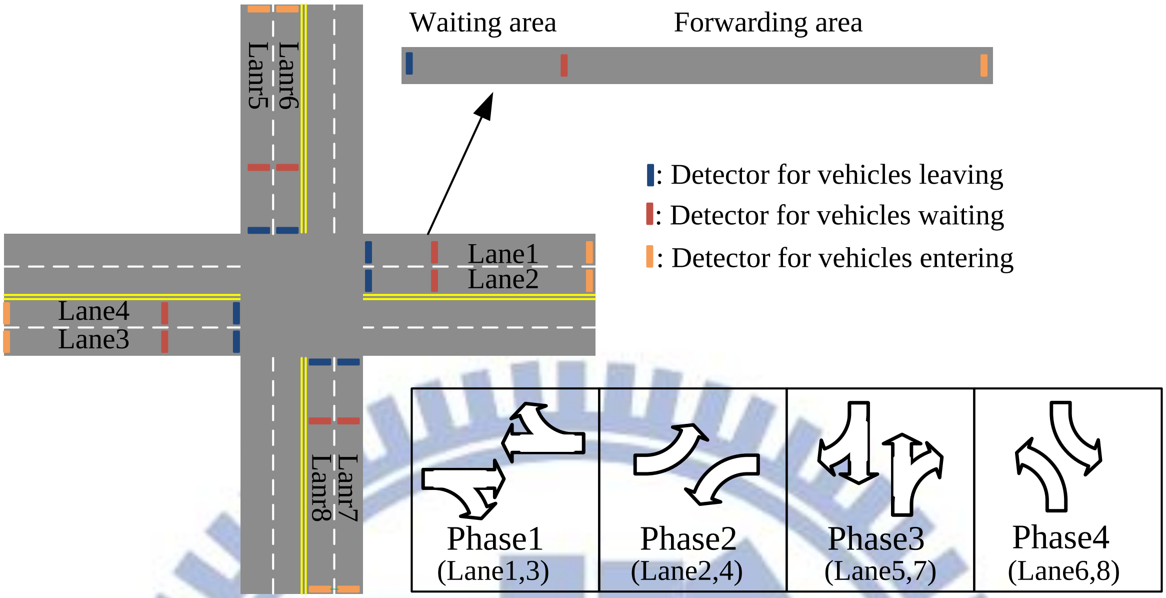

Figure 3. Intersection model

3.2 System Flow

With a non-fixed phase scheme, we should decide the phase which has higher priority to be the next phase, and allocate time to the phase. The flow chart of the system is shown in Figure 4, when the current phase is over, we will collect traffic information to calculate the necessary time of each phase first. Then we will check whether there is a phase who has not been adopted over a threshold time, and it will be selected as the next phase due to the fairness if there is overtime phase. Otherwise, we will use the information about passengers' waiting time, headways and schedules of buses to determine the demand of each phase. After we have the demand value of phases, we select the phase has highest priority to be the next switch. Finally, we control the signal switch to the deiced phase. After the phase ends, we will repeat above actions again.

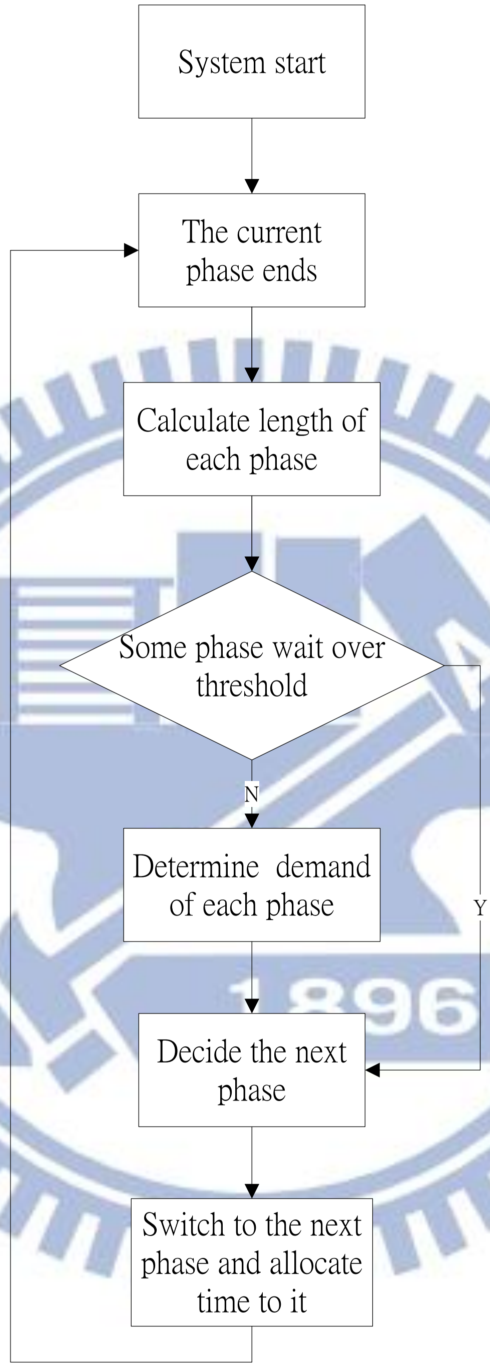

Figure 4. System flowchart

Chapter 4

System Design

We adopt non-fixed phase sequence to deal with the real-time changing of traffic flow and requests of buses, so we have to determine how long each phase should be and which phase should be selected to be next phase. The first one we can use collected data includes location and speed of vehicles to calculate necessary time of each phase, and introduced it more detail in section 4.1.The second one, we have to concern about ordinary vehicles and buses, then we select three factors to design a phase demand function. After we get the allocated time of each phase, we can calculate the first factor: total passengers waiting time in each unit of time. Then we consider about bus regularity, we calculate the bus schedule delay ratio and bus headway ratio to be the second and third factor. After we calculate the phase demand value of each phase, the phase with highest green demand value will be selected as next phase. Section 4.2 introduces the details of phase demand determination.

4.1 Phase Length Determination

Before determining the length of each phase, we should know number of vehicles in the waiting area. As the intersection model mentioned, vehicles can pass through an intersection only two lanes in a phase. First, we calculate the time of dispersing all vehicles in two lanes of a phase, and we define $dist(i, f)$ as the distance between the stop line and the farthest vehicle in the waiting area in the two lanes of phase f at intersection i. An example of Phase1 is shown as see Figure 5.

