Applying Matsuoka Neuronal Oscillator in Traffic Light Control of Intersections

A thesis presented in partial fulfillment of the
requirements of the degree of

Master of Engineering

In

Mechatronics

At

Massey University,

Auckland, New Zealand

Kuo-Chun Lin

2009

Abstract

The objective of this thesis is to implement Matsuoka Oscillators into a traffic control system at an isolated intersection in order to allocate the duration of green time depends on the dynamic traffic demands. The oscillator is a model of central pattern generators (CPG) which has been successfully used in various humanoid robotic applications. A Matsuoka Oscillator was chosen in this project because of its stable and predictable rhythmic outputs. In this thesis, the inputs of a Matsuoka Oscillator are the number of vehicles, and the outputs of the model are the duration of green time in the next phase. The purpose of this thesis is to study how the unbalanced traffic demand conditions affect the control system with Matsuoka Oscillators. The results of this research are compared with the fixed time control system. The expectation of this thesis is to make the time interval more fixable and reduce the delay time in order to balance the traffic condition at the isolated traffic intersection.

Acknowledgements

I would like to express my deepest gratitude and sincerest appreciation to the advisors Dr. Johan Potgieter, Prof. Peter Xu and Dr. Fakhrul Alam for supervision, enthusiastic guidance and continuous encouragement throughout the course of study.

Gratitude is also expressed to the staffs of Auckland Traffic Management Unit for their help and support.

I am also thankful to his friends Van C. Pham and Aeron Yu for assisting in many ways.

Finally I owe a special dept of thanks to my family members who have been behind all his achievements in life.

Table of contents

List of figures

List of tables

CHAPTER 1 Introduction

1.1 Background of intersection problems

There are many types of intersections such as 3-way, 4way, 5way, 6way, etc. The classification of intersections depends on the number of segments coming together at the intersection. The most common types are 4 way intersections which are usually used in two roads or streets crossing each other. The intersections can be classified by traffic control such as uncontrolled, yield-controlled, stop-controlled and signal-controlled intersections. In the urban areas, the most common types are signal-controlled intersections which depend on traffic signals. The signal indicates which traffic is allowed to proceed at any particular time. In the rush hours, the traffic congestions sometime occur during the unbalanced traffic situations. For example, the green time of the major streets is not long enough or too much green time in the minor streets.

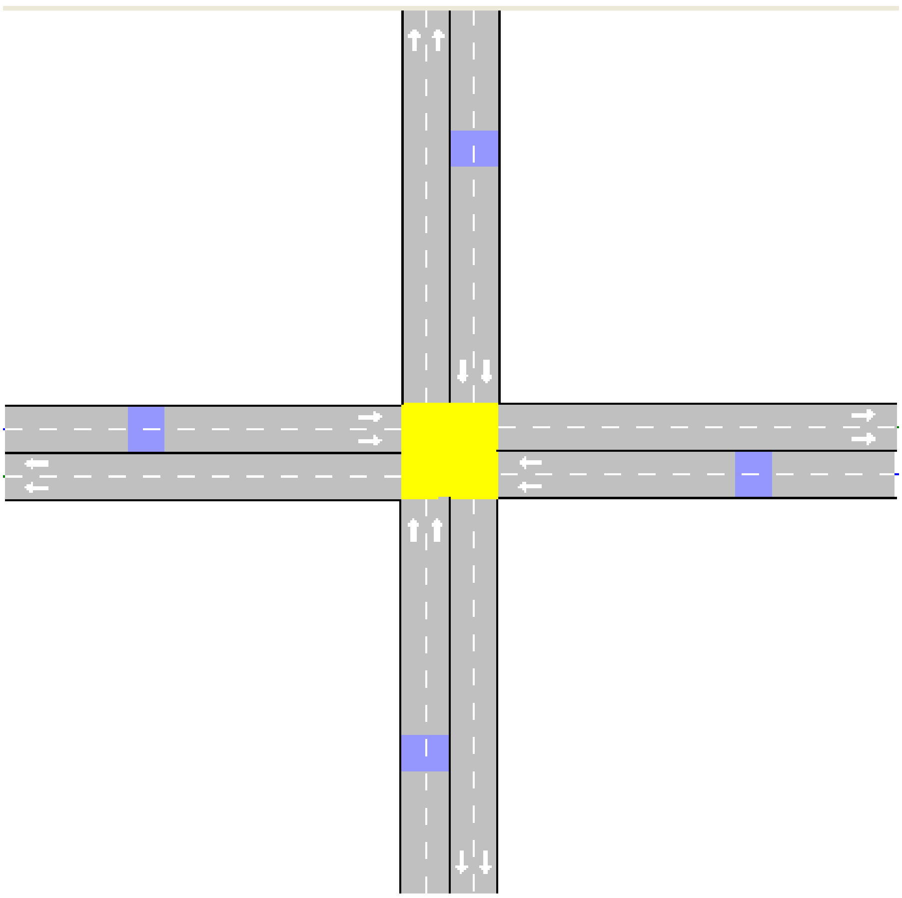


Figure 1-1 Geometric layout of an isolated intersection

1.2 Adaptive signal control

Generally speaking, the traffic control systems can be classified into two types which are fixed time control and actuated control (Wann, 2001). Fixed time control operates on fixed intervals, phase sequences, and fixed cycle length. In New Zealand, this signal control is widely used in suburbs or minor streets in urban area. During the rush hour when the traffic conditions change rapidly, this signal control will become less effective.

Actuated control uses gap-seek logic to respond to traffic fluctuations. The controller extends the green beyond a minimum time until a gap in the traffic flow on the approaches currently with green has been detected, or until the pre-defined maximum green time has been reached. Actuated signal control has certain limitations including a tendency to extend green inefficiently under low traffic flow conditions, and great sensitivity to incorrectly set maximum green times (Bell, 1990).

Adaptive control is one type of actuated control. This control can be defined as any signal control strategy that can adjust signal operations in response to fluctuating traffic demand in real time according to certain criteria (Lin and Vijayayumar, 1988). This control is made by some algorithms which adjust signal timing and extend the current green duration immediately. The idea of adaptive control was initiated by Miller (1963). He described an algorithm for adjusting signal timings in small time intervals of 1~2 seconds.

1.3 Matsuoka Oscillator

The Matsuoka Oscillator is a model of a central pattern generator (CPG) which has been applied to some robots that perform various rhythmic movements. CPG can be described as the rhythmic movements such as locomotion of animals are known to be generated by certain neural oscillators. CPG can be also mathematically modeled by an artificial neural oscillator (Matsuoka, 1985) and applied to biologically inspired locomotion control systems (Taga, 1995).

There are two neurons in the Matsuoka Oscillator model and each neuron receives an excitatory tonic input, a mutual inhibition, and external inhibitory input. The mutual and self inhibitions of the neurons are the nonlinear functions that generate a stable oscillation without the external input. Since the model is represented by some linear differential equations, the relationship between the parameters and the behavior of the oscillator is easy to predict. The output of the oscillator tends to a stationary periodic motion.

In view of the above, the characteristic of a Matsuoka Oscillator could be used to design an adaptive signal control system at an insolated intersection. In this thesis, a Matsuoka Oscillator is proposed to balance the dynamic traffic conditions.

1.4 Objectives of the thesis

The objective of this thesis is to implement the Matsuoka Oscillators in the signalized traffic control system at an isolated intersection with two and four phases. Chapter 2 describes the classification of signal control systems and some optimization methods for adaptive signal control. The introduction and example of a Matsuoka Oscillator are discussed in this chapter. In Chapter 3, two Matsuoka Oscillators are implemented in the control system in order to control two signals at an isolated intersection with two phases. These two Matsuoka Oscillators are designed and calibrated based on the 30 seconds fixed time control system. In Chapter 4, the traffic control system has four Matsuoka Oscillators controlling four signals at an isolated intersection with four phases. The traffic conditions are simulated by AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks). There are five major objectives have been identified:

- To design the signalized traffic control system based on the characteristic of a Matsuoka Oscillator.
- To establish the structure which connects with the traffic environment in AIMSUN software and Matsuoka Oscillators
- To analyze the inputs and outputs of Matsuoka Oscillators during the dynamic traffic demand scenarios
- To analyze the relationship of delay time in each phase between the traffic control system with the Matsuoka Oscillator and fixed time control system.
- To compare the entire traffic performance such as total travel time (hours), delay time (seconds/km), and flow (vehicles/hour) by using traffic control system with the Matsuoka Oscillator and a fixed time control system.

CHAPTER 2 Literature review

2.1 Introduction

The definition of an intersection is a road junction where two or more roads either meet or cross. Intersections can be classified as 3-way, 4-way, 5-way, 6-way, etc depending on the number of roads joint together. The traffic system is really complex and unpredictable in the real life. So the signal control system of traffic intersection becomes very important and significant. Intersections under signal control can separate time periods on each phase and make efficient use of lane space available. It is very important to find out the suitable algorithm for calculating the signal time and make the reasonable relationship between dynamic traffic demands and signals.

2.2 Intersection traffic signal control

Generally speaking, the traffic control systems can be classified into two types:

1) Fixed-time Control: Each phase signal has a fixed duration of green time and change interval that are repeated in each cycle to produce a constant cycle length. The Urban Traffic Control System (UTCS) was developed by the Federal Highway Administration in the 1970's. The characteristic of UTCS is the timing schedules by using manual or computerized techniques. The timing schedules are obtained by maximum of the bandwidth on arterial streets or minimizing a disutility index that is generally a measure of delay and stops (Wey et al, 2001).
2) Actuated Control: It can be divided to three types:

A. **Semi-actuated control**:

Semi-actuated controllers are used to maintain the green signal on the major street in the absence of a minor street actuation. Semi-actuated control also is classified as coordinated or un-coordinated. In semi-actuated coordinated control, the major movement always is coordinated and detection is along the minor movement. This means that the major movement always is green for a certain fixed time during a signal cycle thereby providing progression along a corridor. For the remaining duration of the cycle, the side street receives green time only if a vehicle is detected. If no vehicle is detected along the minor movement, the additional green time is given to the major movement. In semi-actuated un-coordinated control, detection is similar to semi-actuated coordinated control but the major movement is not under progression. The major movement remains green until a vehicle is detected along the minor movement, in which case the minor movement receives green. The minor movement then remains green until traffic is cleared or it reaches its maximum and then green is transferred back to the major movement (Bhargava et al, 2003).

B. **Fully actuated control**:

Fully actuated controllers operate with timing on all approaches being influenced by vehicle detectors. Each phase is subject to a minimum and maximum green time, and some phases may be skipped if no demand is detected. The cycle length for fully actuated control will vary from cycle to cycle (Fang, 2004). The moving traffic will receive green time unless the opposing vehicles are stopped at the intersection. The minimum green time often is set equal to the time required for a pedestrian to safely cross the intersection (Bhargava et al, 2003).

C. **Adaptive signal control**:

The system collects the data from dynamic traffic conditions and determines a desired timing plan and then implements this plan into each cycle or every five minutes (Fang, 2004). The following section will discuss some methods for adaptive signal control.

2.3 Optimization methods for adaptive signal control

There many adaptive signal controls were developed and used around the world such as SCATS (Sydney Coordinated Adaptive Traffic System), SCOOT (the Split, Cycle and Offset Optimization Technique), OPAC (Optimized Policies for Adaptive Control), RHODES (Real-time Hierarchical Optimized Distributed and Effective System), and LA-ATCS (Los Angeles Adaptive Traffic Control System) etc. Adaptive signal controls are third generation signal systems that make constant changes in signal timings based on measured flow. Reacting to these flow variations results in reduced delay, shorter queues and decreased travel times (Martin et al, 1995). Table 2-1 respectively shows the installation locations, and the operational philosophies of the five different adaptive control systems.

Table 2-1 Summary of adaptive control system (taken from Bhargava et al, 2003).

SYSTEM (Origin)	Installations	Type of Installation	Processing Location	Central Computer	Field Controllers	Sensor Locations
SCOOT (United Kingom)	More than 170 installations worldwide (4-600 intersections)	Field installation, Simulation	Central	DEC Alpha	NEMA, 170, 2070, TCT and TR0141	Upstream end of controlled link
RHODES (United States)	Three installations (Tempe, Arizona; Tucson, Arizona and Seattle, Washington)	Test deployment	Distributed	Not required	2070 with VME coprocessor	Upstream end of controlled link and stop-line
SCATS (Australia)	More than 50 installations worldwide (Australia, New Zealand, United States, China, Ireland, Singapore, Hong Kong and Tehran)	Field installation	Central for overall network control Distributed for local control of green phase	IBM PC with Windows ® NT™	2070/2070N 170 NEMA-Delta 3N In Australia, microprocessor based Philips and AWA models	Immediately in advance of stop-line Minor intersections require side street sensors only
OPAC (United States)	Two installations (Reston Parkway, Virginia and New Jersey)	Test deployment	Distributed, except for central control of cycle length	IBM PC with Windows ® NT™	2070 with VME coprocessor, 170 with 68360 processor, LMD 9200	Upstream about 8 to 12s from stop line or upstream of worst queue of all through phases
LA-ATCS (United States)	One installation (City of Los Angeles)	Field installation	Central	IBM PC	2070(new model) or 170	200 to 300 feet upstream of the stop-line

2.3.1 SCOOT

SCOOT is one of the most commonly used adaptive traffic control system in the urban area (David, 2000). It gives good progression for operating all the traffic signals through the traffic network. It responds quickly and intelligently depending on the traffic demands. It takes away the sophisticated systems of the signal plans that are expensive to update. SCOOT responses automatically to alteration in traffic flow according to the vehicle detectors. The utilization of SCOOT can reduce the traffic jam and maximize the efficiency of the economy in the cities. SCOOT is used in more than 200 cities and 14 countries around the world that have been proven improvements of reducing congestion and delay time.

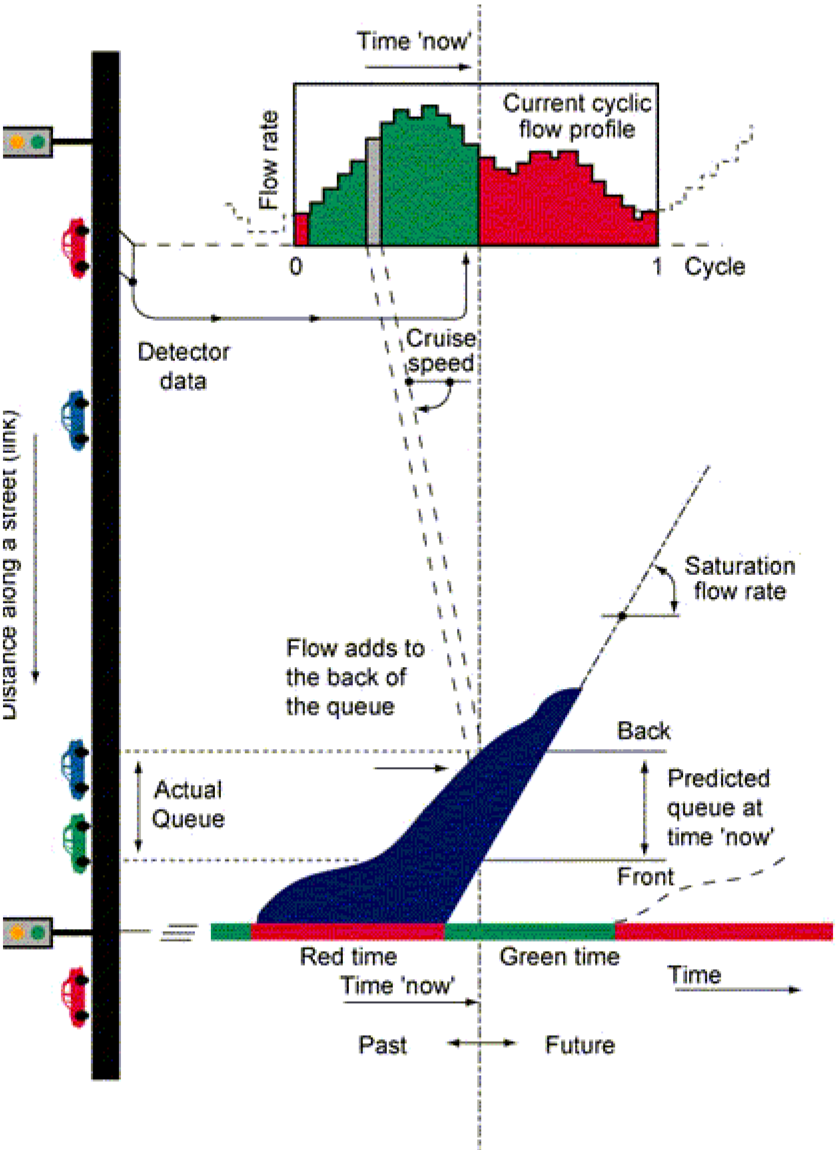


Figure 2-1 The operation of SCOOT model (taken from http://www.scoot-utc.com/DetailedHowSCOOTWorks.php?menu=Technical)

SCOOT obtains the dynamic traffic flows from detectors which are normally positioned on every link. SCOOT can respond to changes in flow immediately depend on good traffic data. The positions of detectors are important and they are usually positioned at the upstream end of the approach link.

Figure 2-1 shows the operation of SCOOT model. SCOOT obtains the information when the vehicles pass the detector and converts the data into its internal units and uses them to construct “Cyclic flow profiles” for each link. During the green signal, the vehicles discharge from the stop line on the link.

There are three major traffic control parameters of SCOOT model: the amount of green signal (split), the time between adjacent signals (offset) and the cycle time. These three parameters are used to reduce the delay time, stop time and minimizing wasted green time at intersections (David, 2000).

2.3.2 SCATS

SCATS is a computer system that can monitor and control the signals in real-time. The amount traffic uses each approach in the intersection to connect to SCATS that is used to calculate how much green time for each approach and to coordinate spaced intersections. SCATS is used in more than 80 cities around the world such as most cities in New Zealand and Australia, Detroit, Singapore, Manila, Hong Kong, Shanghai, Teheran, Qatar, Dublin, Minneapolis, and Mexico City (http://www.baseplusworld.com/mainpages-EN/scats.htm).

SCATS has a hierarchical control architecture consisting of two levels, strategic and tactical (Lowrie, 1982). At strategic level, the regional computers coordinate the signal timings and control a subsystem (up to 10 intersections). Theses subsystems can be linked together and operated on a common cycle time. At the tactical level, optimization occurs at the intersection level within the constraints imposed by the regional computer’s strategic control. Tactical control allows early termination of green phases when the demand is less than average and for phases to be omitted entirely when there is no demand. All the extra green time is added to the main phase or can be used by subsequent phases (Bhargava et al, 2003).

SCATS is able to change traffic conditions automatically every moment in the daily life. It can change in traffic demands, directions, and traffic volume, therefore providing the best signal control. SCATS can operate independently during the higher traffic volumes period such as sporting events. It adjusts the green time for each individual signal depending on the dynamic traffic conditions. Generally speaking, the benefits of the SCATS are reduction in overall travel times, reduction in vehicle stops, fuel consumption, and reduction of waiting times at red traffic signals.

2.3.3 RHODES

RHODES responds to the natural stochastic behavior of traffic, which refers to spatial and temporal variations and tries to optimize a given performance measure by setting timing plans in terms of phase durations for any given phase sequence (Gartner, 1983).

There are three levels of hierarchy in the RHODES architecture. The highest level is the dynamic network model which takes into account the slow-varying characteristic of traffic. The second level is called the "network flow control model" which allocates the green time depend on the different traffic demand scenarios. The lowest level is the "intersection control model" that assigns the phase change patterns.

Each level above has two components which are prediction and control. These components have been developed and used in the second and lowest level. The lowest level uses the PREDICT algorithm (Head, 1995) to predict the traffic flow and Optimization of Phases algorithm (Sen et al, 1997) to control and adjust the splits. The APRES-NET model (Dell'Olmo et al, 1996) predicts the arrivals and REALBAND algorithm (Dell'Olmo et al, 1995) performs the optimization calculations at the network flow control level.