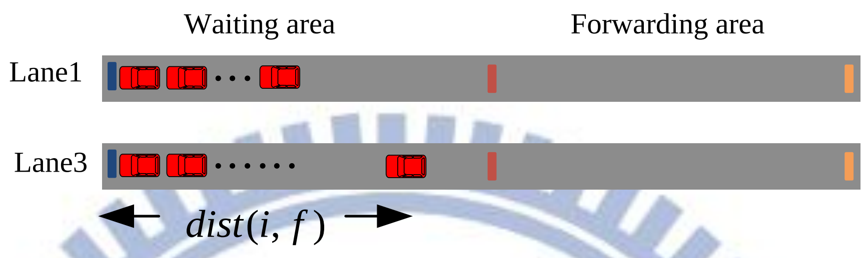

Figure 5. Distance between stop line and the farthest vehicle of phase1

After getting $dist(i, f)$, we could calculate how long can disperse the all vehicles in the waiting area of phase f. $disperse\_time(i, f)$ is defined as the time needed to disperse all vehicles of phase f at intersection i,.Where a means the acceleration of vehicles, and V_{max} means the max speed of vehicles.

$$disperse\_time(i, f) = \begin{cases} \sqrt{\dfrac{2(dist(i, f))}{a}}, & if \quad dist(i, f) < \dfrac{V_{max}^2}{2a} \\ \dfrac{V_{max}}{a} + \dfrac{dist(i, f) - \dfrac{V_{max}^2}{2a}}{V_{max}}, & if \quad dist(i, f) \geq \dfrac{V_{max}^2}{2a} \end{cases} \qquad (1)$$

When $dist(i, f) < \frac{V_{max}^2}{2a}$, it means that the vehicle will arrive at the stop line before it speed up to the V_{max}, and $dist(i, f) \geq \frac{V_{max}^2}{2a}$ means the vehicle will speed up to the V_{max} and forwarding a distance at the V_{max} speed before it arrive at the stop line (see Figure 6).

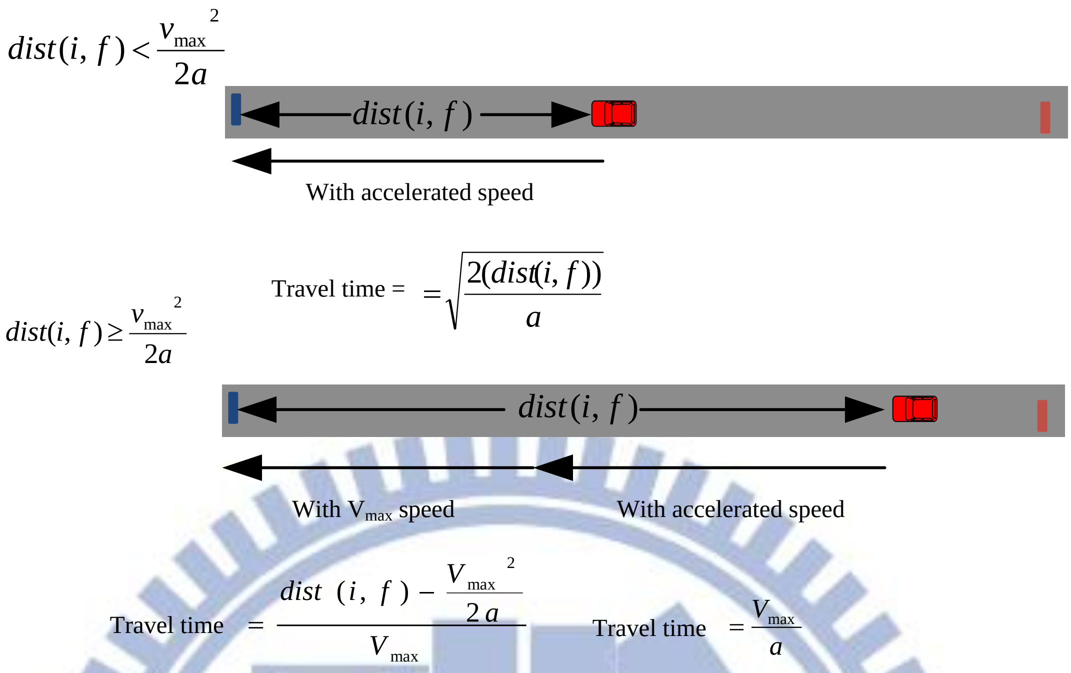

Figure 6. Example of calculating time to disperse vehicles.

We can determine the time should allocate to each phase after we know have $disperse\_time(i,f)$, $green\_time(i,f)$ is defined as the green time allocated to phase f at intersection i, where $green\_\min$ is minimum duration we should allocate to a phase. If we didn't set the minimum, the signals may change frequently, and this that is not acceptable for drivers.

$$green\_time(i,f) = \max\{disperse\_time(i,f), green\_\min\} \quad (2)$$

4.2 Phase Demand Determination

To decide which phase should be selected, we calculate three factors including passengers' waiting time, bus schedule delay and bus headway deviation. Then we use a phase demand function to determine the demand of each phase. And select the phase with the highest value to be the next phase.

4.2.1 Passengers' Waiting Time

The first factor is passengers' waiting time, and it's also the most evaluated item of traffic signal control systems. We calculate the total passengers' waiting time of other phases caused if a phase is adopting. We calculate the passengers' waiting time of two types of vehicles, the first type of vehicles is the vehicle in waiting area, the other type of vehicles is the vehicle in forwarding area and will stop at waiting area for the red signal. To calculate the waiting of the second type, we defined $CL(i,l,v_j)$ as the current location of the j th vehicle on lane l at intersection i, and $PL(i,l,v_j)$ as the location of the j th vehicle will be and stop for the red signal on lane l at intersection i.Then we can calculate the $TNA(i,l,v_j)$ as the time needed for j th vehicle arrive at $PL(i,l,v_j)$ and stop for the red signal on lane l at intersection i. The $TNA(i,l,v_j)$ of first type of vehicles is zero because $CL(i,l,v_j)$ is equal to $PL(i,l,v_j)$ of these vehicles, the current location and the predicted location of the vehicle in the forwarding area is shown as Figure 7. Where V is the current speed of v_j, and d is the deceleration of vehicles .

$$TNA(i,l,v_j) = \begin{cases} 0 & ,if \quad CL(i,l,v_j) = PL(i,l,v_j) \\ \dfrac{V}{d} + \dfrac{CL(i,l,v_j) - PL(i,l,v_j) - \dfrac{1}{2}\dfrac{V^2}{d}}{V} & , \; if \quad CL(i,l,v_j) \neq PL(i,l,v_j \end{cases} \tag{3}$$

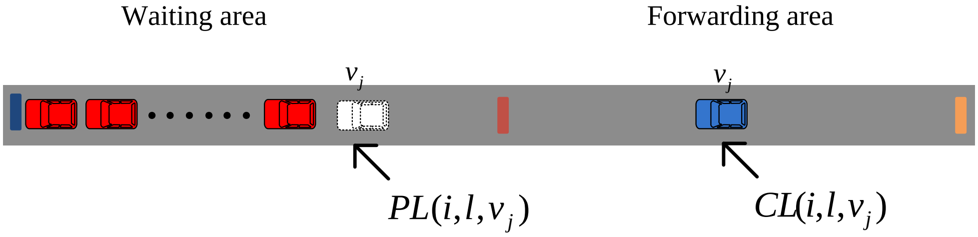

Figure 7. The current location and predicted location of the vehicle

Then we can calculate the waiting time of each vehicle for a time period. $wait\_time(i,f,T)$ is defined as the total passengers' waiting time if phase f sustains for the red signal for a time period of T time, and the $p(v_j)$ means the number of passengers on v_j. If the T is less than $TNA(i,l,v_j)$, $T-TNA(i,l,v_j)$ would be negative, and that means the vehicle will not stop at the period of T, so the $wait\_time(i,f,T)$ would be zero.

$$wait\_time(i,f,T)=\sum_l\sum_j \max\{0,(T-TNA(i,l,v_j))p(v_j)\} \tag{4}$$

An example of passengers' waiting time cumulated by a lane is shown in Figure 8. There are *i* vehicles in waiting area and one vehicle in the forwarding area.

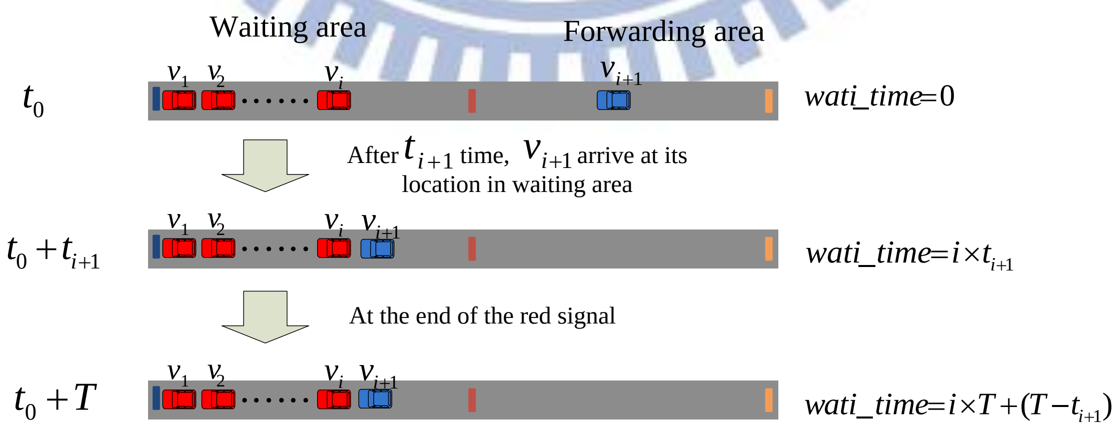

Figure 8. Passengers' waiting time cumulated in a lane

Then we define $wait\_time^{+}(i,f)$ as the total passengers' waiting time cumulated if we allocate $green\_time(i,f)$ to phase f .

$$wait\_time^{+}(i,f)=\sum_{f'\neq f} wait\_time(i,f',green\_time(i,f)) \qquad (5)$$

Each phase may be allocated different length, but they may have the same $wait\_time^{+}(i,f)$. Obviously, the phase be allocated shorter time but cause the same total passengers' waiting time is not effective relative to the phase has longer length. We defined $wait\_unit(i,f)$ as the total passengers' waiting time in each unit of time if phase f is be assigned the next phase.

$$wait\_unit(i,f)=\frac{wait\_time^{+}(i,f)}{green\_time(i,f)} \qquad (6)$$

The previous work with non-fixed phase sequence only use the number of vehicles to decide which phase will be assigned as the next phase and time .But they don't concern the waiting time cumulated by other vehicles at the period of allocated time and passengers on each vehicle. In our traffic signal control system, we have concerned these elements in equation (6).

In general, the phase with lower $wait\_unit(i,f)$ value will cause lower passengers' waiting time, and the phase with higher $wait\_unit(i,f)$ will cumulate more passengers' waiting time. If we don't concern features of buses, we should select the phase with lower $wait\_unit(i,f)$ as the next phase, and it should have better performance compare to the previous work.

4.2.2 Bus Schedule Delay

Bus schedule of buses is an important feature, because people can use it to save the time at bus stops. The schedule of a bus route is always designed based on an ideal experience of the bus. But because the traffic flow changes at any time, buses always will be influenced and can’t arrive at each bus stop on the scheduled time, they may arrive at bus stops late or early compare to its scheduled time. The buses are late from its bus schedule should be benefited at intersections by control the traffic signal, and the buses is early than its schedule should have lower priority at each intersection to adjust it to close to its bus schedule.

To calculate the schedule delay, we first define $schedule\_arrive(i, j)$ as the time bus *j* should be in phase *f* at intersection *i*, and $actual\_arrive(i, j)$ as the actual arrival time of bus *j* in phase *f* at intersection *i*. Then we can calculate schedule delay of each bus. $schedule\_delay(i, f)$ is defined as the highest schedule delay of buses in phase *f* at intersection j. There may be more than one bus in the same phase at the intersection, and they may be late or early from its schedule, but the bus with highest schedule delay should be benefited first of all. So we select the highest schedule delay of buses in each phase to be the $schedule\_delay(i, f)$ of phase f .

$$schedule\_delay(i, f) = \max\{actual\_arrive(i, f, j) - schedule\_arrive(i, f, j)\} \qquad (7)$$

4.2.3 Bus Headway Deviation

In normal situation, each bus can carry the close number of passengers and people will not wait a bus than the headway. Although each bus departures from the first bus stop in a fixed time interval, they may be delay or early than their predefined headway, and it will cause people waste much time at bus stops and make some buses carry many passengers in a delay situation.