2.3.4 OPAC

OPAC (Optimization Policies for Adaptive Control) was developed by Gartner at al (1983) and identifies the optimal signal timing sequence for a relatively long future period of time that is defined as a projection horizon (Fang, 2004). The range of projection horizon is about 50-100 seconds and it is divided into an integral number of intervals. The purpose of signal time is to minimize the delay and stop time of vehicles.

The algorithm of OPAC is to measure and model the traffic demand in order to measure the optimal phase switching sequences at the signal which is restricted by minimum and maximum green times. The “rolling horizon” concept is implemented in the OPAC because it is difficult to obtain the reliability of future arrival information for the entire optimization period. Figure 2-2 shows the detail of rolling horizon concept. At the head of the projection horizon, the arrival data are gained for r intervals. The rest part is the “tail” part which represents projection horizon (k-r) intervals and flow data are obtained from a simple model. This simple model is made up by a moving average of all previous arrivals. The optimal policy is to calculate the entire projection horizon but only use for the head section. Then the projection horizon is rolled by r units ahead, the new arrival data can be obtained from new stage of projection, and the process is repeated.

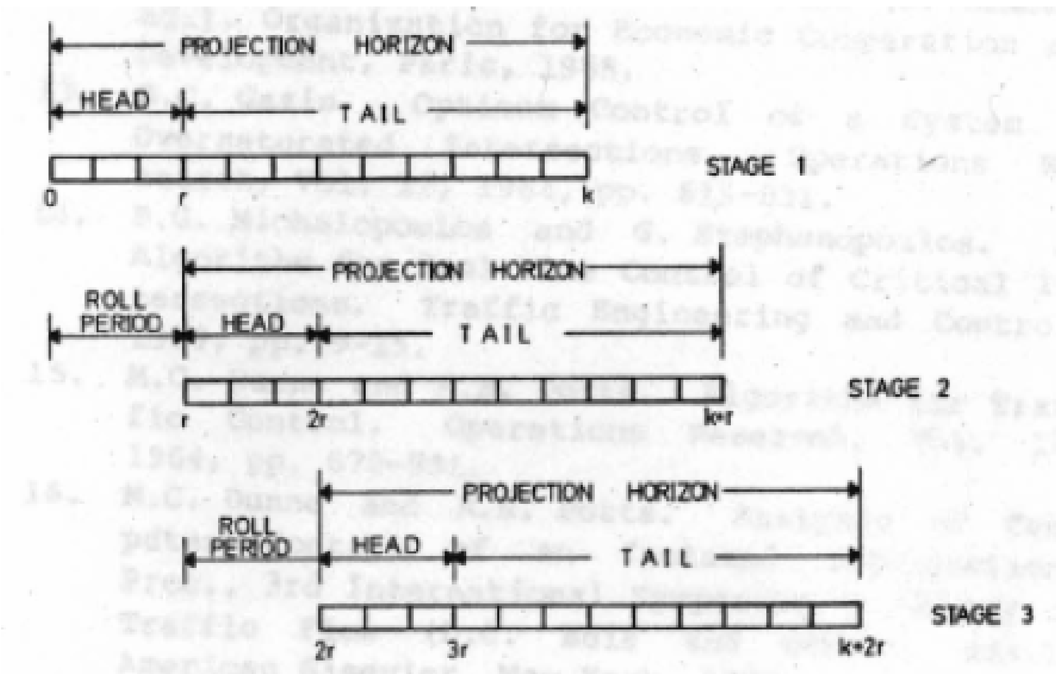


Figure 2-2 Rolling Horizon Concept (taken from Gartner, 1983)

There are two models of OPAC transition; they are congested networks and uncongested networks. In the uncongested networks, the signal timings can be determined by two ways which are fixed-time plans are obtained off-line and “virtual cycle” is determined the dynamic traffic conditions. The signal timing plans are based on detected data and predicted data. In the congestion networks, the saturation flows and the maximum number of vehicles passing through an intersection are considered in OPAC.

2.3.5 LA-ATCS

LA-ATCS is a personal computer-based traffic signal control program (Vincent and Young, 1986). There are three modes of LA-ATCS which are adaptive, time-of-day, and operator control. It can control a group of intersections. In the adaptive control mode, LA-ATCS operates on a common cycle time determined by the basis of current traffic flow conditions. Splits are calculated depending on the traffic volumes at each intersection and offsets are optimized in order to reduce the stops. In the time-of-day control mode, the fixed time control plan is operated. The operator control mode is good to handle the traffic conditions during the incidents and special events. LA-ATCS uses the common cycle time depend on the traffic flow at intersection during the rush hour. The lengths of cycle time are determined by the engineer and can be different for each intersection. Splits are calculated at each intersection depending on the traffic flow from each approach of the intersection.

2.4 Other methods for signalized intersection

2.4.1 Fuzzy logic method

Gao, et al (2002) designed a fuzzy controller in the isolated traffic intersection. When the vehicles waiting on the queue is short, the time of the green signal should be short, but no shorter than P x 15 seconds (P is the number of phases) in order to make the single car have enough time to pass the intersection safely; When the waiting queue of vehicles is long, the signal period is long, but no longer than 150 seconds. The inputs represent by queue length (Q_g and Q_r) and the output is green phase extension time (T). Under the rules, they set up six membership functions of input variables and six membership functions of output variables which are VS-very short, S-short, RS-relatively short, RL-relatively long, L-long, and VL-very long. Based on the values of $Q_g(t)$, $Q_r(t)$, using fuzzy reasoning to decide the green phase extension time.

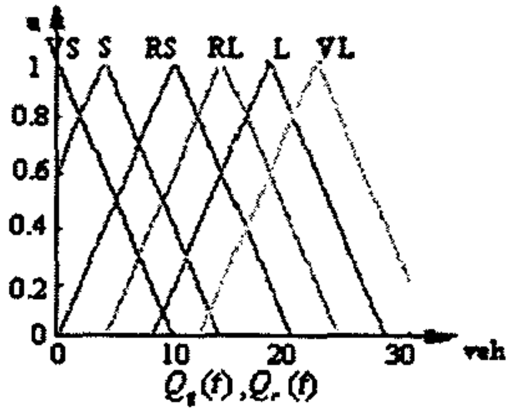


Figure 2-3 The membership function of input variable (Taken from Gao et al, 2002).

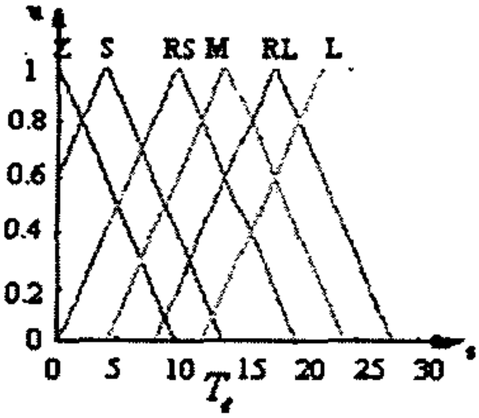


Figure 2-4 The membership function of output variable (Taken from Gao et al, 2002).

Firstly, they let the lanes of an insolated intersection in a set N, and then the minimum green time and maximum green time are represented by G_{min} and G_{max}. They calculate the lengths of wait queue of each lane and choose the biggest one in the Green phase that is represented by N_{green}. Then they choose the lane which has the opposite moving direction with the set N_{green} and let them in the red phase set N_{red}. They make the biggest waiting queue on green phase set N until the set N is empty.

The next step is to let all the lanes in the set N_{green} as a phase, and then gives this phase the minimum green time G_{min}. When this minimum green time is finished, they calculate the number of vehicles between two inductive loops which is vehicle detector then the maximum value is defined as $Q_g(t)$. Meanwhile, the maximum length of waiting queue in the red phase can be defined as $Q_r(t)$. The decision of green extension time is based on the values of $Q_g(t)$ and $Q_r(t)$ by using fuzzy reasoning.

They use four-phase signal control for their simulation under certain signal rules. The maximum green time is 45 seconds, the minimum green time is 15 seconds and the lost time of green interval is 5 seconds. The saturation of each phase is 1800 vehicles/hour, and the arrival of vehicles conforms to Possion distribution.

Table 2-2 The performance of two control methods (Taken from Gao et al, 2002).

Performance	Traditional control	Changeable phases control	Percentage of performance optimization
The delay time of vehicles D (second)	4.8	4.0	16.7%
Number of stopped vehicles S (Veh)	140	118	15.7%
Number of vehicles passing by the intersections P (Veh)	854	936	9.6%

Table 2-2 shows the comparison of two control methods. The delay time decreases from 4.8 to 4.0 seconds by replacing the changeable phases control system. The percentage of optimization for delay time of vehicles is 16.7%. The performance table also shows the improvement of the number of stopped vehicles and number of vehicles passing through by the intersections which are 15.7% and 9.6% performance optimization.

2.4.2 Linear systems control technique

The control of an isolated intersection is formulated as a linear systems control problem on the basis of mathematical models. These models are utilized to develop local traffic signal control strategies under various traffic conditions. This linear control system provides some linear feedback control laws based on the proportional-derivative-integral (PID) concepts. Consider an intersection with two competing one direction flows with a two-phase signal control.

The first mathematical model of an oversaturated intersection was developed by Gazis and Potts (1963). In this paper, the system counts two flows in the intersection. The arrival rates of the vehicles in the two flows are represented by d_1 and d_2. The basic assumption of the system is the number of arriving vehicles from the upstream at each time is independent and deterministic of the traffic conditions. The maximum rates of saturation flow of two directions are defined as S_1 and S_2. Then the effective green phases of the two directions are represented by g_1 and g_2. The cycle time will be given and defined as t_c.

The average green time to make all vehicles arriving during a cycle time t_c is

$$t_{gi} = t_c \cdot \frac{d_i}{S_i}, i = 1,2 \qquad (1)$$

When the two flows d_1 and d_2 increase then

$$t_{g1} + t_{g2} > t_c - L \qquad (2)$$

or, it can be wrote as

$$\frac{d_1}{S_1} + \frac{d_2}{S_2} > 1 - \frac{L}{t_c} \qquad (3)$$

Here L represents the total lost time of clearing and acceleration. The queue lengths at the intersection are l_1 and l_2, the equation is:

$$l_i = d_i - S_i \frac{g_i}{t_c}, \qquad i=1,2 \qquad (4)$$

Where $l = \frac{dl(t)}{dt} =$ the time derivative of queue.

The first term of (4) is the arriving flow, while the second term represents the flow served. The difference of these two values is the change rate of the queue length at the intersection.

The equation shows as:

$$r_i = S_i \cdot \frac{g_i}{t_c}, \qquad i=1,2 \qquad (5)$$

but since

$$g_1 + g_2 = t_c - L \qquad (6)$$

they obtain by substituting (5) into (6)

$$\frac{r_1}{S_1} + \frac{r_2}{S_2} = 1 - \frac{L}{t_c} \qquad (7)$$

this equation can be rewritten as

$$r_2 = S_2(1-\frac{L}{t_c}) - \frac{S_1}{S_2} \times r_1 \qquad (8)$$

Substituting (5) and (8) into (4) they obtain the linear equation:

$$l_1 = d_1 - r_1 \qquad (9)$$

and

$$l_2 = d_2 - S_2(1-\frac{L}{t_c}) + \frac{S_2}{S_1} \times r_1 \qquad (10)$$

Then the discrete time equation is formed:

$$\begin{cases} l_1(k+1) = l_1(k) + [d_1(k) - r_1(k)]t_c \\ l_2(k+1) = l_2(k) + [d_2(k) - S_2(1-\frac{L}{t_c}) + \frac{S_1}{S_2} \times r_1(k)]t_c \end{cases} \qquad (11)$$

Here the state variable is $l_i(k)$, input variable is $r_1(k)$, disturbance is $d_i(k)$ and k is the time constant.

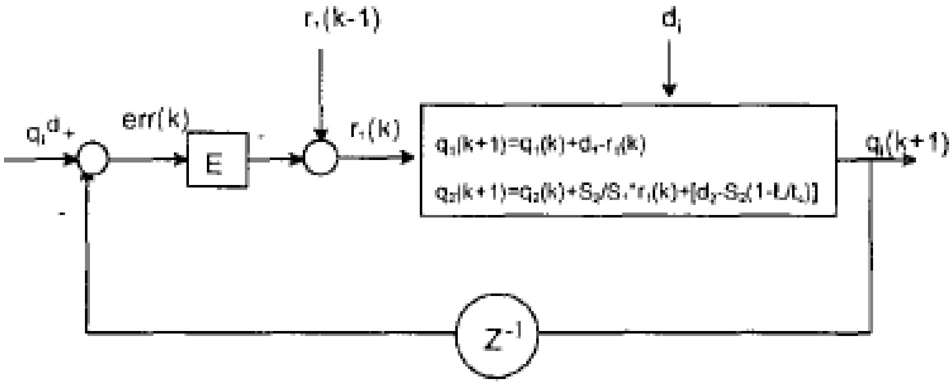


Figure 2-5 Structure of Intersection Signal Feedback Controller (Taken from Wann-Ming et al, 2001).

In this paper, they describe the linear control system problem at the intersection can be solved by the techniques of mathematical transformation. The Laplace transform technique can solve the linear constant coefficient differential equations, and then the use of the z-transform method to solve the linear constant coefficient difference equations.

This paper points out this theory can be implemented into real time traffic control system and the optimal controller can change new frequency as new information depending on the dynamic traffic conditions in order to predict demands for the remaining control period arrival (Wann-Ming et al, 2001).

2.4.3 Simulation optimization

This simulation optimization method was developed in 1986(A.Saka et.al,1986).The strategy of simulation optimization of this paper is to minimize the total expected delay time at the intersection. There are two optimization methods considered in this paper which are simulation and dynamic programming.

The expected delay time can be estimated as:

$$D_j = \sum_{i=1}^{N-1} A_i \int_0^{t_j} \varepsilon \psi_{D_I}(\varepsilon) d\varepsilon + A_j Max \left\{ [\int_0^{t_j} \varepsilon \psi_{D_j}(\varepsilon) d\varepsilon - (\sum_{a=1}^{M} \int_0^{t_j} \alpha \psi_{D_j}(\phi(\alpha_a)) d\alpha)] \right\} \quad (12)$$

Where

$D_j =$ Expected delay with signal phase,j

$A_i =$ Multiplicative factor which converts queue to delay in phase,i

$t_j =$ Service time for signal phase,j

$\psi_D(\bullet) =$ Probability density function of arrival service time for individual time

$\phi =$ Discrete probability function that characterizes vehicular mix

$\varepsilon =$ Random arrival

$\alpha =$ Random service

$M =$ Total number of vehicular classes

$N =$ Total number of signal phases

In this paper, they developed a simulation model in order to obtain the expected queue and delays for each signal phase at the intersection. These models count the mean rate, service distribution, and distribution of different classes of vehicles, the length of cycle time and phase time, and the period of time.

There are several advantages by using the simulation optimization method at the intersection. Firstly, the simulation does not use experimentally derived models to obtain the variables such as delays and queues that are used to determine the new cycle time and signal time of the intersection. Therefore, it is easier to solve some problems by using simulation rather than mathematical programming formulations.

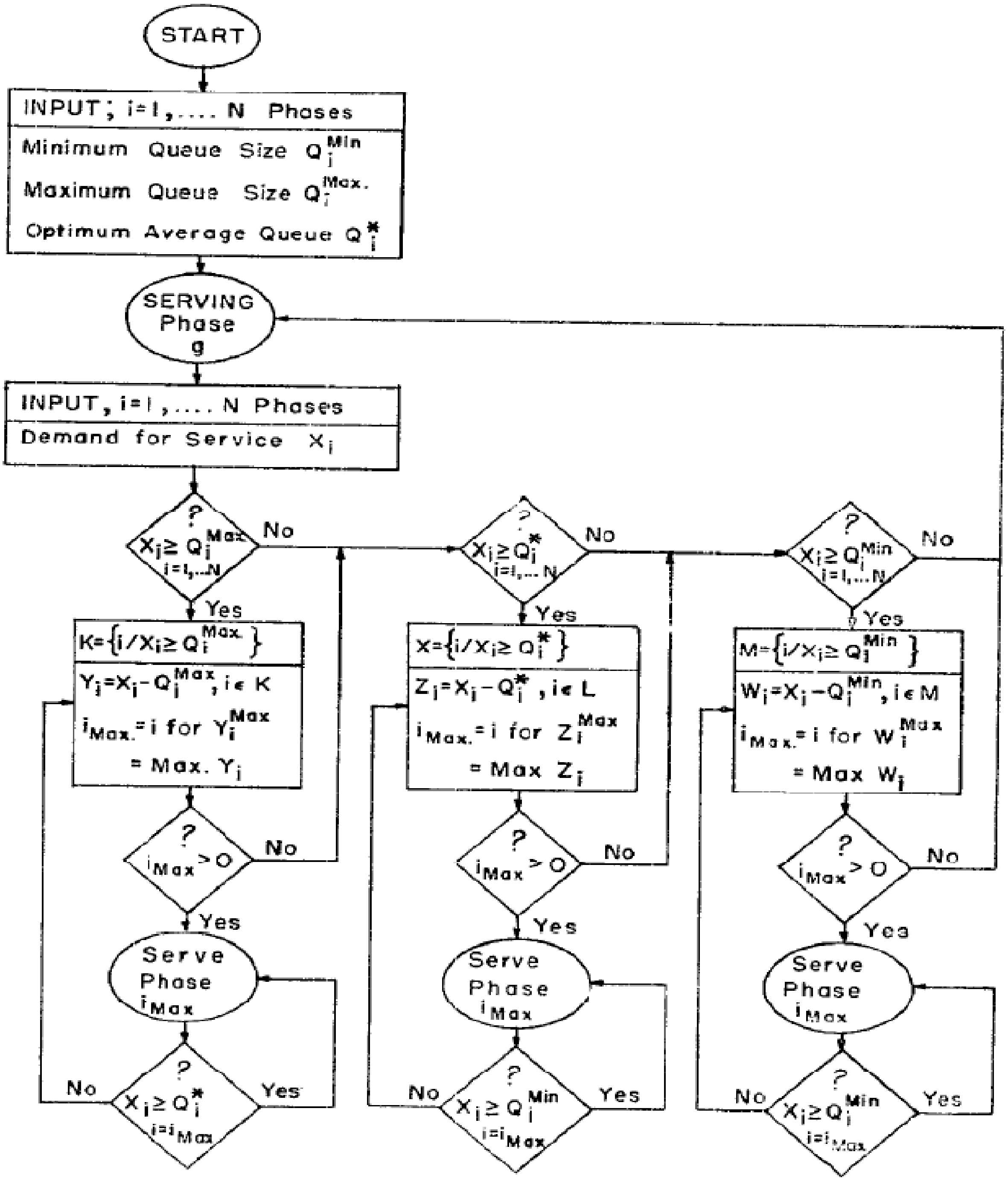


Figure 2-6 A Simplified State Dependent-Server-Vacation Signal Timing (Taken from Anthony et al, 1986)

Figure 2-6 shows the flow chart of programming based on the server in state dependent. The advantage of the state dependent-server-vacation approach is to eliminate the wastage of green time because service is rendered only when there is traffic demand for it. This approach is to limit the queue size in the reasonable range and in order to prevent queue exceeding its maximum tolerable queue size (Anthony et al, 1986).

2.5 Matsuoka Oscillator

2.5.1 Introduction

A model of the central pattern generators (CPG) has been applied to many robots which act with various rhythmic movements. CPG can be defined as neural networks that can endogenously (i.e. without rhythmic sensory or central input) produce rhythmic patterned outputs (Hooper, 1999) or as neural circuits that generate periodic motor commands for rhythmic movements such as locomotion (Kuo, 2007). The advantage of CPG is that it can produce the rhythmic outputs normally without the feedback of motor and sensor from limbs and other muscle targets. While these robots receive some sensor signals as input, some parts of robots vibrate depending on some neural oscillators. The scheme makes the oscillators adapt to the natural dynamic objects and provide energy-efficient actuation. The artificial name of the above-mentioned oscillator is called the Matsuoka Oscillator.