The headway between two buses is using the difference of the arrival time of the current bus and its preceding bus. An example is shown in Figure 9. The difference of arrival time of BusA and BusB is six minutes, and the headway is also six minutes.

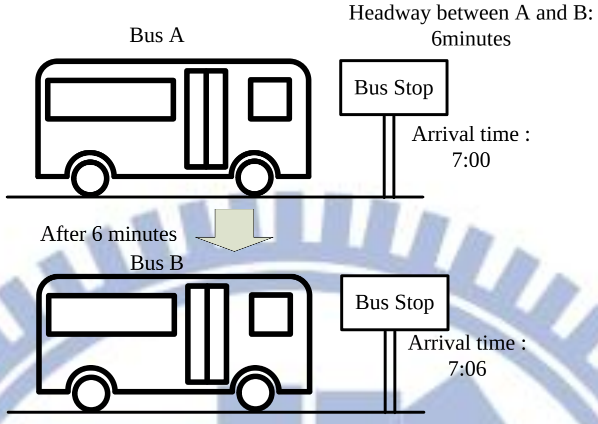

Figure 9. The headway between two buses

Buses on different bus routes travel different places, and each bus may have different number of passengers who want to take thus bus. The bus route have more passengers should have more bus travel on this bus route, thus more buses can save the waiting time of passengers at bus stops and passengers are more comfortable on a bus with less passengers. Hence, each bus route should have own headway which is suitable for this bus route.

We defined $HDR(i, f)$ as the headway deviation ratio of f at intersection i, where $PH(j)$ is the predefined headway of bus j. Because each bus has different predefined schedule, we have to use a ratio to compare headway deviation of a bus with the other one. There may be more than one bus in the same phase at the intersection, and the bus with highest headway deviation ratio should be benefited than buses have lower headway deviation ratio. So we select the highest schedule delay of buses in each phase to be $HDR(i, f)$ of phase f.

$$HDR(i, f) = \max\{\frac{headway(i, j, f) - PH(j)}{PH(j)}\} \quad (8)$$

4.2.4 Phase Demand Function

Now, we define the phase demand function according to the above mentioned measurements. In order to validate the impact from each measurement, we normalize their domain values from zero to one. More specifically, let $wait\_priority\_\max$, $schedule\_priority\_\max$ and $headway\_priority\_\max$ denote the maximal values measured during the simulation, respectively. We will record the total data including $wait\_unit(i, f)$, $schedule\_delay(i, f)$ and $HDR(i, f)$. We set $wait\_priority\_\max$ as the two times of average value of all $wait\_unit(i, f)$, and we set $schedule\_priority\_\max$ and $headway\_priority\_\max$ the same way.

Then we define $wait\_priority(i, f)$, $schedule\_priority(i, f)$ and $headway\_priority(i, f)$.

$$wait\_priority(i, f) = \frac{wait\_unit(i, f)}{wait\_priority\_\max}, \tag{9}$$

$$schedule\_priority(i, f) = \frac{schedule\_delay(i, f)}{schedule\_priority\_\max} \tag{10}$$

$$headway\_priority(i, f) = \frac{HDR(i, f)}{headway\_priority\_\max}.$$

(11)9

Besides, we give three scaling factors α_1, α_2 and α_3 denote as the weight of passenger waiting time, bus schedule delay ratio and bus headway deviation ratio. The phase demand function is defined as follows:

$$
\begin{aligned}
phase\_demand(i, f) = (-\alpha_1) \times wait\_priority(i, f) \\
+ \alpha_2 \times schedule\_priority(i, f) \\
+ \alpha_3 \times headway\_priority(i, f)
\end{aligned} \tag{12}
$$

At each intersection, if there is an overtime phase, the overtime phase will be selected. Otherwise, the phase *f* with the greatest value will be assigned as the next phase.

Chapter 5
Simulation

In this section, we evaluate the performance of ATCB by using NetLogo simulator [23] (version 4.1.3). We compare ATCB with the traditional predefined fixed-time scheme with bus priority strategy like TDTSP [19] and an adaptive fuzzy logic control (AFLC) [21].Beside bus priority, we also compare ATCB with an actuated traffic control and a non-fixed sequence control scheme [10]. The details of each scheme are described below.

We modify the TDTSP: We use a fixed sequence traffic signal control scheme and we benefit bus by extending the current phase if there is a bus can pass through the intersection by the current phase. If there are two buses on different routes meet in an intersection, we compare the headway deviation and schedule delay to decide which bus will be benefits.

Then, we modify AFLC: Like TDTSP, we also adopt a fixed sequence traffic signal control scheme and decide whether to extend the current phase or switch to next phase. In our modification, we compare ordinary vehicles and buses of the current phase with ordinary vehicles and buses of the next phase to decide whether to extend the current phase or switch to the next phase.

Actuated traffic control method controls signals by detecting the coming vehicles. It places sensors at a short distance near the intersection, if the sensor find there are vehicles will cross the intersection in a short period, it will extend the current phase until reach its maximum green time.

In a non-fixed sequence scheme, when the current phase is going to end, it will find the most suitable phase from all phases, the original scheme consider many factors, in our modification, we only focus on the number of vehicles, the phase has the biggest number of vehicles will be selected as the next phase.

We analyze the simulation results of total waiting time of vehicles, total waiting time of buses, total passengers' waiting time, average bus schedule deviation and average bus headway deviation.

5.1 Simulation Environment

As shown in Figure 10, we perform the simulation on a network of 8×8 traditional four-direction intersections, and the length of roads is 500 meters. The length of the waiting area on each road is 200 meters, and each road has four lanes, two are approaching lanes, and two are leaving lanes. We generate the ordinary vehicles on the edge roads of the network in a rate of 10 vehicles/minutes. Each vehicle are created with a speed of 14m/s. The acceleration of vehicles is assigned as $2m/s^2$, it means that each vehicle will reach its limit speed in 7 second. The deceleration of vehicles is $4m/ s^2$. Each vehicle will keep a safe distance when it is driven. And we adopt each vehicle carry average two passengers. In this network, we set five bus routes (RouteA, RouteB, RouteC, RouteD and RouteE), each bus on different bus routes enter this map with different frequencies (predefined headway). And we let them meet at an intersection to generate a pivot intersection, the bus routes is shown in Figures 10. And passengers on each bus is assigned in a range from 10~20. We run each simulation in 2 hours. The detail parameter of simulation is shown in TABLE 1.