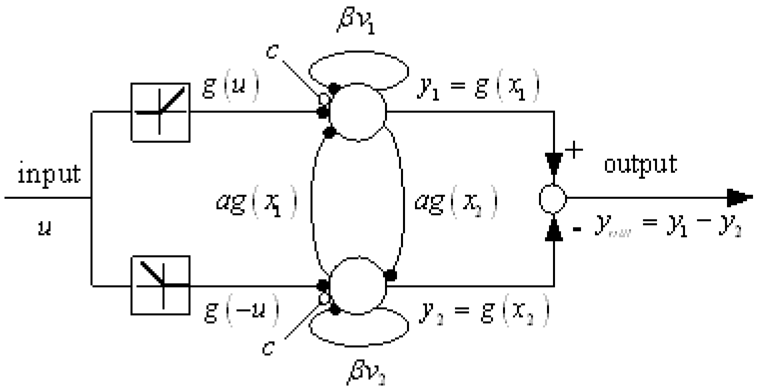


Figure 2-7
Structure of the neural oscillator. The blanked and filled dots represent excitatory and inhibitory synapses. (Taken from http://www.brain.kyutech.ac.jp/~matsuoka/oscillator_English.html).

From the above figure, there are two neurons inside this neural oscillator. Each neuron receives an external inhibitory input, a mutual inhibition, and an excitatory tonic input. The mutual and self inhibitions of the neurons with a nonlinear function produce a stable oscillation without the external input. The equations of Matsuoka Oscillator will be discussed in the Chapter 3.

The relationship between the parameters and the behavior of the neural oscillator is easy to predict because the Matsuoka Oscillator is represented by some linear differential equations. This is the reason why people use this oscillator model to design robots with rhythmic movements.

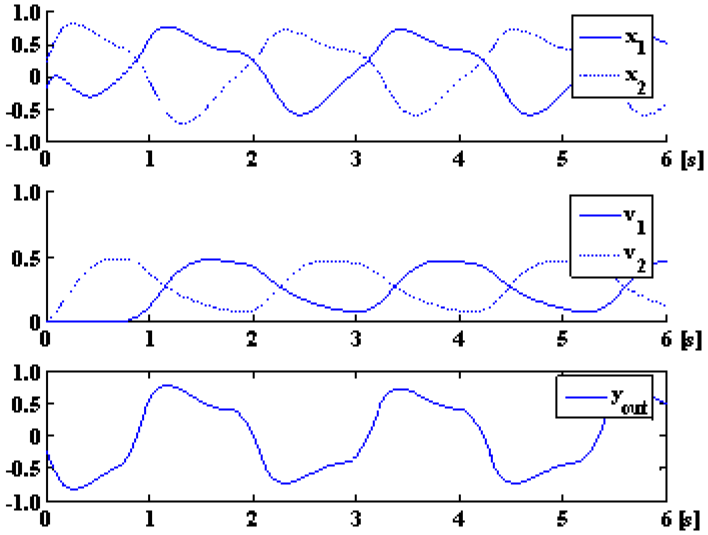


Figure 2-8 Oscillation generated by the model in the absence of external input. (Taken from http://www.brain.kyutech.ac.jp/~matsuoka/oscillator_English.html).

Figure 2-8 shows the oscillation that is generated in the absence of external input. In this figure, the symbol "A" represents the amplitude of the system. The output of the oscillator is represented by a stationary periodic motion and the output time is very quick. The frequency of this stationary oscillation is called the oscillator frequency, which is an inherent frequency of the oscillator. The reaction time and stable output are important parts for designing the robots. That is why this model oscillator is widely used for robots that perform rhythmic movements.

Generally speaking, the common way to connect the neural oscillator and the plant is to make a closed loop system. The output of oscillator drives the system, and the input of the oscillator is fed back to the plant. Typically the oscillator is non-linear and the plant linear.

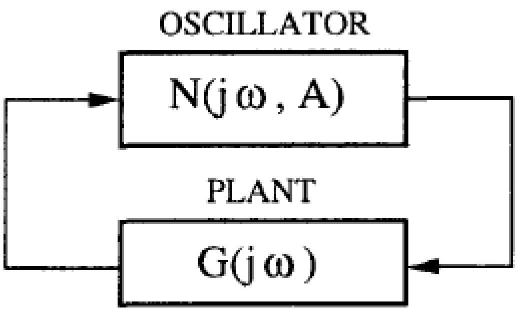


Figure 2-9 System schematic. (Taken from Matthew, 1999)

Figure 2-9 shows the closed loop system which is composed of oscillator and plant. The frequency response of the oscillator is N (jω, A) and the plant is G (jω). The frequency is represented by w and A is the input amplitude. Calculating N and solving above equation provides the way to design and tune the system. The only way to make stable oscillations is when the loop gain is unity as follows:

$$|N(j\omega, A)\, G(j\omega)| = 1 \tag{13}$$

2.5.2 The example and application of using a Matsuoka Oscillator

Some applications of the Matsuoka Oscillator are used as an artificial neural oscillator in the robotics field that can imitate rhythmic movements of animals. Evan, et al (2008) designed a simple hopping robot controlled by an artificial neural oscillator. The dynamic equations for a reciprocal inhibition oscillator are developed by Matsuoka.

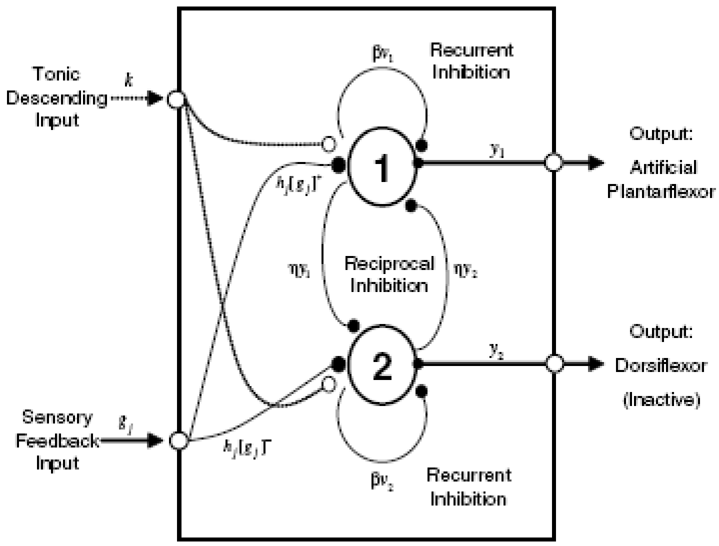


Figure 2-10 Artificial neural oscillator schematic (Taken from Evan et al, 2008).

The above graph shows the artificial neural oscillator with two neurons. There are two inputs that represented by descending neural drive and sensory feedback served by ankle angle. The output of the oscillator included flexor and extensor muscle activation signals. In their testing, they only used plantar flexor oscillator half centre as the output. The other output is the dorsiflexion of the robot which was achieved by a passive rubber spring.

2.6 Summary of literature review

Several signal timing systems have been developed and implemented at intersections around the world. Some strategies of these systems utilize the traffic flow as the optimization parameters in order to adjust the cycle time, splits, or offsets. The proposes of these signal timing systems are to eliminate the waste of green time, minimize the delay and stop time of vehicles, and reduce the travel time of traffic at intersections during the dynamic traffic conditions.

In this study, the adaptive signal control system is developed based on the characteristic of a Matsuoka Oscillator. From the literature review, a Matsuoka Oscillator is defined as a model of the central pattern generators (CPG) which has been usually applied to robots with various rhythmic movements. The outputs of a Matsuoka Oscillator are predictable and stable because of some linear differential equations. These predictable and stable outputs of the oscillator could be used to adjust the green signals depending on the dynamic traffic volumes. In Chapter 3 and Chapter 4, Matsuoka Oscillators will be designed and implemented at isolated intersection with two and four phases. This study will analyze how the adaptive signal control system with Matsuoka Oscillator affects the unbalance traffic conditions.

CHAPTER 3 Matsuoka Oscillators for a two-phase isolated intersection

3.1 Introduction

In this chapter, two independent Matsuoka Oscillators are implemented into a traffic control system at an isolated intersection with two phases (Figure 3-1) which is simulated by AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Network). We assume the initialized isolated intersection has two fixed time signals which are 30 seconds in green time. We utilize the characteristic of the Matsuoka Oscillator to design a signalized control system for this isolated intersection with dynamic traffic demands. Each of Matsuoka Oscillator controls the duration of green time in each phase. The methodology will be discussed in the following sections.

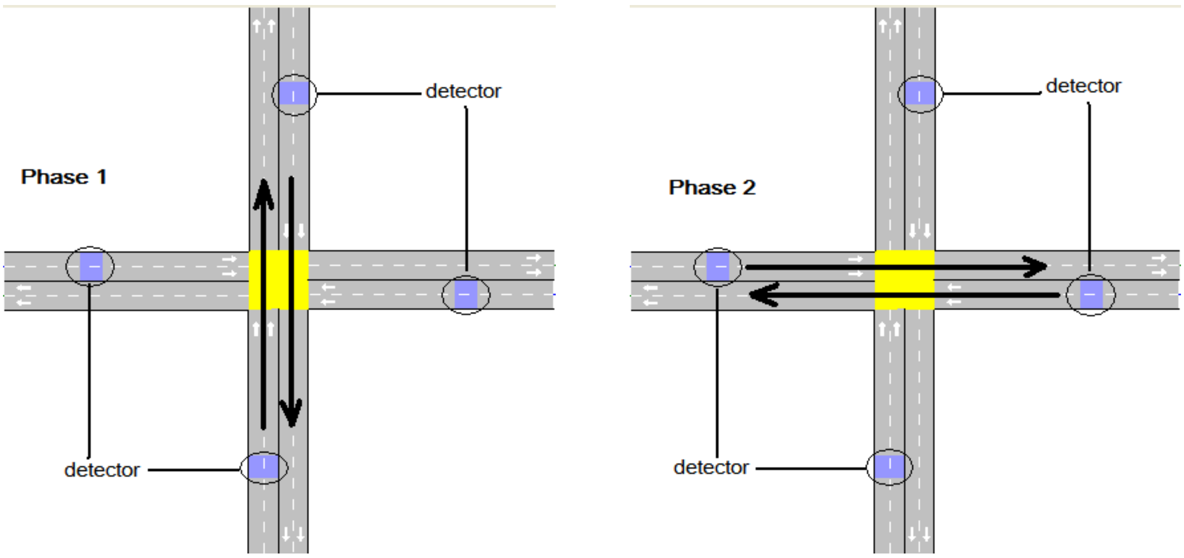


Figure 3-1 The intersection with two phases

3.2 Formulation and structure of a Matsuoka Oscillator

A Matsuoka Oscillator consists of two neurons. Each neuron receives an excitatory tonic input, external inhibitory input, and a mutual inhibition. The two neurons affect each other by variable parameters shown in equations (14) and (15). There are two outputs generated by the oscillator. The structure and equations of a Matsuoka Oscillator can be represented by:

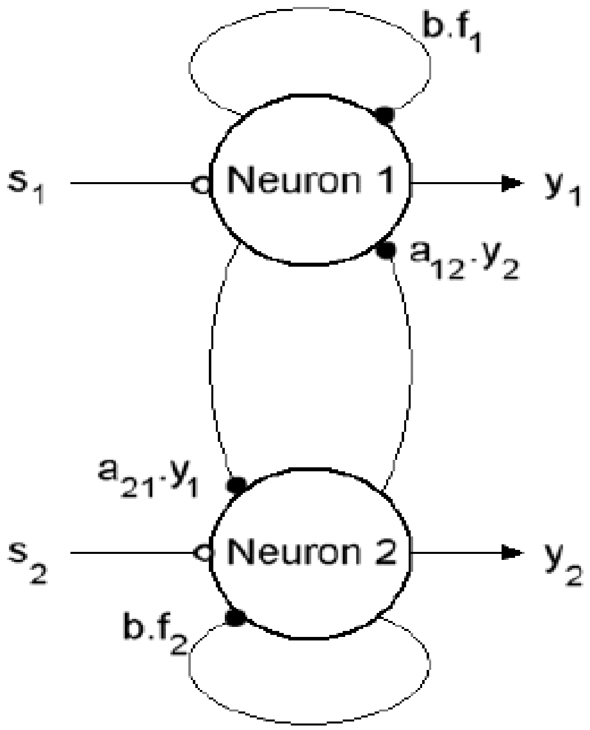


Figure 3-2 Matsuoka Oscillator with two neurons. (Taken from Bouhet et al, 2007).

$$\begin{cases} T_r \cdot \dfrac{dx_1}{dt} + x_1 = -a_{12} \cdot y_2 + s_1 - b \cdot f_1 \\ y_1 = g(x_1) \\ T_a \dfrac{df_1}{dt} + f_1 = y_1 \end{cases} \quad (14)$$

$$\begin{cases} T_r \cdot \dfrac{dx_2}{dt} + x_2 = -a_{21} \cdot y_1 + s_2 - b \cdot f_2 \\ y_2 = g(x_2) \\ T_a \dfrac{df_2}{dt} + f_2 = y_2 \end{cases} \quad (15)$$

$$g(x) = \max(x, 0)$$

Where T_r and T_a are time constants of adaptation effect inside the oscillator which can adjust the shape and frequency of the oscillator, a_{ij} is the constant that affects mutual inhibition between two neurons, b is another constant that affects self inhibition of each neuron, s_1 and s_2 are external outputs which represent the number of vehicles waiting on the queue or passing through on each phase, y_1 and y_2 represent the outputs of oscillator which are the duration of green time of each phase in the traffic control system.

3.3 Designing the controller

3.3.1 Graphic User Interface

As we know, a Matsuoka Oscillator model can be described by some nonlinear equations. A Graphic User Interface (GUI) for analyzing the behaviors of Matsuoka Oscillator was developed by Bouhet et al (2007). This GUI can allow the user to specify the constant values of the parameters, generate the outputs, visualize the characteristic values of the outputs, and visualize the influence of each parameter on the output.

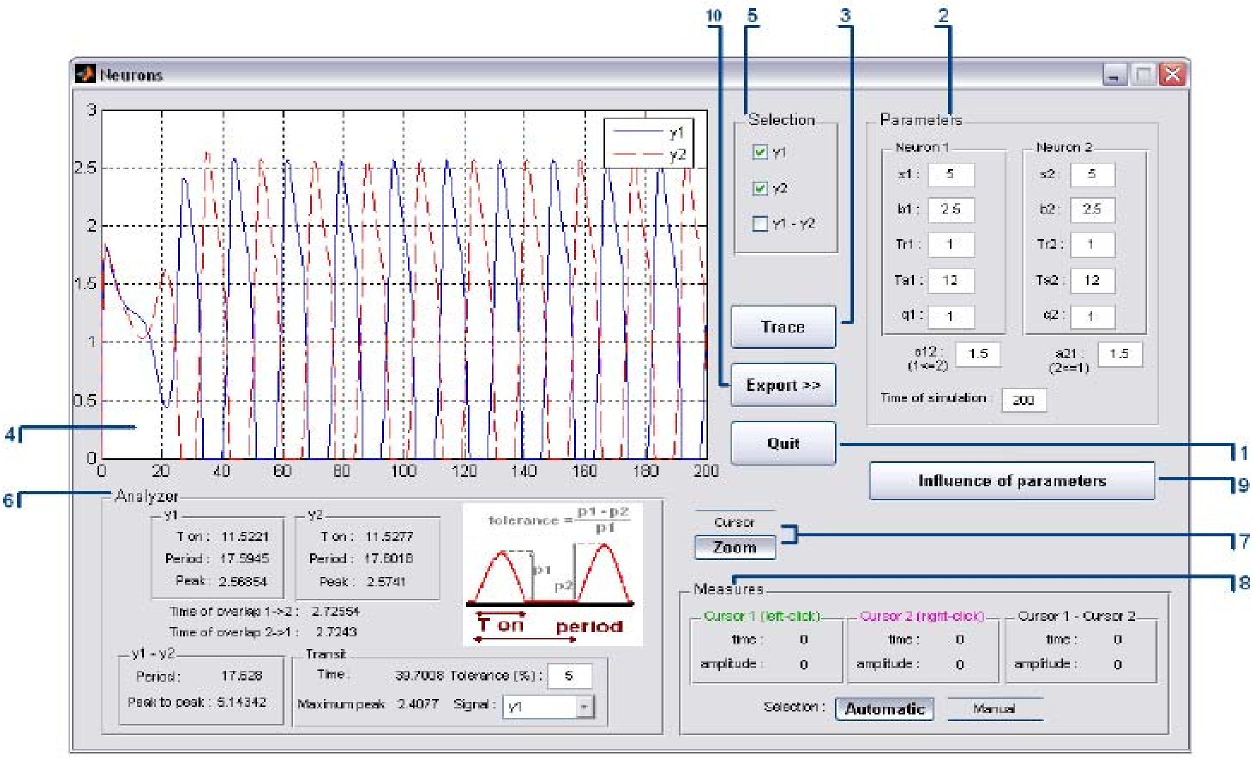


Figure 3-3 Graphic User Interface window ((Taken from Bouhet et al, 2007).

3.3.2 Analysis

By using the GUI, each parameter takes effect on the model but in different ways. The stationary periodic motion of the outputs is generated by the Matsuoka Oscillator (Figure 3-4). In this thesis, the variations of parameter are used only for s_1 and s_2 that are represented the two external inputs for the oscillator. These two variations are varied by the number of vehicles in the traffic condition. The other parameters do not have to change after calibrating the model. T_a and T_r represent the time constant, and thus modifying the two parameters is the first thing if we want to change the shape and frequency of the oscillator which is time values (T_{on} and period) of output (Figure 3-6), but we have to note that T_a should be about ten times larger than Tr. In order to prevent the shape of output pattern to be impaired, we have to keep a coefficient $2/3$ between a_{ij} and b ($a_{ij}/b = 2/3$).

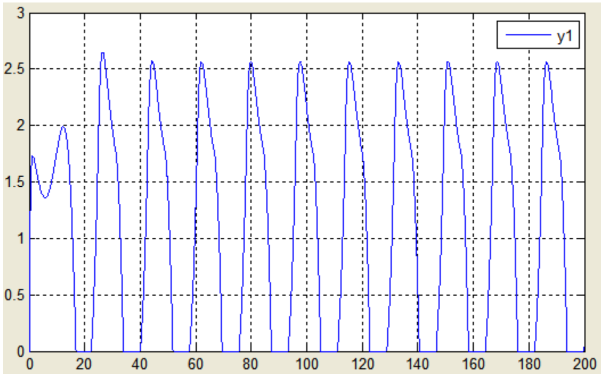


Figure 3-4 The stationary periodic output of Matsuoka Oscillator

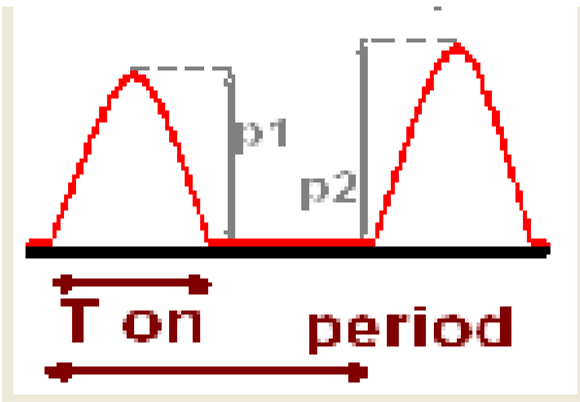
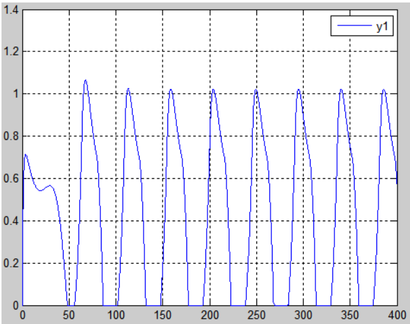
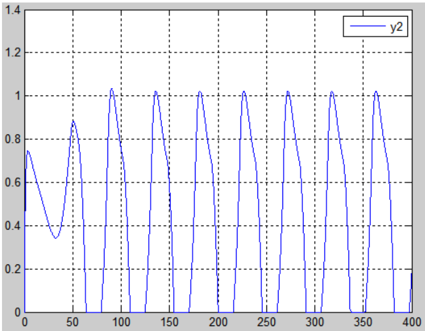


Figure 3-5 The time values of T_{on} and period

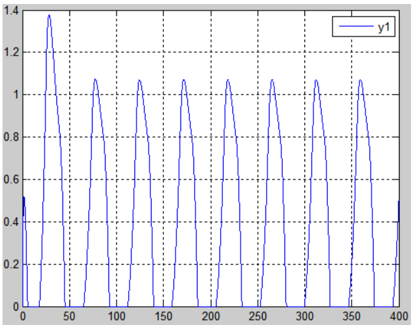
The next step is to analyze the relationship between external inputs and outputs under the condition that s_1 and s_2 are only two changeable parameters in the oscillator. Then we assume other variables are fixed that represent as: $b_1 = b_2 = 2.5$, $a_{12} = a_{21} = 1.5$, $T_{r1} = T_{r2} = 1$, and $T_{a1} = T_{a2} = 15$. Let external input 1 (s_1) be a constant of 3 and increase the input 2 (s_2) from a constant of 3.