We generate these five routes randomly. First, we randomly select a pivot intersection, and the distance between the pivot intersection and edges of this map is at least two intersections. For each route, we give an entry and an exit randomly, and the entry can't be also the exit. The buses of the route will pass through the pivot intersection, if the route is illegal or the length of this route is less than eight intersections, we will generate a new route until the route is legal and enough long. The frequency of each bus route is from 3 minutes to 10 minutes randomly.

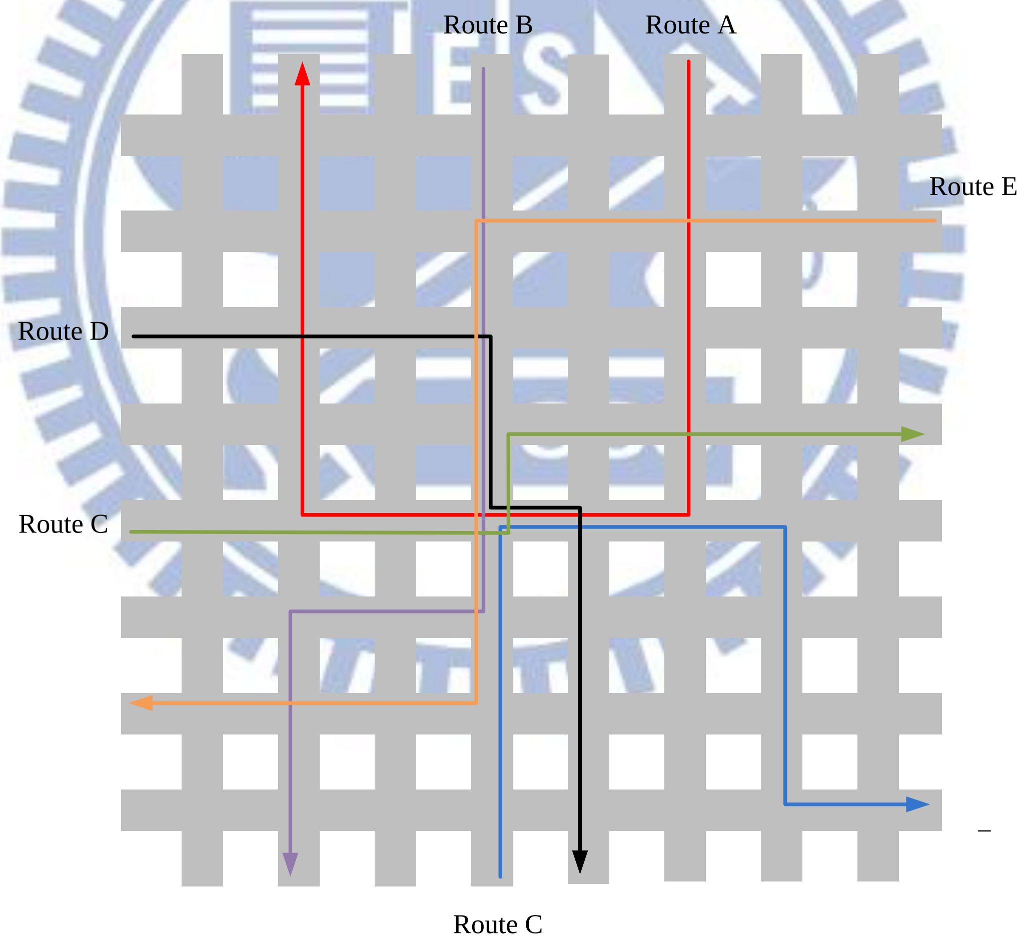

Figure 10. An Example of random network and bus routes

Table 1. Simulation parameters

Map size	8*8 grid
Length of roads	500 m
Length of waiting area	200 m
Traffic flow the edge road	10 vehicles/min
Speed limit	14 m/s (50 km/h)
Acceleration	2 m/s^2
deceleration	4 m/s^2
Passengers of a ordinary vehicle	2
Passengers of a bus	10~20
Run time	2h
Route A predefined headway	3~10 min
Route B predefined headway	3~10 min
Route C predefined headway	3~10 min
Route D predefined headway	3~10 min
Route E predefined headway	3~10 min

5.2 Simulation Results

In the preliminary experiment, we fine the appropriate value of each weight (α_1:0.5, α_2:0.5, α_3 : 0.75) to reduce the headway deviation and schedule delay of buses and don't produce huge impact on the passengers' waiting time. And we use these value in the below simulation.

We first evaluate the waiting time of buses in ATCB and other control strategies, which is the sum of waiting time at intersection of all buses. Figure 11 is the result of total waiting of all buses, and it shows that our scheme ATCB has the best performance at reducing bus waiting time, and it is better than other methods at least 40 percent. Both TDTSP and ADT consider bus priority which extends its current phase, the former one considers headway deviation, and the later one considers both the ordinary vehicles and buses. They have better performance than the actuated scheme which doesn't consider bus priority. The non-fixed phase scheme doesn't consider bus priority, but the non-fixed scheme is better than actual due to it is better for all vehicles include buses and ordinary vehicles.

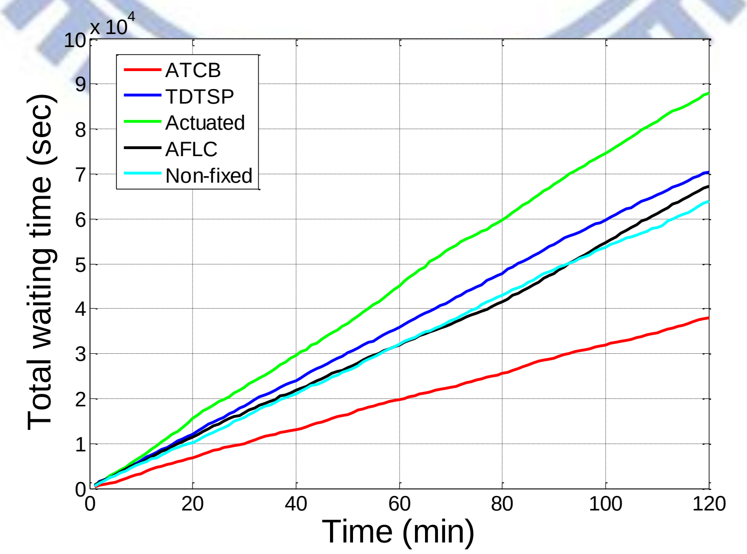

Figure 11. Total waiting time of buses

Table 2. Total waiting time of buses and average waiting time of each bus in one intersection

Scheme	Total waiting time in two hours	Average waiting time of each bus in one intersection
ATCB	3.79×10^4 sec	12.31 sec
TDTSP	7.04×10^4 sec	22.57 sec
Actuated	8.79×10^4 sec	28.04 sec
AFLC	6.71×10^4 sec	21.72 sec
Non-fixed	6.38×10^4 sec	20.66 sec

We could see that the best performance is non-fixed scheme, since that the non-fixed scheme don't concern bus priority. And our ATCB concern bus priority from bus schedule delay, headway deviation, number of passengers so our total waiting time of all vehicles is more than the non-fixed scheme. But the difference is just 3.8 percent, and it is acceptable because we can save 40 percent waiting time of buses as shown in Figure 11. And TDTSP has the poor performance due to that it doesn't concern the real-time information except bus information. Actuated scheme extends the current phase to permit vehicles pass through intersections is more better than TDTSP due to that it can avoid vehicles wasting a lot of time waiting for signals just because it misses few seconds to pass through the intersection.

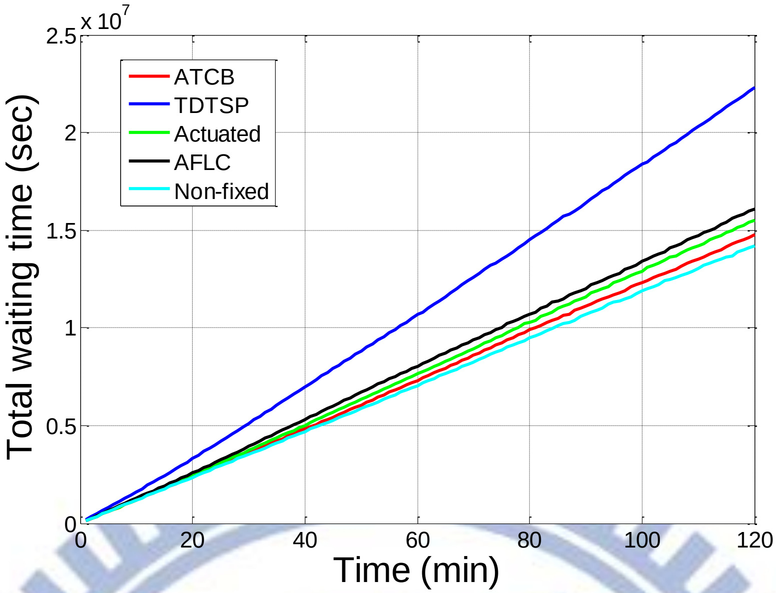

Figure 12. Total waiting time of vehicles

Table 3. Total Waiting time of buses and average waiting time of each vehicle in one intersection

Scheme	Total waiting time in two hours	Average waiting time of each vehicle in one intersection
ATCB	1.47×10^7 sec	25.95 sec
TDTSP	2.23×10^7 sec	38.11 sec
Actuated	1.55×10^7 sec	26.78 sec
AFLC	1.61×10^7 sec	27.26 sec
Non-fixed	1.42×10^7 sec	24.67 sec

The passenger's total waiting time is shown in Figure 13. And we could find that the result shown in Figure 13 is similar to Figure 12, but the performance of our ATCB is better than the non-fixed phase scheme, because we consider the number of passenger of each vehicle in our equation (5). If we don't consider number of passengers of each vehicles like non-fixed phase scheme, the bus will be treated as ordinary vehicle without bus priority. And we could see it has better performance of ordinary vehicles as shown in Figure 12, but it has poor performance in the result of passengers' waiting time.

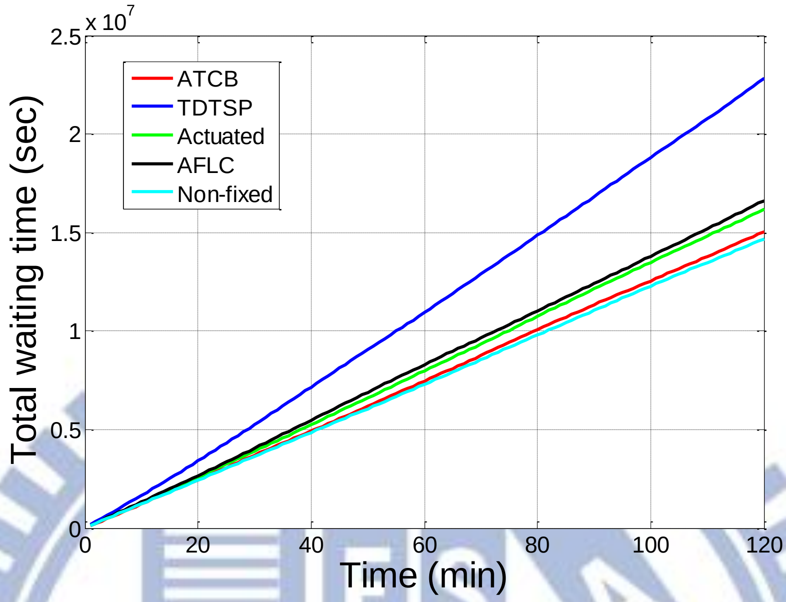

Figure 13. Total waiting time of passengers

Table 4. Total waiting time of passengers and Average waiting time of each vehicle in one intersection

Scheme	Total waiting time in two hours	Average waiting time of each passenger in one intersection
ATCB	1.50×10^7 sec	24.32 sec
TDTSP	2.28×10^7 sec	36.96 sec
Actuated	1.61×10^7 sec	26.10 sec
AFLC	1.66×10^7 sec	26.91 sec
Non-fixed	1.46×10^7 sec	23.67 sec

Then we evaluate the schedule delay of buses. We need buses travel a distance to produce bus schedule delay, so we collect the information from pivot intersection, and this intersection is a congested intersection because it is passed through by buses of all bus routes. As shown in Figure 14 and Table 5, we record 30 records of the schedule delay of buses on RouteA when it arrives at this intersection. We could find that our ATCB has a lowest average schedule delay, which is better at least 25 percent than other schemes. The variance of bus schedule delay of ATCB is 337.79, and it is better than other schemes at least 63.7 percent.