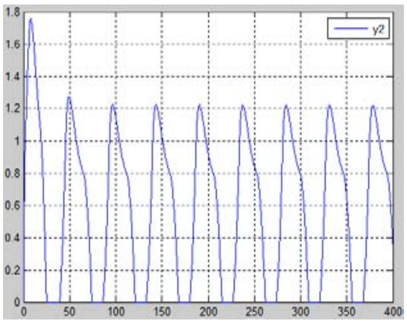
When Input 1 =3



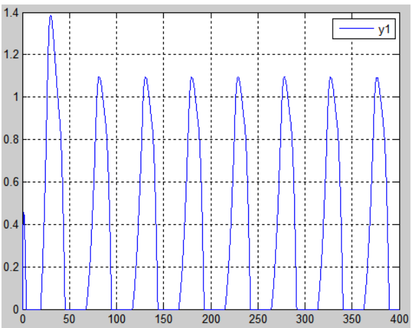
Input 2 = 3



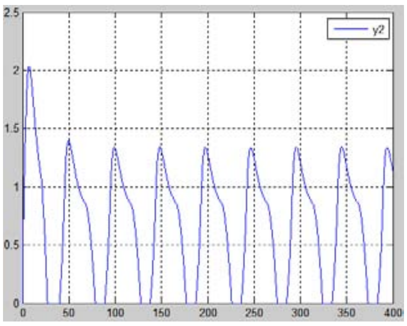
When input 1 = 3



Input 2 = 3.5



When input 1 = 3



Input 2 = 4.0

Figure 3-6 The outputs with constant input 1 and increasing input 2.

We can find the characteristics and the relationship between inputs and outputs of a Matsuoka Oscillator by this experiment. From figure 3-6, the output 1 and output 2 have the same amplitude, period, and T_{on} (shown in figure 3-5) with the same value of input 1 and input 2 which are constant 3. Then we keep input 1 as constant 3 and increase input 2 to 3.5. The average amplitude of output 1 keeps the same as previous test and T_{on} is narrow, and then the average amplitude of output 2 increases from 1 to about 1.2 and T_{on} of input 2 becomes larger. T_{on} of output 1 is going narrow and T_{on} and average amplitude of output 2 become larger and larger after increasing the value of input 2 up to 4.0.

There is another characteristic of the Matsuoka Oscillator that can be analyzed by using a GUI. In the procedure of this test, we find out that there must be met a certain range of ratio between two external inputs (s_1 and s_2). For example, we use the constant 3 as the input 1 and increase the value of input 2 by 0.1 each time, then we find out that the biggest value of input 2 will be 4.9 (Table 3-1). The output 2 can not generate the oscillation if the value of input 2 is bigger than 4.9. The biggest rate of input 1 and input 2 is about 1.63 in this case. If we keep input 1 as constant 4 and increase the value of input 2 by 0.1 each time from 4, then the biggest value of input 2 will be 7. The certain range of ratio between input 1 and input 2 is 1.75.

In conclusion, the relationship between T_{on} of outputs and the difference between two inputs are proportional. A larger difference between input 1 and input 2 will generate a larger T_{on} of outputs. There is a certain range of ratio between input 1 and input 2 that must be met.

Table 3-1 The relationship of outputs ($T_{on}1$ and $T_{on}2$) in a Matsuoka Oscillator with constant input 1 (3.0) and increasing input 2.

Input 1 (s1)	Input 2 (s2)	Output 1 (Ton 1)	Output 2 (Ton 2)	Difference
3.0	3.0	30.0	30.0	0
3.0	3.1	29.4	30.5	1.1
3.0	3.2	29.0	31.1	2.1
3.0	3.3	28.6	31.7	3.1
3.0	3.4	28.3	32.4	4.1
3.0	3.5	27.9	33.1	5.2
3.0	3.6	27.7	33.7	6.0
3.0	3.7	27.5	34.6	7.1
3.0	3.8	27.3	35.4	8.1
3.0	3.9	27.1	36.2	9.1
3.0	4.0	27.0	37.2	10.2
3.0	4.1	27.1	38.1	11.0
3.0	4.2	27.0	39.1	12.1
3.0	4.3	27.0	40.3	13.3
3.0	4.4	27.1	41.4	14.3
3.0	4.5	27.2	42.8	15.6
3.0	4.6	27.4	44.2	16.8
3.0	4.7	27.6	46.0	18.4
3.0	4.8	27.8	48.0	20.2
3.0	4.9	28.1	51.3	23.2

3.3.3 Calibration of the Matsuoka Oscillator

The purpose of this thesis is to design the traffic control system with Matsuoka Oscillator which is calibrated based on fixed time control system. We set up the fixed time schedule with total fixed cycle time 68 seconds and it consists of 30 seconds of green time on each phase and 4 seconds of amber time (Figure 3-7).

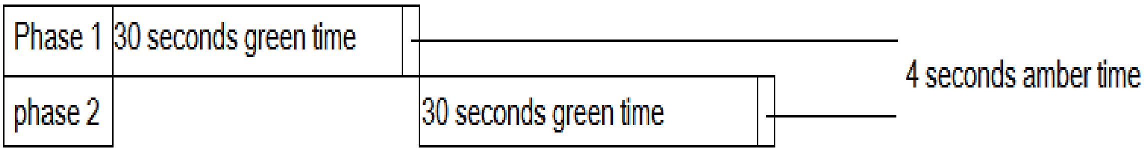


Figure 3-7 The table of fixed cycle time

As we know, T_{on} of the outputs has the proportional relationship with the difference within two external inputs. So we let T_{on} as the output of the traffic system with Matsuoka Oscillator which represents the green time on each phase. In order to calibrate the Matsuoka model, we need to set value of T_{on} equals 30 which is same as the green time on each phase in fixed time control system. By testing, we can get T_{on} = 30 when $b_1 = b_2$ = 2.5, $T_{r1} = T_{r2}$ =3, $T_{a1} = T_{a2}$ =28, and $a_{21} = a_{12}$ =1.5.

According to the characteristic of Matsuoka Oscillator, external inputs s_1 and s_2 have a constant difference. By analyzing, the certain range of ratio is proportional to the values of s_1 and s_2. But the certain range of ratio dose not significantly affects the outputs of oscillator.

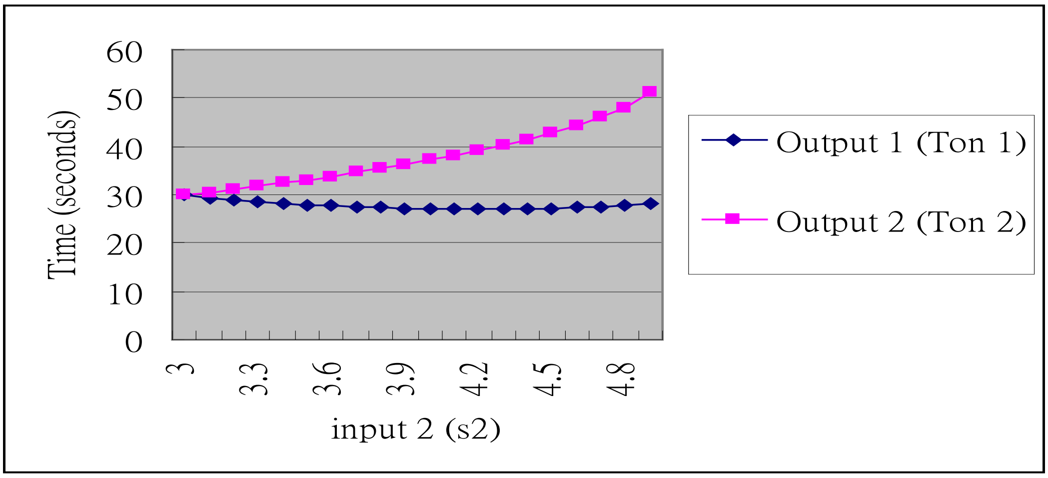


Figure 3-8 The relationship between Ton 1 and Ton 2 with increasing s2 and constant s1.

The figure 3-8 shows the relationship between $T_{on}1$ and $T_{on}2$. In this experiment, we keep the input 1 as constant value 3.0, then increasing the value of input 2 from 3.0 to 4.9. The biggest ratio between s_1 and s_2 is about 1.63 (4.9 / 3 = 1.63). $T_{on}1$ and $T_{on}2$ represent the duration of signal time in seconds. From the figure 3-8, the values of output 1 drops down from 30s to 27s. The values of output 2 increase dramatically from 30s to 51s.

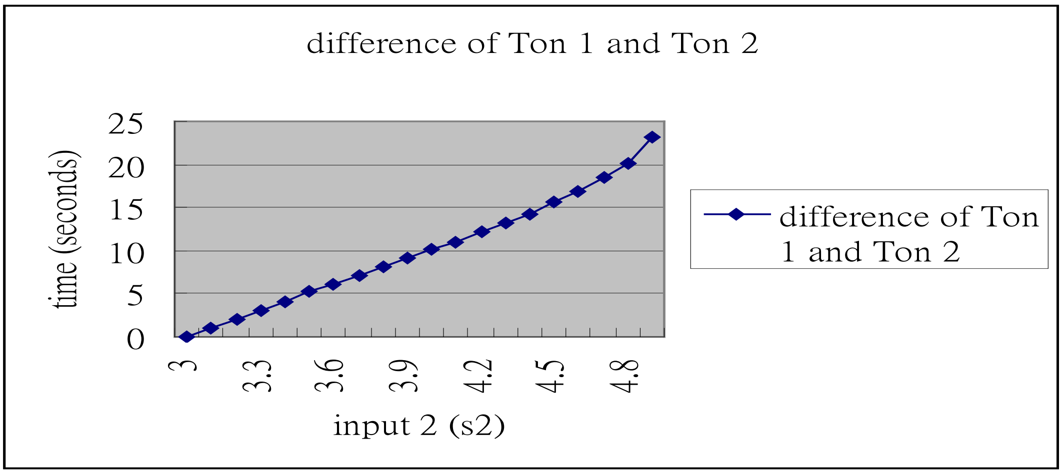


Figure 3-9 The difference of Ton 1 and Ton 2 (the value of input 1 is 3.0 and input 2 is increasing from 3 to 4.9).

Figure 3-9 shows an approximately linear relationship between the difference within output 1 ($T_{on}1$) and output 2 ($T_{on}2$) when input 1 is constant and increasing input 2. The maximum difference values of $T_{on}1$ and $T_{on}2$ is 23s.

According to above experiments, we can assume that there is no vehicle waiting or passing through the intersection in the phase 1 (s_1) and the number of vehicles waiting on the queue or passing through in phase 2 (s_2) is increasing. In this scenario, the control system gives more and more green time in phase 2 (T_{on} 2) because of increasing the number of vehicles.

Table 3-2 The relationship of outputs ($T_{on}1$ and T_{on} 2) for a Matsuoka Oscillator with increasing input 1 (from 3.0 to 4.9) and decreasing input 2 (from 4.9 to 3.0).

Input 1 (s1)	Input 2 (s2)	Output 1 (Ton 1)	Output 2 (Ton 2)	Difference
3.0	4.9	28.1	51.3	23.2
3.1	4.8	27.4	45.0	17.6
3.2	4.7	27.0	41.5	14.5
3.3	4.6	27.0	38.9	11.9
3.4	4.5	27.2	36.8	9.6
3.5	4.4	27.4	35.1	7.7
3.6	4.3	27.7	33.7	6.0
3.7	4.2	28.2	32.4	4.2
3.8	4.2	28.9	31.3	2.4
3.9	4.0	29.5	30.4	0.9
4.0	3.9	30.3	29.6	-0.7
4.1	3.8	31.4	28.8	-2.6
4.2	3.7	32.4	28.2	-4.2
4.3	3.6	33.7	27.7	-6.0
4.4	3.5	35.2	27.3	-7.9
4.5	3.4	36.8	27.1	-9.7
4.6	3.3	38.9	27.0	-11.9
4.7	3.2	41.5	27.1	-14.4
4.8	3.1	45.0	27.4	-17.6
4.9	3.0	51.3	28.1	-23.2

Table 3-2 shows the relationship of outputs ($T_{on}1$ and T_{on} 2) in Matsuoka Oscillator with increasing input 1 (from 3.0 to 4.9) and decreasing input 2 (from 4.9 to 3.0). This analysis indicates that there is a proportional relationship between the difference within inputs (s_1 and s_2) and the difference within outputs ($T_{on}1$ and T_{on} 2) in Matsuoka Oscillator.

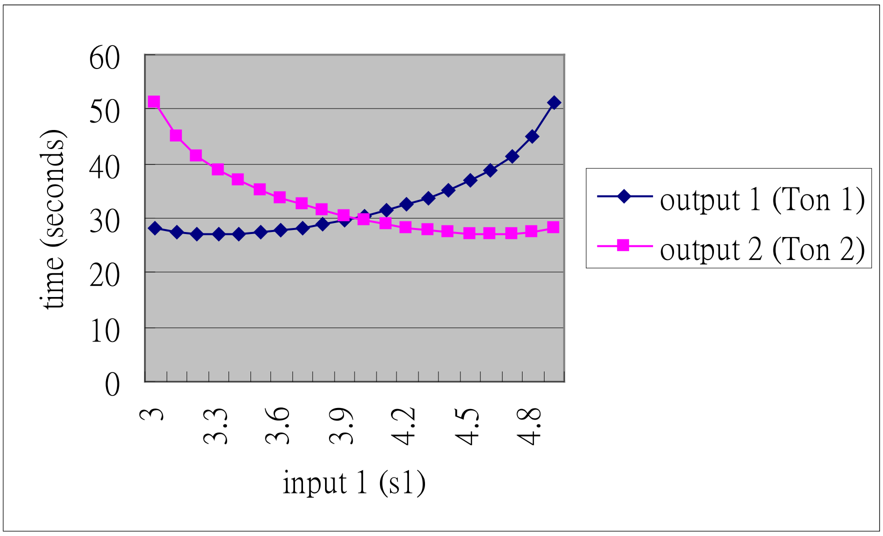


Figure 3-10 The outputs with increasing input 1 from 3 to 4.9 and decreasing input 2 from 4.9 to 3.

Another important characteristic of Matsuoka Oscillator is the fixed value of outputs when two external inputs have the same values. From figure 3-10, we find the value of output 1 is same as the output 2 which is 30s when input 1 equals input 2 which is value 4. This figure also indicates the proportional relationship of the difference within two outputs and difference within two inputs.

3.3.4 Initialization of external inputs of a Matsuoka Oscillator

From previous analysis of Matsuoka model, there must be a certain range of ratio between two external inputs of Matsuoka Oscillator. When input 1 is a constant value 3, the biggest value of input 2 is 4.9. The table below shows that the number of vehicles as the input of Matsuoka Oscillator.

Table 3-3 The number of vehicles present in inputs of Matsuoka Oscillator

The number of vehicles	Matsuoka model input
0~5	3.0
6	3.1
7	3.2
8	3.3
9	3.4
10	3.5
11	3.6
12	3.7
13	3.8
14	3.9
15	4.0
16	4.1
17	4.2
18	4.3
19	4.4
20	4.5
21	4.6
22	4.7
23	4.8
>23	4.9

3.3.4 Green extension time

For traffic actuated controller, the green time for each phase is determined by the volume of traffic on the corresponding street and may vary from cycle to cycle. A maximum and minimum green time are predetermined and set within the controller. The minimum initial green time is set to be adequate for the number of vehicles waiting between the stop line and detector. Each additional vehicle which triggers the detector during the green phase calls for a vehicle interval extension (Carl, 1995).

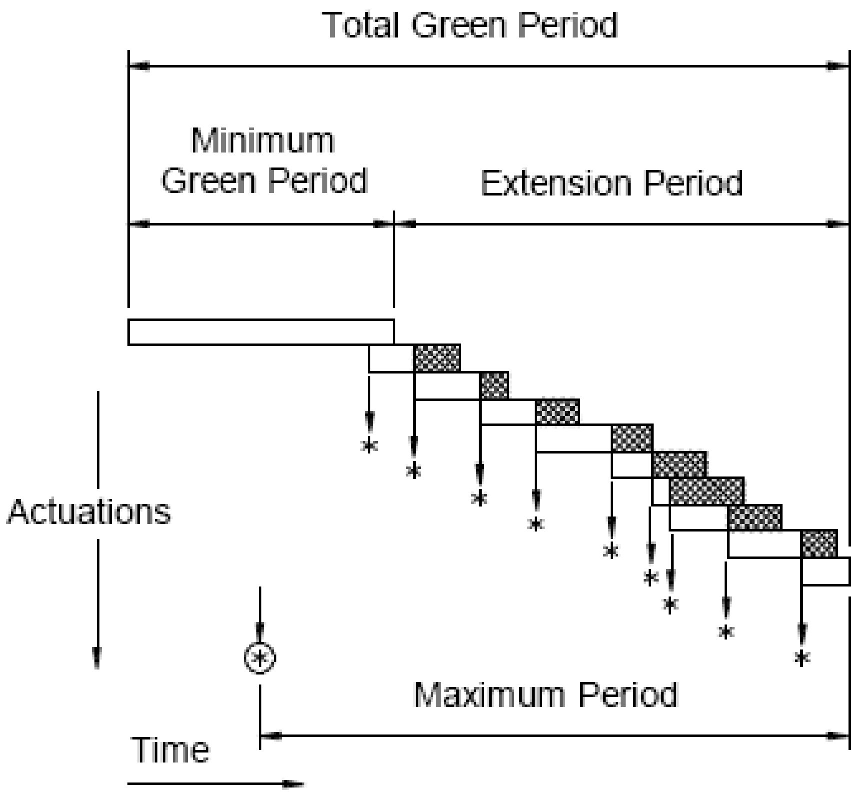


Figure 3-11 Actuated controller intervals (Taken from Carl, 1995).

According to the previous analysis, the minimum green period is 27 seconds, the maximum green time is 51 seconds and the extension period is 24 seconds in this traffic control system with Matsuoka Oscillator. The variation of extension period and maximum period depend on the difference of the number vehicles passing or waiting on each phase.

3.4 The structure of the traffic system controller

The entire control system is a closed loop system which is simulated using AIMSUN software. The traffic condition is generated by AIMSUN environment and the inputs are the number of vehicles waiting on the queue or passing through the intersection in phase 1 and phase 2. The Matsuoka Oscillator equation is written by C++ program and connected to AINSUM by API (Application Programming Interface). Each Matsuoka Oscillator generates two outputs but only one of them is used which represent the duration of next green time. Therefore, the results of the outputs will return back to the AIMSUN simulation environment in order to predict and control the traffic signals.