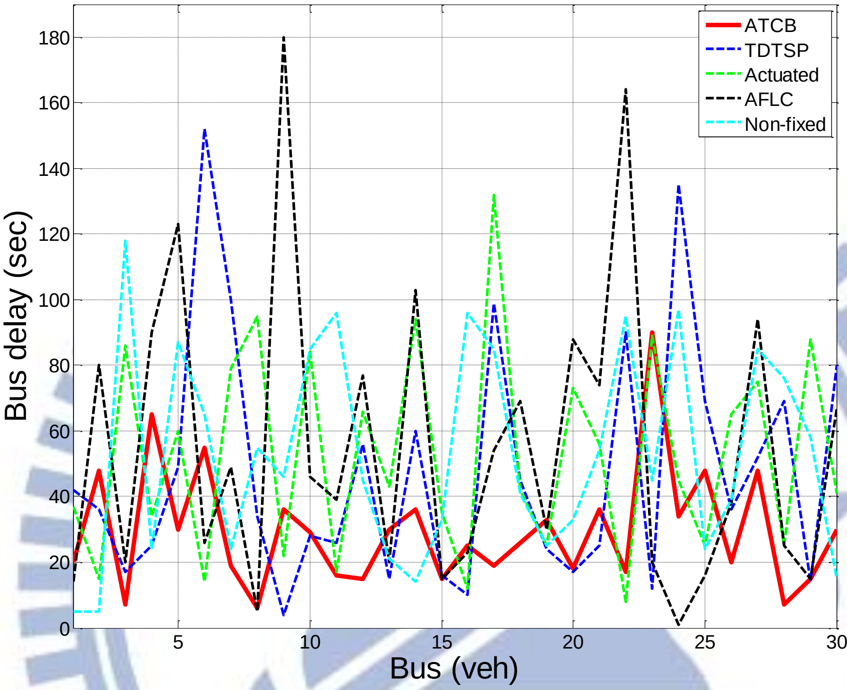

Figure 14. Bus schedule delay in a bus stop at a pivot intersection

Table 5. Average schedule delay time and Variances of buses at a pivot intersection

Scheme	Average schedule delay time	Variances of bus schedule delay
ATCB	30.87 sec	337.79 sec
TDTSP	46.88 sec	930.52 sec
Actuated	47.77 sec	1360.84 sec
AFLC	57.22 sec	1971.85 sec
Non-fixed	55.80 sec	985.0 sec

As shown in Figure 15 and Table 5, we evaluate headway deviation of buses. We still collect records of bus headway deviation ratio at the pivot intersection. As shown in Figure 14 and Table 5, in ATCB, the average bus headway deviation ratio is 22.19 percent, and the range of bus headway deviation ratio is from -44 percent to 39 percent and variance is 601.54 percent. The second best performance is TDTSP, and its average bus headway deviation ratio is 22.19 percent, and the range of bus headway deviation ratio is from -68 percent to 70 percent and variance is 601.54 percent.

We also evaluate the total schedule delay time and bus headway deviation ratio which is shown in Table 7, and the result is similar to the result shown in Table5 and Table6. Our ATCB still have the best performance.

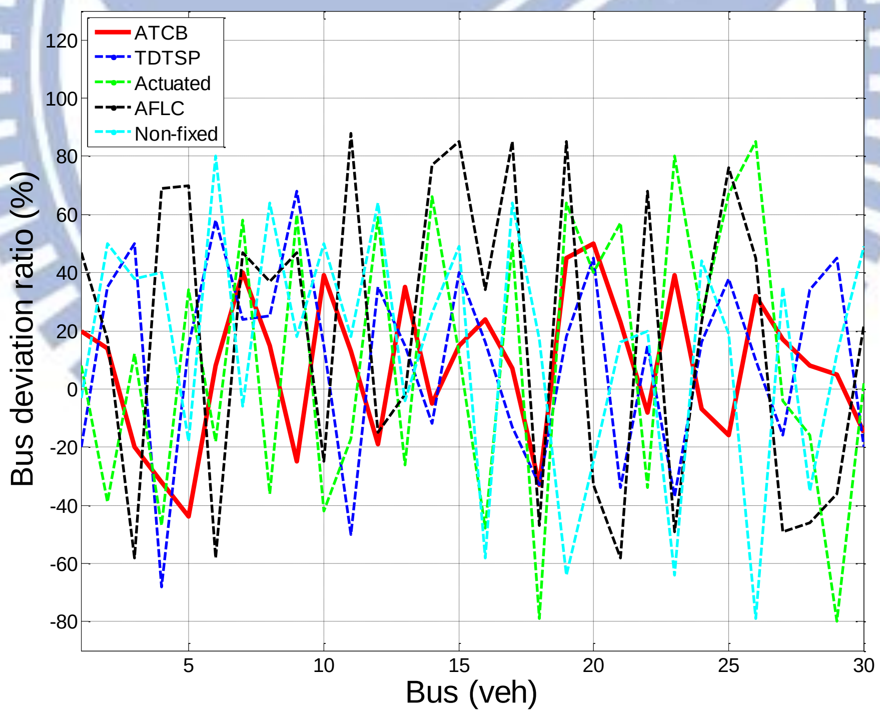

Figure 15. Bus headway deviation ratio in a bus stop at a pivot intersection

Table 6. Average headway deviation ratio and variances of buses at a pivot intersection

Scheme	Average headway deviation ratio	Variances of bus headway deviation ratio
ATCB	19.19 %	601.54
TDTSP	35.16 %	1105.39
Actuated	49.39 %	2215.51
AFLC	54.35 %	2603.06
Non-fixed	37.54 %	1681

Table 7. Simulation result

Scheme	Total waiting time of buses	Total waiting time of vehicles	Total waiting time of passengers	Average schedule delay	Average headway deviation ratio
ATCB	3.79×10^4 sec	1.47×10^7 sec	1.50×10^7 sec	38.27 sec	29.21 %
TDTSP	7.04×10^4 sec	2.23×10^7 sec	2.28×10^7 sec	46.32 sec	35.01 %
Actuated	8.79×10^4 sec	1.55×10^7 sec	1.61×10^7 sec	55.21 sec	43.12 %
AFLC	6.71×10^4 sec	1.61×10^7 sec	1.66×10^7 sec	53.92 sec	42.22 %
Non-fixed	6.38×10^4 sec	1.42×10^7 sec	1.46×10^7 sec	54.25 sec	38.56 %

5.3 A Simulation in Real Urban Environment

To prove ATCB is still effective in real world, we have designed a road network of Taipei City in Taiwan, a rough map is shown in Figure 16. This network has 16 intersections. And we have select 5 real bus routes to simulate.