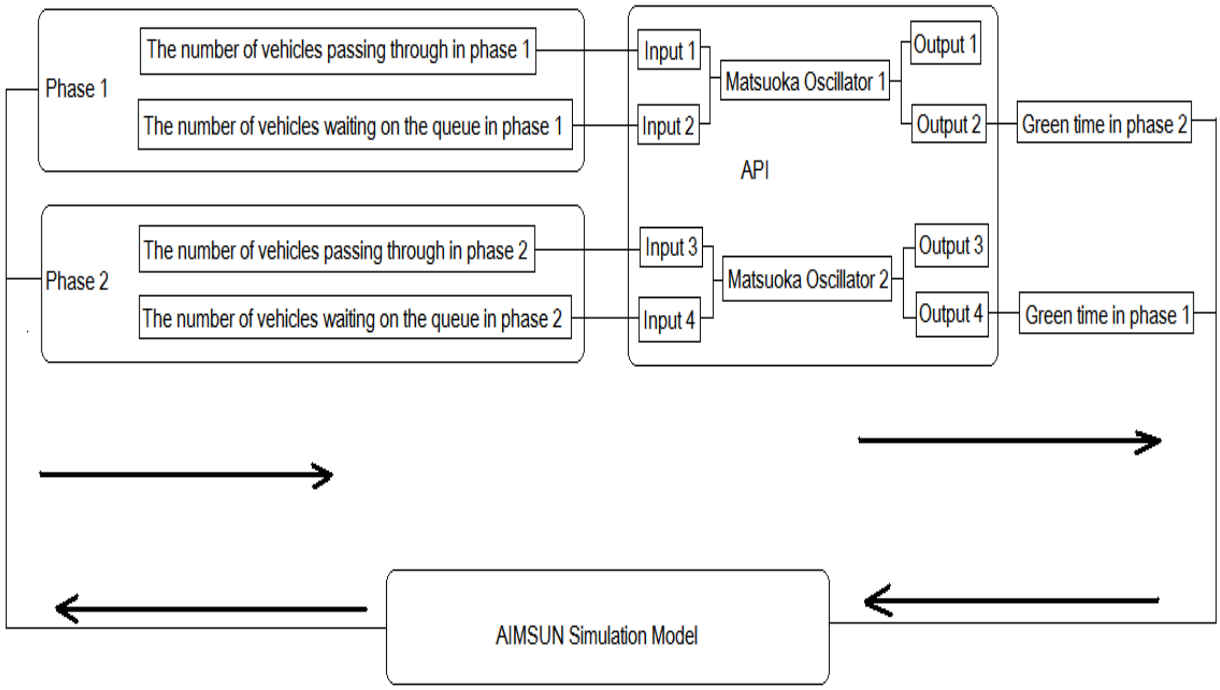


Figure 3-12 The structure of traffic system with two Matsuoka Oscillators.

3.5 The procedure of the control system

The isolated intersection with two phases (Figure 3-13) is operated by two control signals which work in a cycle. Figure 3-13 shows the traffic control time, each signal has 30 seconds green time and 4 seconds amber (yellow) time, the total cycle time is 68 seconds.

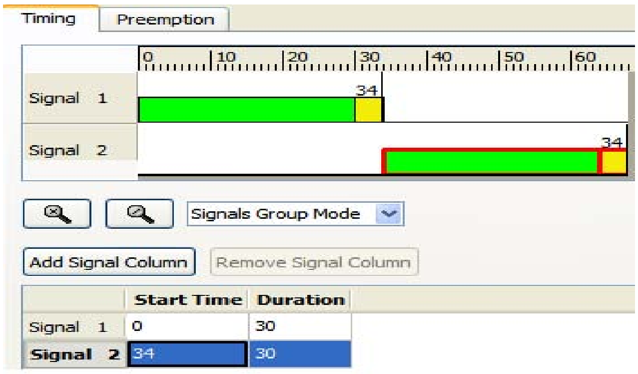


Figure 3-13 The traffic control cycle time

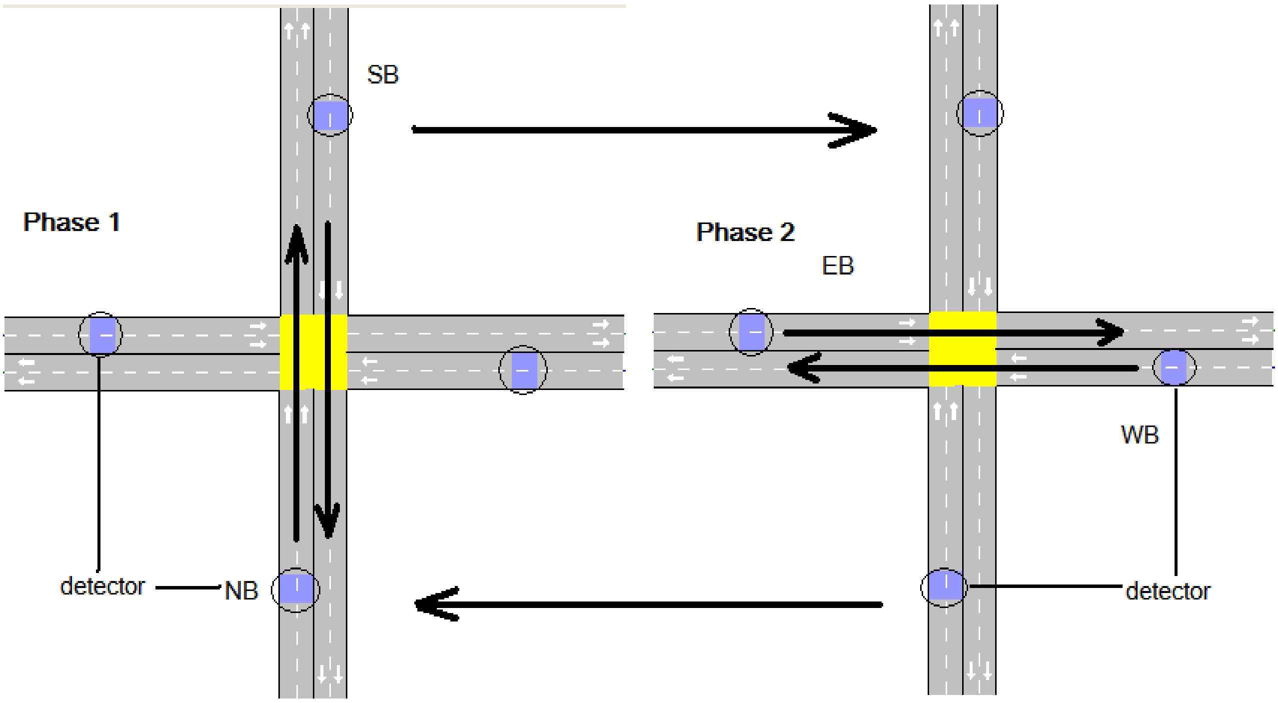


Figure 3-14 An insolated intersection with two phases

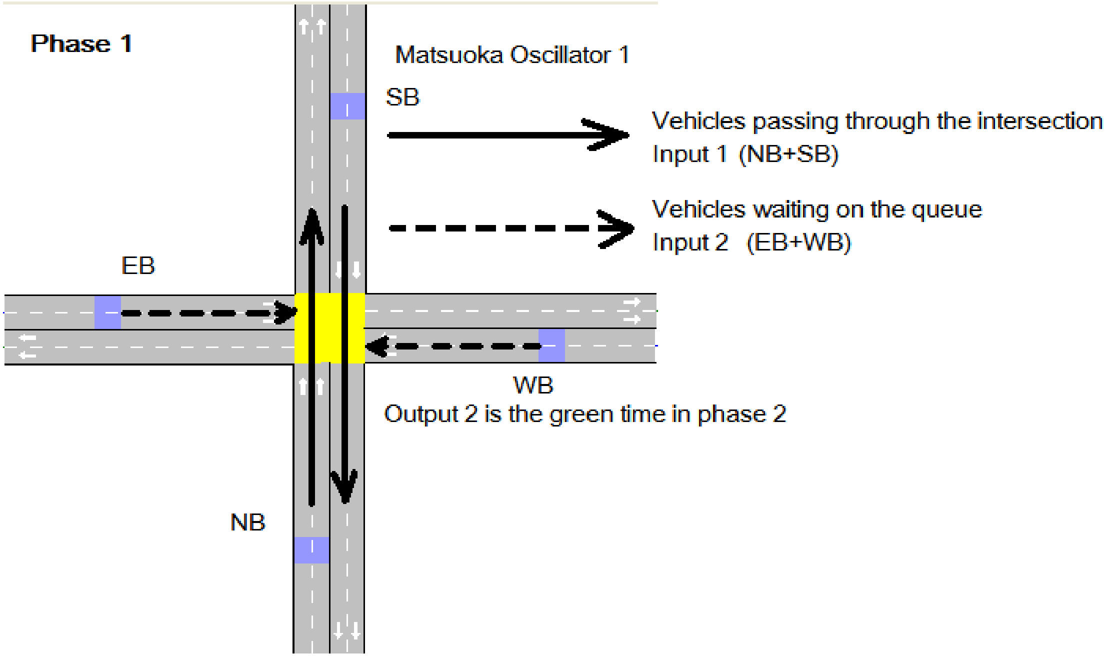


Figure 3-15 The relationship of input and output of Matsuoka Oscillator 1 in phase 1.

There are two phases in this isolated intersection which is controlled by two independent Matsuoka Oscillators. Firstly, the number of vehicles passing through the intersection from NB and SB is the input 1 in Matsuoka Oscillator 1, and then the number of vehicles waiting on the queue from EB and WB is input 2. The number of vehicles will be scaled to suitable input number in order to transform into a constant rate for the Matsuoka Oscillator. In this case, only output 2 is used in order to predict the green time for next phase (phase 2).

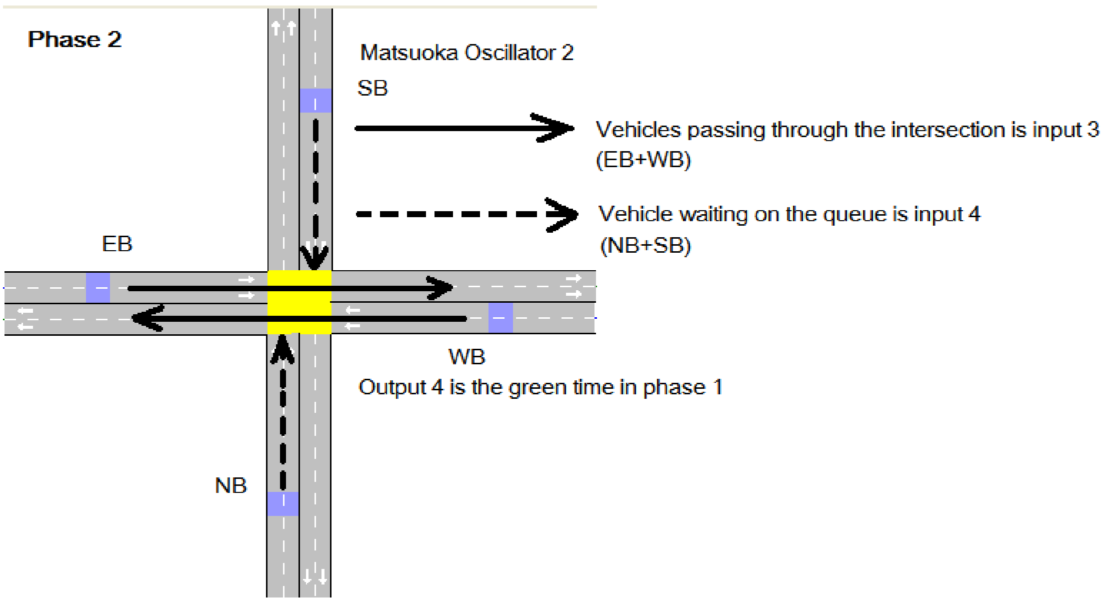


Figure 3-16 The relationship of input and output of Matsuoka Oscillator 2 in phase 2.

In phase 2, Matsuoka Oscillator 2 is implemented into the control system with input 3 and input 4 which represent by the number of vehicles passing through the intersection (EB and WB) and the number of vehicles waiting on the queue (NB and SB). The output 4 is used in this condition in order to predict how much green time for the next phase.

The traffic control system with Matsuoka Oscillators compares the number of vehicles passing through in one phase and waiting on the other. The phase gets more vehicles waiting on the queue that compare with number of vehicles passing through in other phase, the system allocates more extension green time to it. The main purpose of the Matsuoka Oscillator controller is to balance the traffic condition according to the dynamic traffic volume.

3.6 Simulation

3.6.1 AIMSUN v.6

AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Network) is part of GETRAM (Generic Environment for Traffic Analysis and Modeling) software which is developed at the Universitat Politècnica deCatalunya in Barcelona, Spain. GETRAM consists of a user-friendly graphical interface, a traffic network graphical editor (TEDI, Traffic Editor) which supports any kind of road type or network geometry, a network database and a module for storing and presenting results. It includes the traffic network editing, simulations, and the display performance of simulation that shows the moving vehicles through the network.

The model of an isolated intersection is described and simulated by AIMSUN software. The Matsuoka Oscillator controller is implemented by C++ (Visual Basic) and imported by AIMSUN. The purpose of the method is to adapt the green signal time and cycle time depending on the dynamic traffic volumes. The results of implementing Matsuoka Oscillator controller are compared against those based on the fixed time traffic controller. The performances of the simulation are total travel time (hours), delay time (seconds/km), and flow (vehicles/hr).

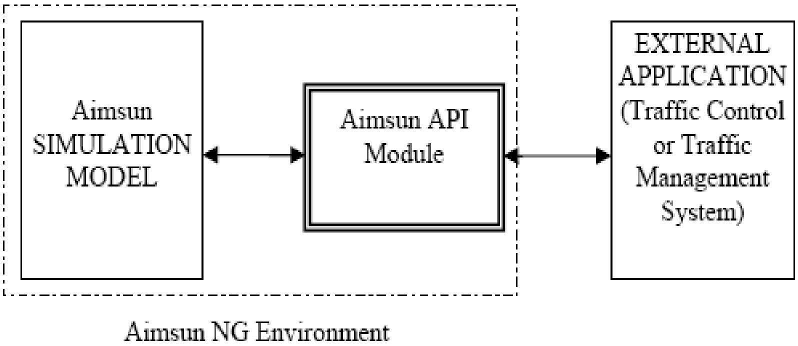


Figure 3-17 Communication between AIMSUN and other external applications. (Taken from Aimsun Microsimulator API Manual Draft Version, 2008)

The AIMSUN API (Application Programming Interface) module is used to enable the communication between the AIMSUN simulation model and a user-built control algorithm. Figure 3-17 shows the conceptual structure of how AIMSUN working with user application by means of AIMSUN API module.

There are eight high level functions that can guarantee the communication between the AIMSUN API Module and the AIMSUN Simulation model: AAPILoad, AAPIInit, AAPIManage, AAPIPostManage, AAPIFinish, APIUnLoad, AAPIEnterVehicle and AAPIExitVehicle (adapted from Aimsun Microsimulator API Manual Draft Version, 2008):

- AAPILoad (): It is called when the module is loaded by AIMSUN.
- AAPIInit (): It is called when AIMSUN starts the simulation and can be used to initialize whatever the module needs.
- AAPIManage (): This is called in every simulation step at the beginning of the cycle, and can be used to request detector measures, vehicle information and interact with junctions, metering and VMS in order to implement the control and management policy.
- AAPIPostManage (): This is called in every simulation step at the end of the cycle, and can be used to request detector measures, vehicle information and interact with junctions, metering and VMS in order to implement the control and management policy.
- AAPIFinish (): It is called when AIMSUN finish the simulation and can be used to finish whatever the module needs.
- AAPIUnLoad (): It is called when the module is unloaded by AIMSUN.

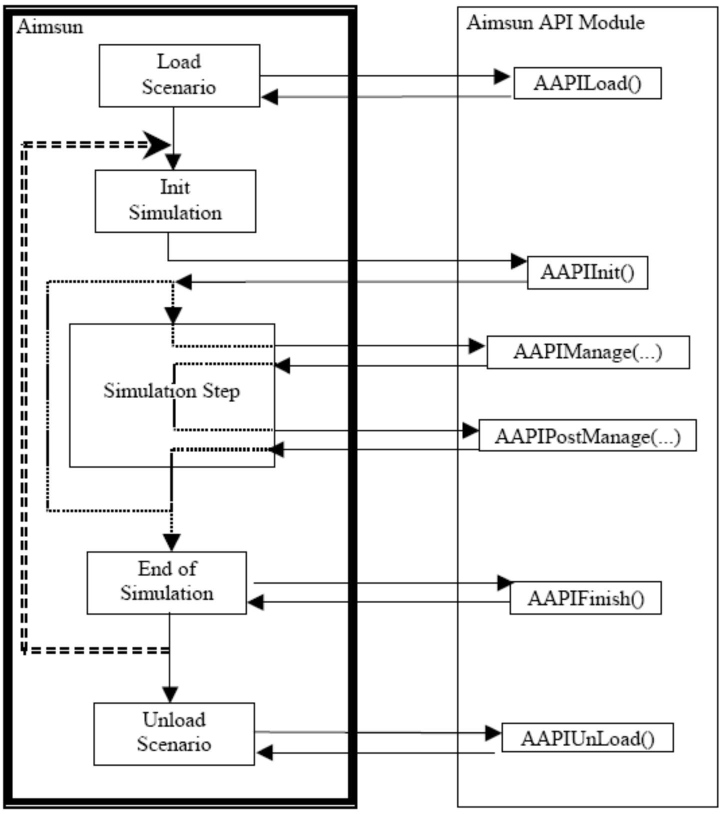


Figure 3-18 Interaction between AIMSUN and its API (Taken from Aimsun Microsimulator API Manual Draft Version, 2008)

3.6.2 Calibration of the AINSUM Environment

Table 3-4 shows the calibration of data requirement for calibrating the AINSUM environment. The signal information is set for a fixed time control system with the total cycle length 68 seconds. The duration of signals are changed depending on the variation of dynamic traffic volume in a traffic control system with the Matsuoka Oscillator.

Table 3-4 Data requirements for calibrating the AINSUM environment

Section Information	Vehicles Information
Road type: arterial Length: 50 metres Capacity: 1800 vehicles/hr Visibility distance: 25 metres Jam Density: 200 vehicles/km Vehicle Speed in the intersection: 10km/h	Driver's reaction time: 0.5 seconds Response time to stop: 1.35 seconds The mean of length: 4 metres The mean speed of vehicle: 50 km/hour Max acceleration: 3 m/s^2 Max deceleration: 6 m/s^2
Detectors Information	Signals Information (fixed time)
Length: 4.5 metres Distance to exit: 35 metres	Cycle length: 68 seconds Green time in phase 1: 30 seconds Green time in phase 2: 30 seconds Yellow time: 4 seconds

Table 3-4 Data requirements for calibrating the AINSUM environment

3.7 Analysis

This section includes two types of analysis in order to characterize the traffic control system with Matsuoka Oscillator. First, the stability of Matsuoka model is tested with same traffic volume from each band but different total traffic demand at the isolated intersection with two phases. The traffic performance is compared with the fixed time control system and the system with Matsuoka Oscillator in section 3.7.1. Section 3.7.2 discusses how the unbalance traffic demands affect the inputs and outputs of Matsuoka model and traffic performance in the entire system. This section compares the delay time on each band by using Matsuoka model and fixed time control model. This section also discusses the performance of traffic condition such as total travel time (hours), average delay time (seconds/km), and flow (vehicles/ hour).

3.7.1 Different total traffic demand

Table 3-3 shows the five scenarios with same traffic volume from each band but different total traffic demand during an hour. The total traffic demand increases from 2000 vehicles/hour to 6000 vehicles/ hour and each band has the same traffic volume.

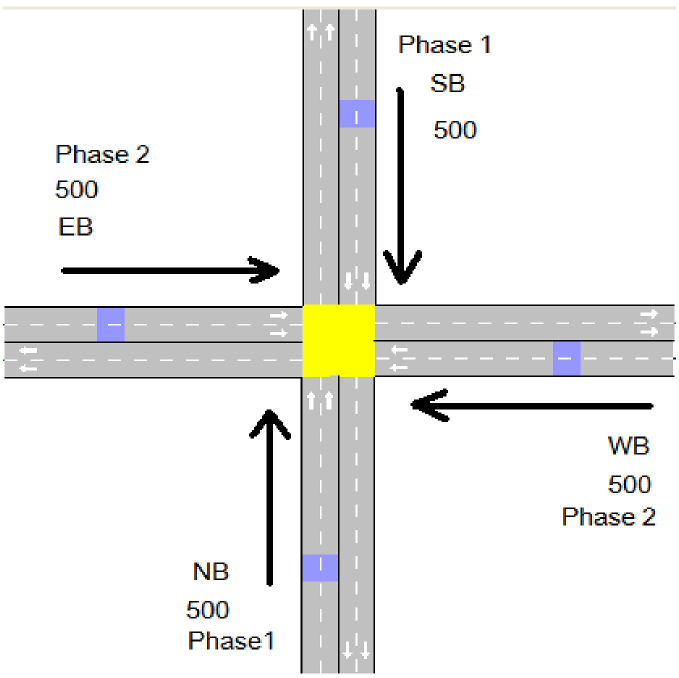


Figure 3-19 The simulated isolated intersection with same traffic volume scenario

Table 3-5 Traffic scenarios with same traffic volume on each band but increasing total traffic demands.

#	Scenario	Movement Type	Demand (vehicles/h)	Total Demand (1h)
1	Low Demand	NB	500	2000
		WB	500	
		SB	500	
		EB	500	
2	Medium Demand	NB	750	3000
		WB	750	
		SB	750	
		EB	750	
3	Medium Demand	NB	1000	4000
		WB	1000	
		SB	1000	
		EB	1000	
4	High Demand	NB	1250	5000
		WB	1250	
		SB	1250	
		EB	1250	
5	High Demand	NB	1500	6000
		WB	1500	
		SB	1500	
		EB	1500	

Table 3-6 The inputs and outputs of Matsuoka model with same traffic volume on each band but different total traffic demand after the simulation.

#	Scenario	Input = (total vehicles/hour) Average = (average vehicles/cycle)					Output (seconds)		
1	Low Demand (2000 vehicles/hour)	MO1	Input1	417	Average	8	Output 2	Phase 2 average green time	30.93
			Input2	422	Average	8			
		MO2	Input3	434	Average	8	Output 4	Phase 1 average green time	30.59
			Input4	428	Average	8			
2	Medium Demand (3000 vehicles/hour)	MO1	Input1	685	Average	12	Output 2	Phase 2 average green time	30.88
			Input2	660	Average	12			
		MO2	Input3	692	Average	13	Output 4	Phase 1 average green time	28.93
			Input4	662	Average	12			
3	Medium Demand (4000 vehicles/hour)	MO1	Input1	876	Average	16	Output 2	Phase 2 average green time	30.75
			Input2	863	Average	15			
		MO2	Input3	947	Average	17	Output 4	Phase 1 average green time	28.03
			Input4	874	Average	16			
4	High Demand (5000 vehicles/hour)	MO1	Input1	1125	Average	20	Output 2	Phase 2 average green time	30.54
			Input2	1026	Average	19			
		MO2	Input3	1219	Average	22	Output 4	Phase 1 average green time	27.23
			Input4	1051	Average	19			
5	High Demand (6000 vehicles/hour)	MO1	Input1	1339	Average	24	Output 2	Phase 2 average green time	31.41
			Input2	1212	Average	22			
		MO2	Input3	1597	Average	29	Output 4	Phase 1 average green time	27.58
			Input4	1289	Average	23			

3.7.1.1 Inputs and outputs analysis

Table 3-6 shows the actual inputs and outputs in Matsuoka Oscillators after the simulation. The average of input 1 and input 3 represent the average number of vehicles passing through the intersection in each cycle time from each phase. On the other hand, the average of input 2 and input 4 are the average number of vehicles waiting on the queue in each cycle time from each phase.

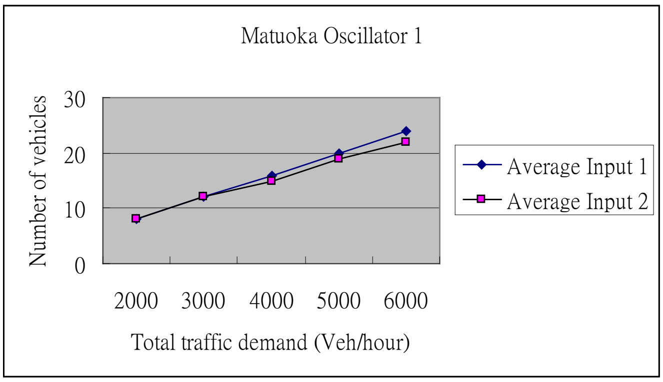


Figure 3-20 The average inputs of Matsuoka Oscillator 1 with different total traffic demands.

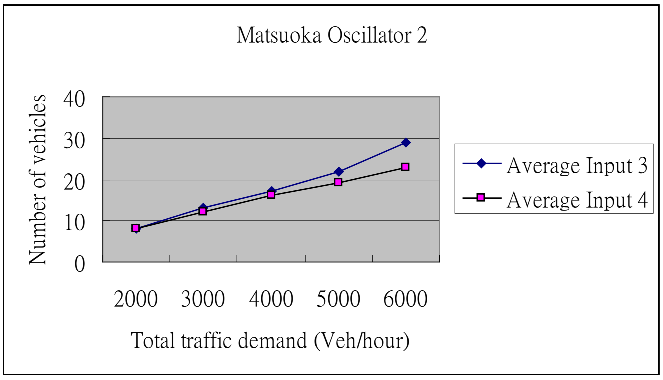


Figure 3-21 The average inputs of Matsuoka Oscillator 2 with different total traffic demands.

From above figures, the average inputs of two Matsuoka Oscillators have almost the same values when the total traffic demand is less than 4000 vehicles/hour. In Matsuoka Oscillator 1, the average input 1 and input 2 do not have much difference during the high total traffic demand scenarios. In Matsuoka Oscillator 2, the difference between average input 3 and input 4 increases in the high total traffic demand scenarios. The largest difference between these two inputs is 6 which occur when the total traffic demand is 6000 vehicles/hour.

Figure 3-22 shows the average green time in phase 1 and phase 2 with different total traffic demand scenarios. The average green time in phase 1 (Output 4) keeps between 30 seconds and 31 seconds until the total traffic demand is larger than 6000 vehicles/hour. The average time in phase 2 (Output 2) decreases slightly from 30.6s to 27.6s with increasing total traffic demands. The largest difference between average green time in phase 1 and phase 2 is 3.8s which occurs when the total traffic demand is 6000 vehicles/hour.

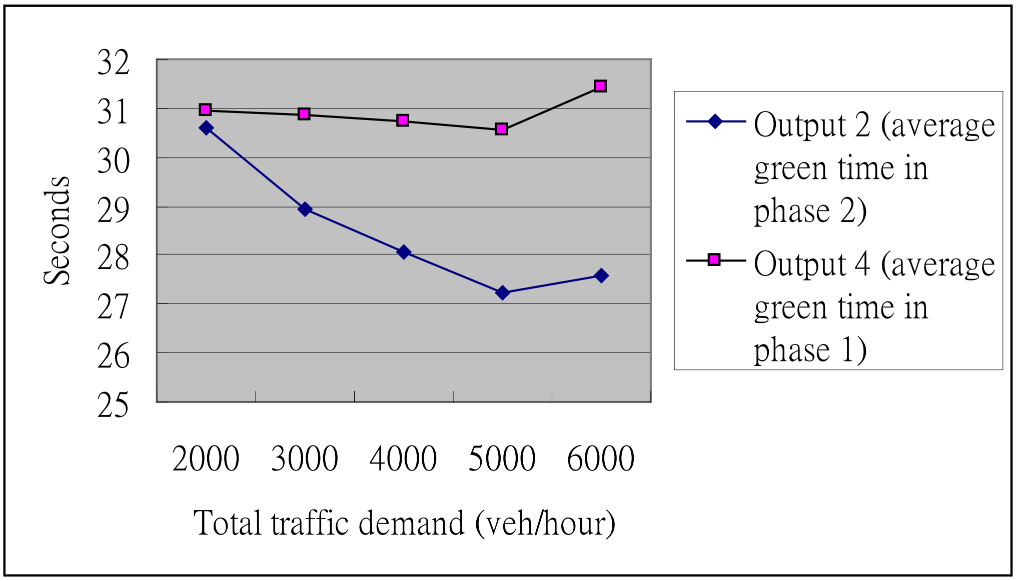


Figure 3-22 The average green time in phase 1 and phase 2 with different total traffic demand scenarios.

3.7.1.2 Comparison of traffic performance

Scenario	Total travel time (hours)		Improvement % Change	Delay time (seconds/km)		Improvement % Change	Flow (veh/hour)		Improvement % Change
	Matsuoka	Fixed		Matsuoka	Fixed		Matsuoka	Fixed	
1	10.24	10.26	+0.1%	103.15	101.14	-2.0%	1942	1974	-1.6%
2	16.13	16.32	+1.2%	106.99	107.84	+0.8%	3000	3018	-0.6%
3	21.83	22.54	+3.3%	111.26	116.64	+4.8%	3960	3968	-0.2%
4	28.21	29.44	+4.4%	119.02	123.19	+3.5%	4920	5003	-1.7%
5	35.33	36.18	+2.4%	126.01	128.10	+1.7%	5913	5949	-0.6%

Table 3-7 The comparison of performance between control system with Matsuoka Oscillator and fixed time control system.

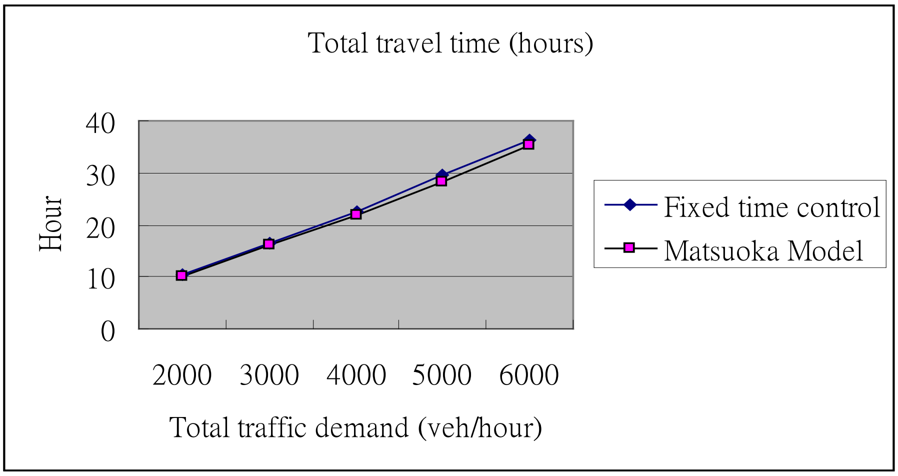


Figure 3-23 Comparison of total travel time (Matsuoka model v.s. Fixed time control).

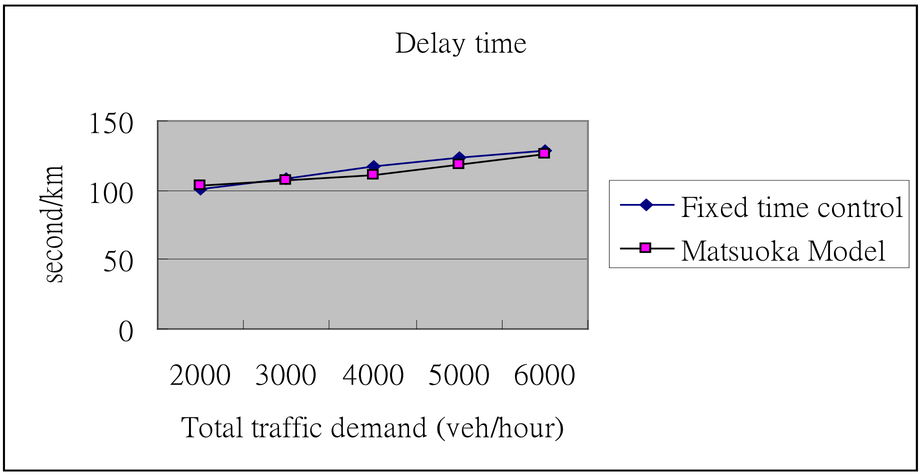


Figure 3-24 Comparison of delay time (Matsuoka model v.s. Fixed time control).

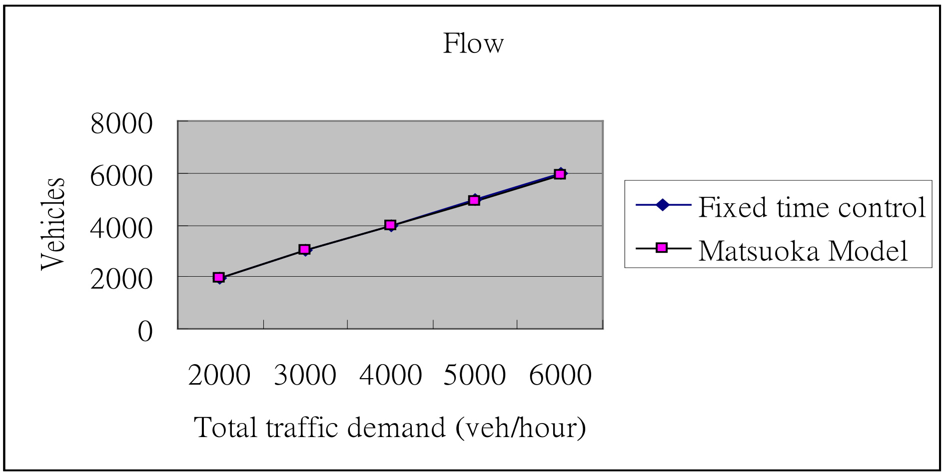


Figure 3-25 Comparison of flow (Matsuoka model v.s. Fixed time control).

Figure 3-23 indicates the Matsuoka model has improvement of total travel time from 3.3% to 4.4% which is compared with the fixed time control system in the medium and high total traffic demand scenarios. There is no change between Matsuoka model and fixed time control system when the total traffic demand is low.

The performance of delay time in the Matsuoka model is improved by 4.8% and 3.5% in the scenarios with total traffic demand 4000 and 5000 vehicles/hour respectively. It does not change much when the traffic demand is low. Figure 3-25 shows the performance of flow between Matsuoka model and fixed time control system is almost the same.

3.7.1.2 Summary

The main propose of this section is to test the stability of the control system with Matsuoka Oscillator with the same traffic volume but different total traffic demands. According to the methodology of Matsuoka Oscillator, the ideal inputs of Matsuoka Oscillators should be equal when there is same traffic volume from each band. From section 3.7.1.1, there is no difference between two inputs and outputs of Matsuoka Oscillators when the total traffic demand is less than 3000 vehicles/hour. In the scenarios with high total traffic demands, the difference between two inputs of the Matsuoka Oscillator is becoming larger.

From the analysis of traffic performance, the slight differences between average green times between two phases do not affect much in the entire traffic performance which is compared with the fixed time control system. In conclusion, the traffic control system with Matsuoka Oscillator is stable in the scenarios with the same traffic volume from each band.

3.7.2 Unbalanced traffic demand

This section studies three types of analysis in the scenarios with unbalanced traffic demands. Firstly, section 3.7.2.1 analyzes the variation of inputs and outputs in Matsuoka Oscillators with unbalanced traffic demands. The comparison of delay time on each band by using Matsuoka model and fixed time control system will be discussed in section 3.7.2.2. The comparison of traffic performance between Matsuoka model and fixed time control is discussed in section 3.7.2.3.

Firstly, we assume that more and more vehicles coming on EB at this isolated intersection. This section increases the traffic demand on EB by 500 vehicles/ hour in each scenario and maintains the traffic volume 500 vehicles/ hour from the other three bands.

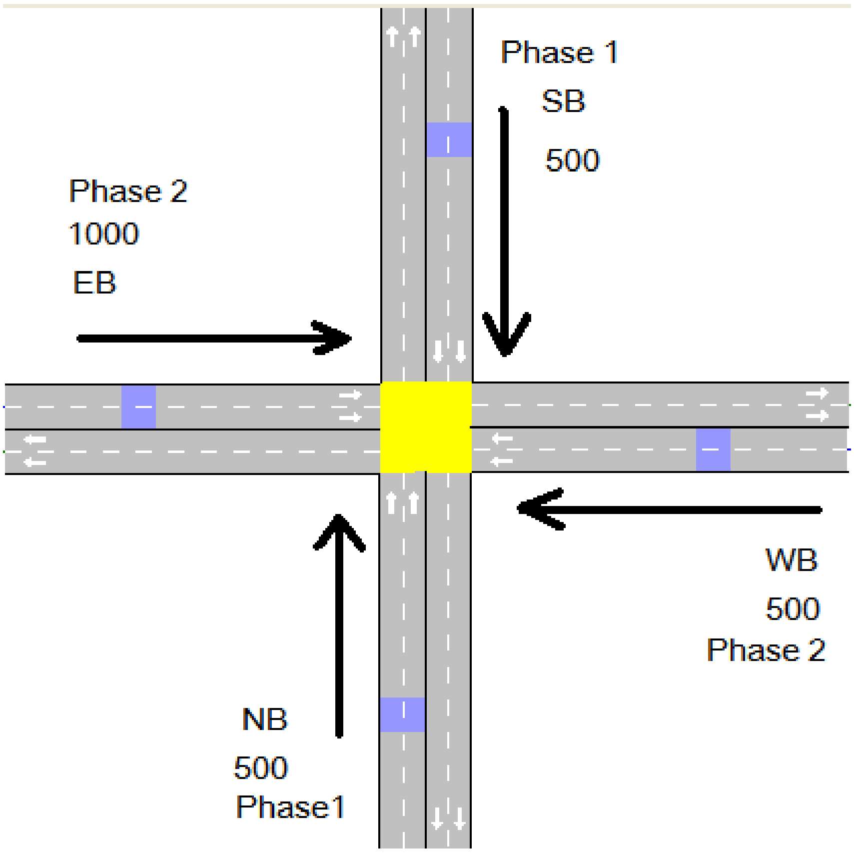


Figure 3-26 Unbalance traffic demand scenario with increasing travel volume on the EB.

Table 3-8 Unbalanced traffic demand scenarios with increasing traffic volume on EB.

#	Scenario	Movement Type	Demand (vehicles/hour)	Total Demand (1h)
1	Medium EB Demand (1000 vehicles/hour)	NB	500	2500
		WB	500	
		SB	500	
		EB	**1000**	
2	Medium EB Demand (1500 vehicles/hour)	NB	500	3000
		WB	500	
		SB	500	
		EB	**1500**	
3	High EB Demand (2000 vehicles/hour)	NB	500	3500
		WB	500	
		SB	500	
		EB	**2000**	
4	High EB Demand (2500 vehicles/hour)	NB	500	4000
		WB	500	
		SB	500	
		EB	**2500**	
5	High EB Demand (3000 vehicles/hour)	NB	500	4500
		WB	500	
		SB	500	
		EB	**3000**	

Table 3-9 The table of inputs and outputs in Matsuoka model in unbalanced traffic demand scenarios after the simulation.

#	Scenario	Input = (total vehicles/hour) Average = (average vehicles/cycle)					Output (seconds)		
1	Medium EB Demand (1000 veh/hour)	MO1	Input1	378	Average	7	Output 2	Phase 2 average green time	33.3
			Input2	604	Average	11			
		MO2	Input3	736	Average	14	Output 4	Phase 1 average green time	28.6
			Input4	464	Average	8			
2	Medium EB Demand (1500 veh/hour)	MO1	Input1	397	Average	7	Output 2	Phase 2 average green time	35.0
			Input2	759	Average	14			
		MO2	Input3	1060	Average	12	Output 4	Phase 1 average green time	27.8
			Input4	485	Average	9			
3	High EB Demand (2000 veh/hour)	MO1	Input1	365	Average	7	Output 2	Phase 2 average green time	37.3
			Input2	853	Average	17			
		MO2	Input3	1439	Average	28	Output 4	Phase 1 average green time	27.7
			Input4	511	Average	10			
4	High EB Demand (2500 veh/hour)	MO1	Input1	370	Average	7	Output 2	Phase 2 average green time	35.9
			Input2	793	Average	15			
		MO2	Input3	1779	Average	34	Output 4	Phase 1 average green time	27.6
			Input4	461	Average	9			
5	High EB Demand (3000 veh/hour)	MO1	Input1	362	Average	7	Output 2	Phase 2 average green time	38.4
			Input2	934	Average	19			
		MO2	Input3	1775	Average	36	Output 4	Phase 1 average green time	27.7
			Input4	470	Average	9			

3.7.2.1 Input and output analysis

Figure 3-27 and 3-28 shows the average inputs of Matsuoka Oscillators with increasing traffic volume on EB. According to the relationship inputs of Matsuoka Oscillators and traffic condition (Table 3-7), input 2 and input 3 increase because of increasing traffic volume EB. The average of input 1 and input 4 maintain as constant between 8 and 10 vehicles in one cycle time. The largest difference occurs when the traffic volume on EB is 3000 vehicles/hour, the difference between average input 1 and input 2 is 12 vehicles, and the difference between average input 3 and input 4 is 27 vehicles.