The result is shown in Table 8, and we can find that the result is similar to the performance in Table 7, that can prove our method ATCB is still effective in a real road network. But because the size of this map is small, so the benefits of reducing waiting of buses are more obvious than the benefits of buses headway and bus schedule than the result of the bigger map.

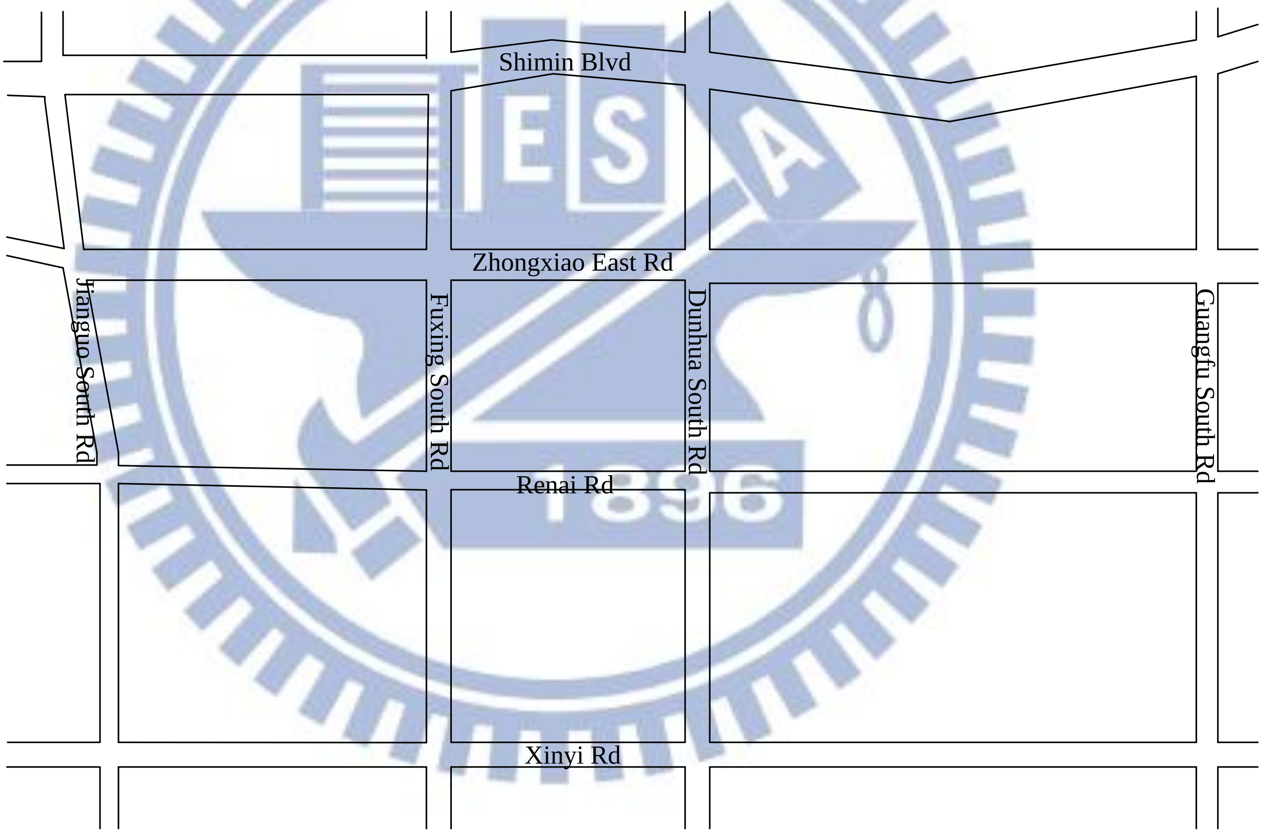

Figure 16. Road network of Taipei City

Table 8. Simulation result of a real urban environment

Scheme	Total waiting time of buses	Total waiting time of vehicles	Total waiting time of passengers	Average schedule delay	Average headway deviation ratio
ATCB	3.84×10^3 sec	2.54×10^6 sec	2.57×10^6 sec	19.12 sec	25.31 %
TDTSP	1.25×10^4 sec	4.35×10^6 sec	4.44×10^6 sec	22.23 sec	31.60 %
Actuated	1.43×10^4 sec	2.78×10^6 sec	2.89×10^6 sec	28.78 sec	39.53 %
AFLC	1.33×10^4 sec	2.85×10^6 sec	2.95×10^6 sec	27.15 sec	34.51 %
Non-fixed	1.15×10^4 sec	2.45×10^6 sec	2.53×10^6 sec	24.74 sec	33.49 %

Chapter 6
Conclusion

In this paper, the adaptive traffic signal control system (ATCB) has been proposed for ordinary vehicles and buses in urban environment. We adopt non-fixed phase scheme, and we use collected traffic information from detectors on roads and buses to determine the next phase and the phase should be allocated. To determine which phase is suitable to be adopted, we concern the passengers' waiting time and bus priority which include bus headway deviation and bus schedule delay to determine the demand of each phase. And the phase which cause lowest passengers' waiting and improve schedule delay and headway deviation will be selected. The simulation results show that ATCB performs better at reducing passenger's waiting time at least 40 percent, and improving schedule delay at least 17.5 percent, and headway deviation of buses at least 6 percent.

For the future works, the prediction model of traffic flow is also an important point in traffic signal control systems, and we could have better performance by implementing the prediction model of traffic flow in our system. Furthermore, we will try to use the information of neighbor intersections to design better control scheme.

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