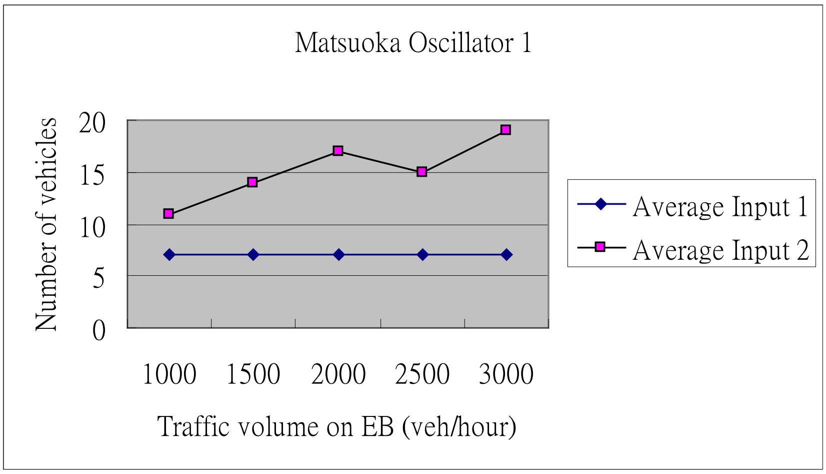


Figure 3-27 The average inputs of Matsuoka Oscillator 1 with unbalanced traffic demands.

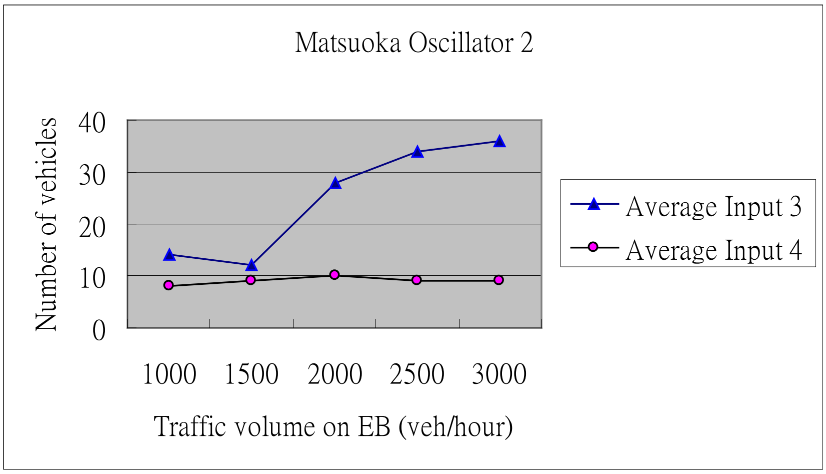


Figure 3-28 The average inputs of Matsuoka Oscillator 2 with unbalanced traffic demands.

The average output 2 of Matsuoka Oscillator 1 increases from 33.3s to 38.4s because of increasing difference between average input 1 and input 2. The largest average green time in phase 2 (average output 2) is 38.4s when traffic volume on EB is 3000 vehicles/hour. The average green time in phase 1 (average output 4) maintain around the minimum green time 27s.

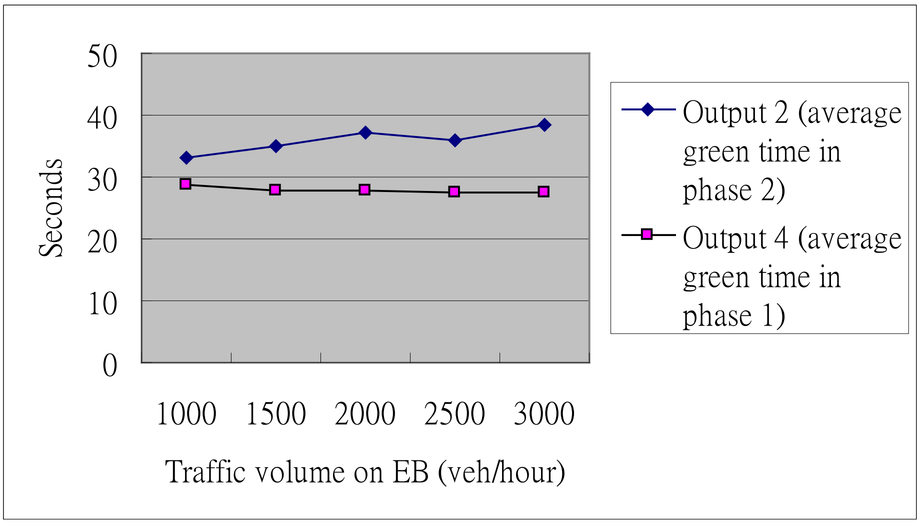


Figure 3-29 The average green time in phase 1 and phase 2 with different total traffic demand scenarios.

This analysis is under the unbalanced traffic demand scenarios which is increasing the traffic volume on EB. In the simulation traffic condition, the numbers of vehicles waiting on the queue and passing through intersection from EB are increasing. From aspect of Matsuoka Oscillator, the input 2 in MO1 and input 3 in MO 2 increases under these scenarios.

This section of analysis indicates the traffic system with the Matsuoka Oscillator controls the duration of green time in each phase according to the dynamic traffic condition. This system allocates more green time in phase 2 because there are more traffic demands from EB, and it maintains the minimum green time in phase 1 in order to balance the unbalanced traffic demand condition.

3.7.2.2 Comparison of delay time on each band

This section shows the comparison of delay time (vehicle/second) on each band between the Matsuoka model and fixed time control system under the different traffic demand scenarios.

Table 3-10 The comparison of average delay time (vehicle/second) on each band between Matsuoka model and fixed time control system.

#	Scenario	Movement Type	Delay time (vehicle/second) in Matsuoka Model	Delay time (vehicle/second) in Fixed time control
1	Medium EB Demand	NB	12.98	11.23
		WB	9.70	10.80
		SB	13.29	11.09
		EB	**11.62**	**12.89**
2	Medium EB Demand	NB	14.36	11.26
		WB	9.54	10.80
		SB	14.01	11.1
		EB	**12.77**	**14.01**
3	Medium EB Demand	NB	15.23	11.28
		WB	9.08	10.80
		SB	14.69	11.14
		EB	**12.34**	**15.48**
4	High EB Demand	NB	15.32	11.30
		WB	8.63	10.80
		SB	15.29	11.09
		EB	**13.30**	**17.99**
5	High EB Demand	NB	15.50	11.29
		WB	9.25	10.80
		SB	15.43	11.12
		EB	**13.56**	**18.06**

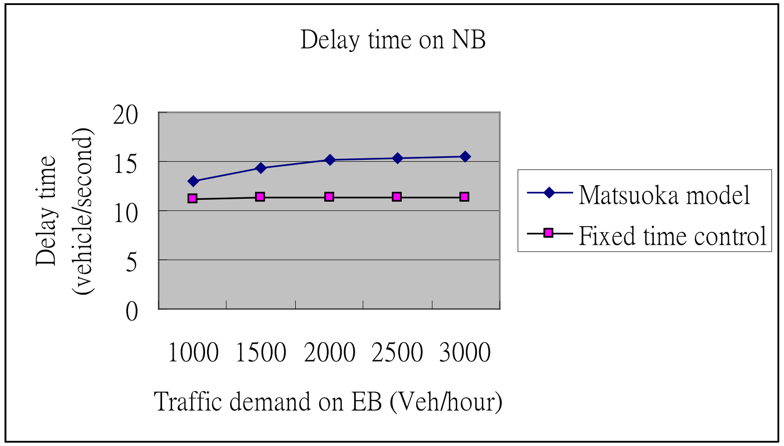


Figure 3-30 Matsuoka v.s. fixed time (Delay time on NB).

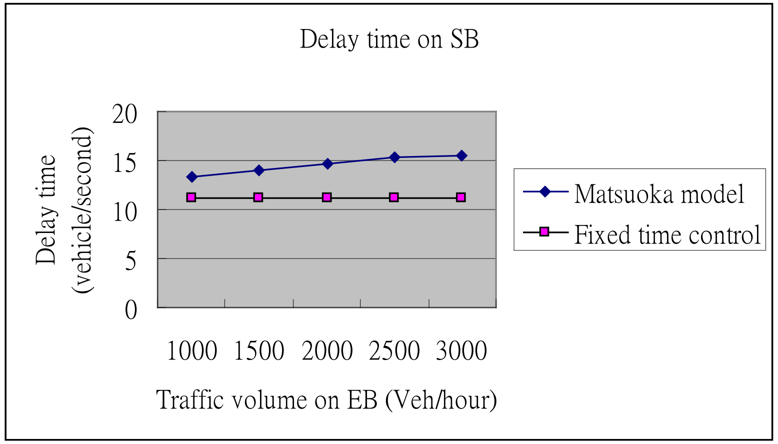


Figure 3-31 Matsuoka v.s. fixed time (Delay time on SB).

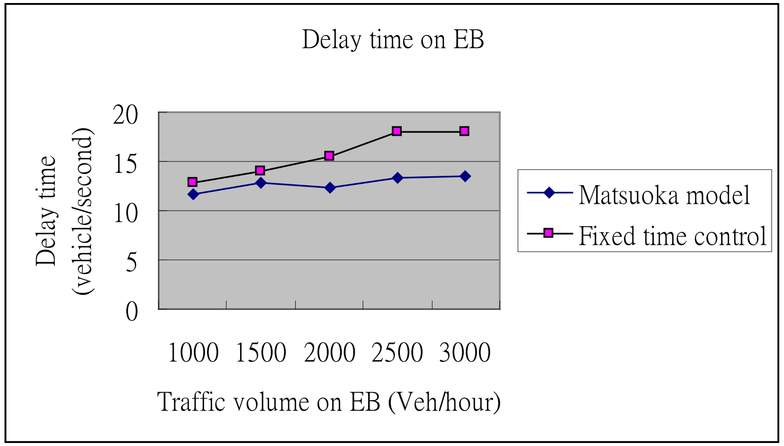


Figure 3-32 Matsuoka v.s. fixed time (Delay time on EB).

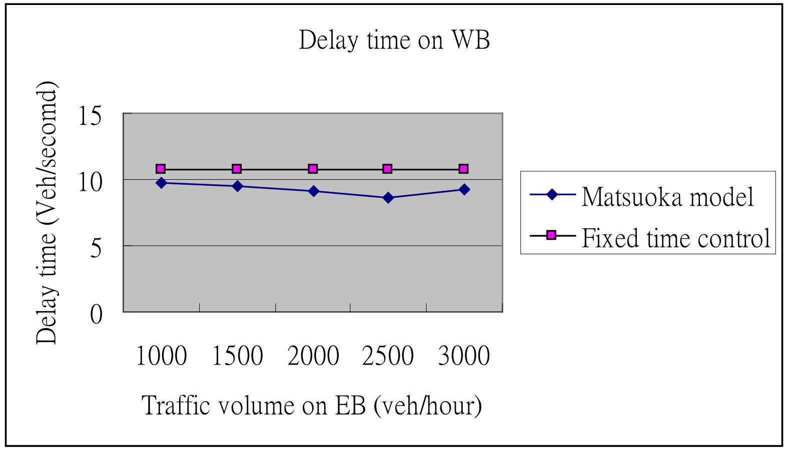


Figure 3-33 Matsuoka v.s. fixed time (Delay time on WB).

The delay time of the fixed time control system is constant at about 11 vehicle/second on NB, SB, and WB because of the same traffic volume on these bands. It increases gradually on EB from 12.89 to 18.06 vehicle/second because of the increasing traffic volume on EB.

By comparing with the Matsuoka model and fixed time control system, the delay time of Matsuoka model is decreased on EB and WB. In this case, more vehicles coming from EB and the Matsuoka model controller allocates more extension green time in phase 2 in order to avoid traffic congestion on EB and balance the traffic condition. Figure 3-32 and 3-33 shows EB and WB have better delay time performance which compare with fixed time control. On the other hand, the green time in the phase 1 is decreased that causes more delay time on NB and SB. From the figure 3-30 and 3-31, the delay time of the Matsuoka model has the same increasing pattern on NB and SB.

3.7.2.3 Comparison of traffic performance

Table 3-11 shows the comparison of entire traffic performance (total travel time, delay time, and flow) between control system with Matsuoka Oscillator and fixed time control system in unbalanced traffic demand scenarios.

Table 3-11 The comparison of performance between control system with Matsuoka Oscillator and fixed time control system in unbalanced traffic demand scenarios.

Scenario	Total travel time (hours)		Improvement % Change	Delay time (seconds/km)		Improvement % Change	Flow (vehicle/hour)		Improvement % Change
	Matsuoka	Fixed		Matsuoka	Fixed		Matsuoka	Fixed	
1	13.14	13.29	+1.1%	104.26	108.10	+3.7%	2480	2456	+1.0%
2	16.66	16.73	+0.42%	114.13	114.82	+0.6%	2971	2974	0%
3	19.58	20.46	+4.5%	115.41	124.54	+7.9%	3467	3450	+0.5%
4	22.29	22.96	+3.0%	116.47	138.23	+18.7%	3921	3612	+8.6%
5	23.31	23.05	-1.1%	123.46	138.67	+12.3%	3949	3618	+9.1%

Total travel time is the time accumulated by all vehicles travelling in the traffic network, is a very good indicator of the traffic system's overall performance. Matsuoka model has improvement 4.5% and 3.0% when the traffic volumes on EB are 2000 and 2500 vehicles/hour respectively. Performance of total travel time does not change much when traffic volume on EB is less than 2000 vehicles/hour.

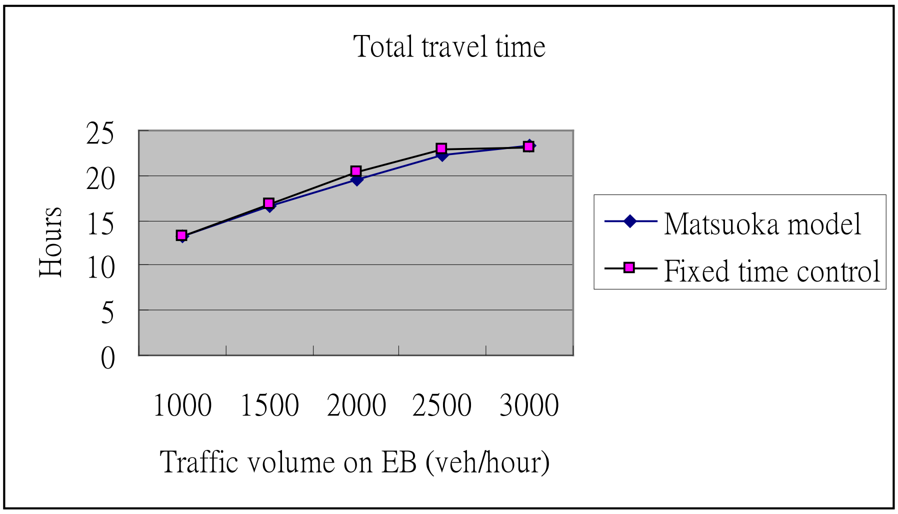


Figure 3-34 Comparison of total travel time (Matsuoka model v.s. Fixed time control).

Figure 3-35 shows the Matsuoka model decrease the performance of delay time effectively when the traffic volume on EB are higher than 2000 vehicles/hour. The biggest improvement percentage is 18.7% which occurs when the traffic volume on EB is 2500 vehicles/hour, the Matsuoka model decreases the delay time from 138.23 to 116.47 seconds/km.

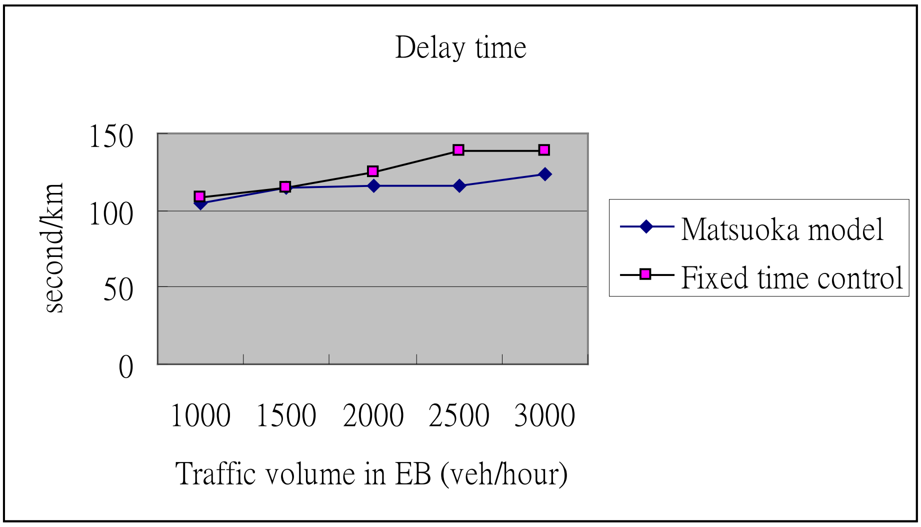


Figure 3-35 Comparison of delay time (Matsuoka model v.s. Fixed time control).

The performances of flow dose not change when traffic volume on EB is less than 2000 vehicles/hour. The Matsuoka model has improvement 8.6% and 9.1% compared with fixed time control during the high traffic demand on EB. In these scenarios, the system increases the traffic flow by about 300 vehicles passing through the intersection during an hour.

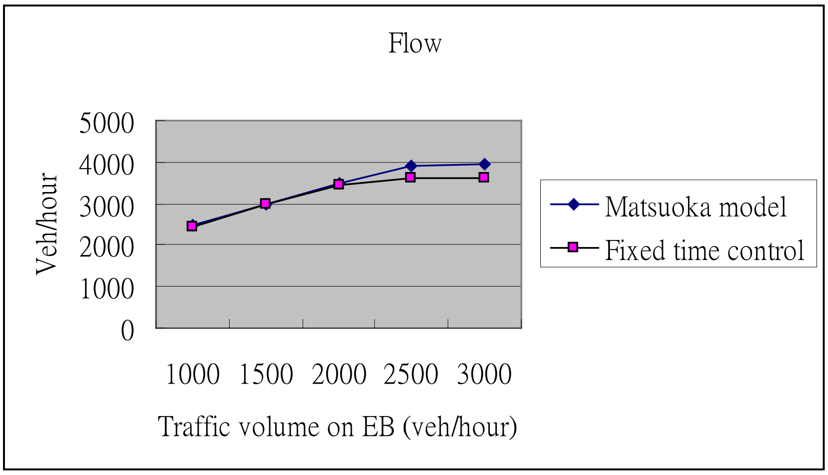


Figure 3-36 Comparison of flow (Matsuoka model v.s. Fixed time control).

3.7.2.4 Summary

The main objective of this section is to analyze how the unbalanced traffic demands affect the Matsuoka Oscillator in the signalized traffic control system and the traffic performance by using the Matsuoka model. Firstly, the average green time in phase 2 is increased from 33.3 to 38.4s according to the increasing traffic demands from EB. On the other hand, the average green time in phase 2 drops down to minimum green time about 27s for the lower traffic demand roads. The difference within these two signals is proportional to the difference of traffic volume between each phase. By comparing the fixed time control system and control system with the Matsuoka model, the delay time on each band is balanced by using the traffic control system with the Matsuoka Oscillator. In section 3.7.2.2, the Matsuoka model reduces the delay time on the band which has higher traffic demand and increases the delay time on the band which has lower traffic demand.

From the aspect of entire traffic performance, the traffic performances of these two systems maintain in the balanced condition when differences of traffic demand is less than 1500 vehicles/hour. The traffic control system with Matsuoka Oscillator provides better traffic performance when the difference between traffic demands is larger than 1500 vehicles/hour.

Chapter 4
Matsuoka Oscillators for a four-phase isolated intersection

4.1 Introduction

The objective of this chapter is to implement four Matsuoka Oscillators into a four-phase (Figure 4-1) isolated intersection and test how the unbalanced traffic demand affects the traffic control system with the Matsuoka Oscillators. The methodology of this control system is to balance the traffic condition according to the traffic demand from each phase. There are four signals at this intersection which are controlled by four independent Matsuoka Oscillators. The calibration of the Matsuoka Oscillator and structure of control system are discussed in the following sections.

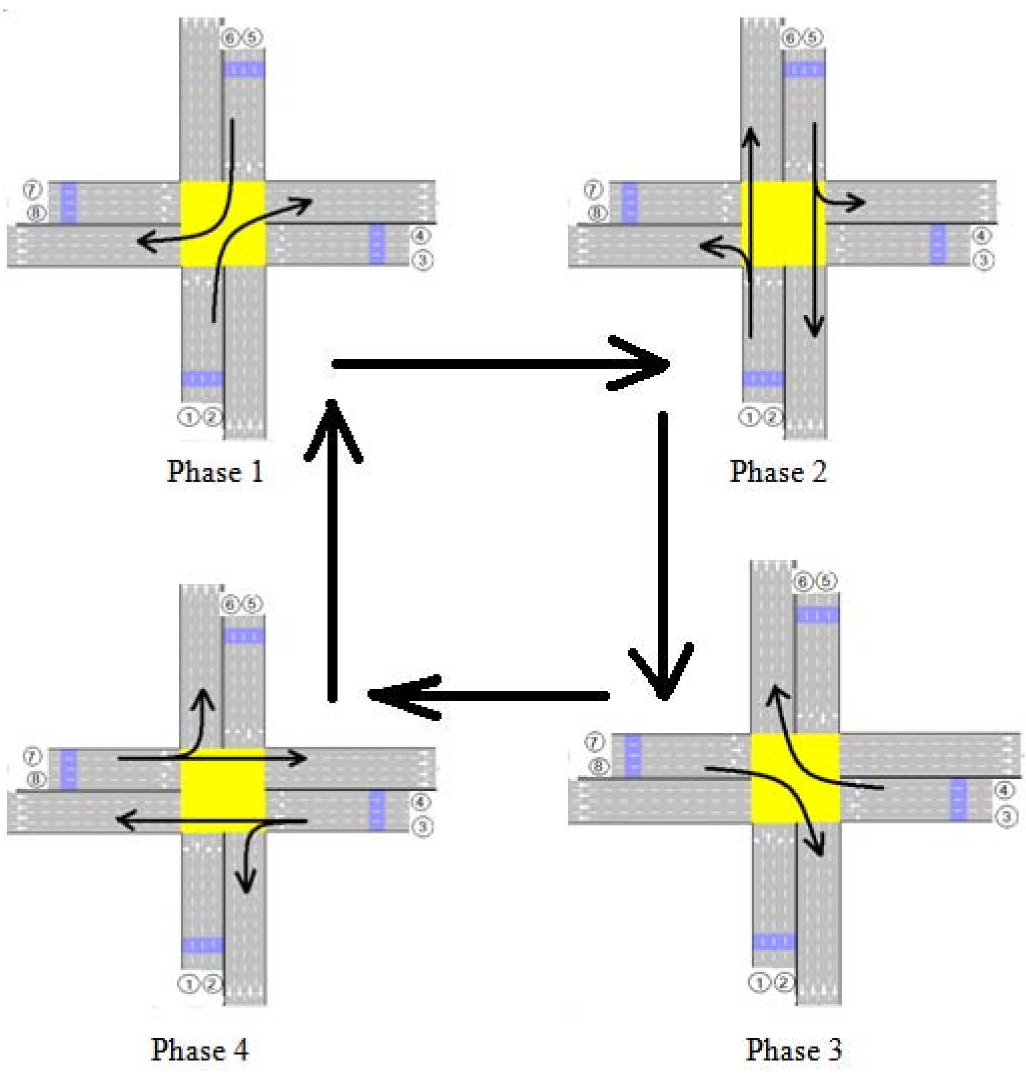


Figure 4-1 An isolated intersection with four phases

4.2 Calibration and analysis

In this chapter, we assume that an isolated intersection with four phases is composed of four signal groups and the total cycle time is 102 seconds. We set 30 seconds green time in phase 2 and phase 4 for vehicles going straight, 15 seconds green time during phase 1 and phase 3 for vehicles turning right, and 3 seconds yellow time for each phase (figure 4-2).

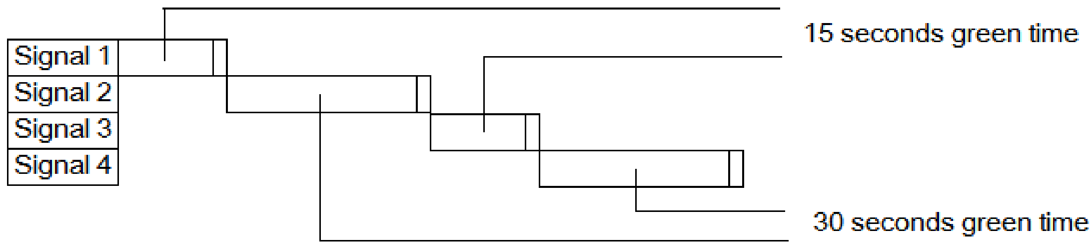


Figure 4-2 Fixed cycle time for four signals.

In this section, four Matsuoka Oscillator controllers are implemented in this traffic control system. Each Matsuoka Oscillators controls one signal in order. We name these four Matsuoka Oscillators as Matsuoka Oscillator 1 (MO1), Matsuoka Oscillator 2 (MO2), Matsuoka Oscillator 3 (MO3) and Matsuoka Oscillator 4 (MO4). All of them are designed and calibrated based on the fixed time cycle.

MO1 and MO3 have been calibrated and analyzed in section 3.1.4.3 which controls signal 2 and signal 4 based on 30 seconds fixed green time. By previous testing, we can get T_{on} = 30 when $b_1 = b_2$ = 2.5, $T_{r1} = T_{r2}$ =3, $T_{a1} = T_{a2}$ =28, and $a_{21} = a_{12}$ =1.5. The constant rate between input 1 and input 2 is about 1.63.

MO2 and MO4 are used to control the signal 3 and signal 1 which is based on the 15 seconds fixed greed time. The calibration result has been done by using Graphic User Interface (GUI) in Matlab. Since $b_1 = b_2$ = 2.5, $T_{r1} = T_{r2}$ =3, $T_{a1} = T_{a2}$ =15, and $a_{21} = a_{12}$ =1.35, then T_{on} = 15. The output is 15 seconds when input 1 equals input 2, and the constant rate between input 1 and input 2 is 1.7 (5.1/3).

Table 4-1 The relationship of outputs in MO2 and MO4 with constant input 1 and increasing input 2.

Input 1 (s1)	Input 2 (s2)	Output 1 (Ton 1)	Output 2 (Ton 2)	Difference
3.0	3.0	15.0	15.0	0.0
3.0	3.1	14.8	15.3	0.5
3.0	3.2	14.6	15.6	1.0
3.0	3.3	14.4	15.9	1.5
3.0	3.4	14.2	16.2	2.0
3.0	3.5	14.0	16.6	2.6
3.0	3.6	13.9	17.0	3.1
3.0	3.7	13.8	17.3	3.5
3.0	3.8	13.7	17.7	4.0
3.0	3.9	13.6	18.2	4.6
3.0	4.0	13.6	18.6	5.0
3.0	4.1	13.5	19.1	5.6
3.0	4.2	13.5	19.6	6.1
3.0	4.3	13.5	20.1	6.6
3.0	4.4	13.6	20.7	7.1
3.0	4.5	13.6	21.3	7.7
3.0	4.6	13.7	22.0	8.3
3.0	4.7	13.7	22.7	9.0
3.0	4.8	13.8	23.6	9.8
3.0	4.9	14.0	24.5	10.5
3.0	5.0	14.1	25.6	11.5
3.0	5.1	14.3	27.3	13.0

Figure 4-3 shows the characteristic of the input and output relationship in MO2 and MO4. The output 2 increases from 15 to 27.3 with the constant input 1 equals 3.0 and increasing input 2 from 3.0 to maximum value 5.1. In this case, the minimum green time can be set as 13.5s and the maximum green time is 27.3s, the green extension time for MO2 and MO4 is 13.8s.

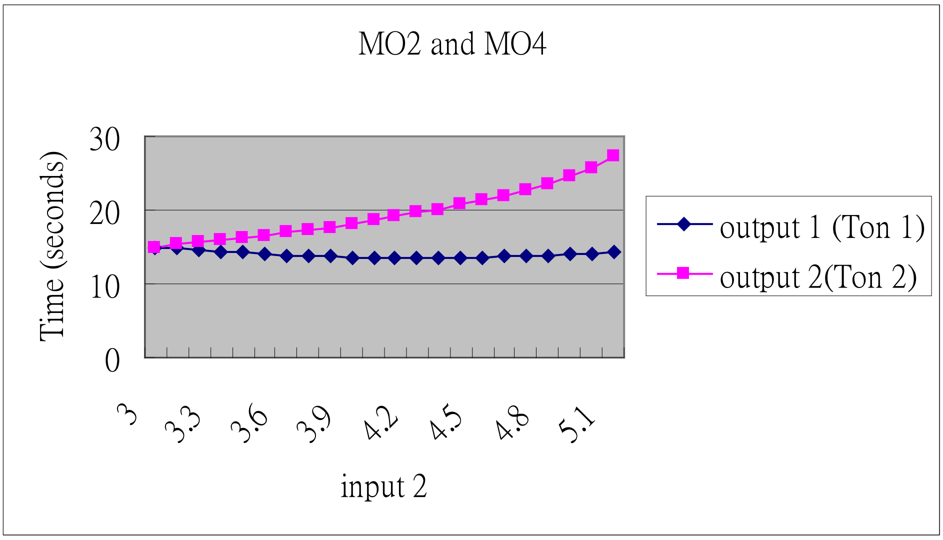


Figure 4-3 The relationship between output 1 and output 2 based on the increasing input 2 and constant input 1 in MO2 and MO4.

Figure 4-4 shows these two outputs are same when input 1 equals input 2 and the difference between output 1 and output 2 is proportional to the difference between input 1 and input 2 in MO2 and MO4. There is an approximate linear relationship of the output difference in this case.

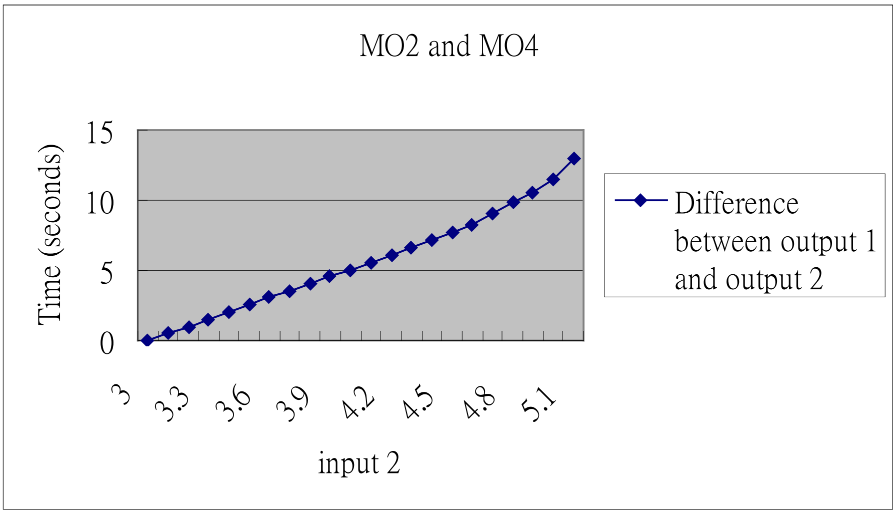


Figure 4-4 Difference between output 1 and output 2 in MO2 and MO4 (input 1 is constant 3 and input 2 increases from 3 to 5.1).

Table 4-2 The number of vehicles presents in the inputs of MO2 and MO4.

The number of vehicles waiting on the queue	Matsuoka model input
0~5	3.0
6	3.2
7	3.4
8	3.6
9	3.8
10	4.0
11	4.2
12	4.4
13	4.6
14	4.8
15	5.0
>15	5.1

Table 4-2 shows the relationship between number of vehicles waiting on the queue and the inputs of MO2 and MO4. When the number of vehicles is less than 6, the input of MO2 and MO4 is 3.0. We set the input of MO2 and MO4 is 5.1 when the number of vehicle waiting on the queue is larger than 15.

4.3 The structure of the control system

From figure 4-5, we can see the structure of four Matsuoka Oscillators connect with AIMSUN simulation environment. The structure of the traffic system is a closed loop control system. Each phase has one Matsuoka Oscillator which controls the signal at the intersection. Each Matsuoka Oscillator has two external inputs and two outputs which represent the number of vehicles waiting on the queue and the duration of green time. In this case, only one of output is used for calculating the duration of green time in next phase. The objective of this model is to predict the next green time according to the comparison of traffic demand on the next two phases. The detail of the process will be discussed in the next section.

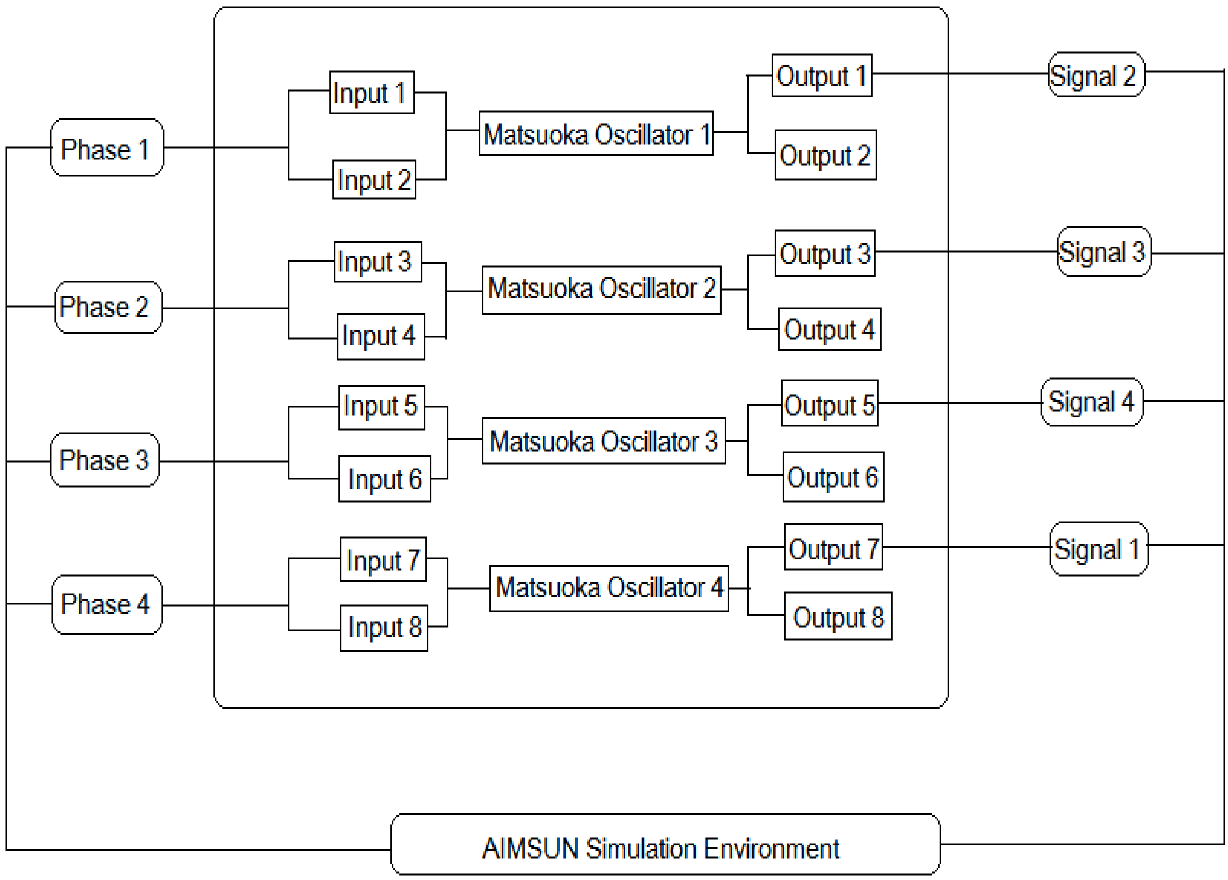


Figure 4-5 The structure of the four-phase intersection with four Matsuoka Oscillators

4.4 The procedure of control system

From figure 4-6, there are two detectors on each phase at the isolated intersection in order to detect the number of vehicles waiting on the queue. MO1 is implemented when the current phase is phase 1. The input 1 is the number of vehicles waiting on the queue in phase 2 (detector 1 and 5) and input 2 is the number of vehicles waiting on the queue in phase 3 (detector 4 and 8). We only use output 1 as the output of the system representing the green time on the next phase which is phase 2. MO1 decides how much green time in phase 2 by comparing the number of vehicles waiting on phase 2 and phase 3. If there more vehicles waiting on the next phase, then the system allocates more extension green time to it in order to balance the traffic demands on each phase.

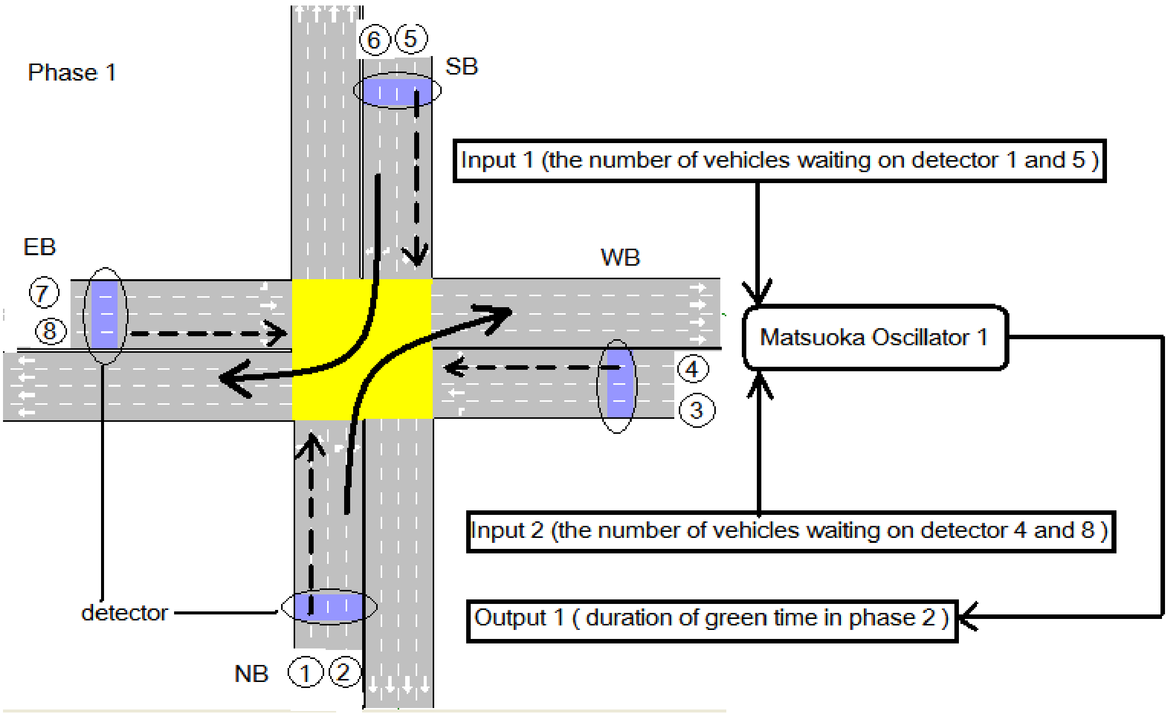


Figure 4-6 The graph of phase 1 (Matsuoka Oscillator 1 is implemented).

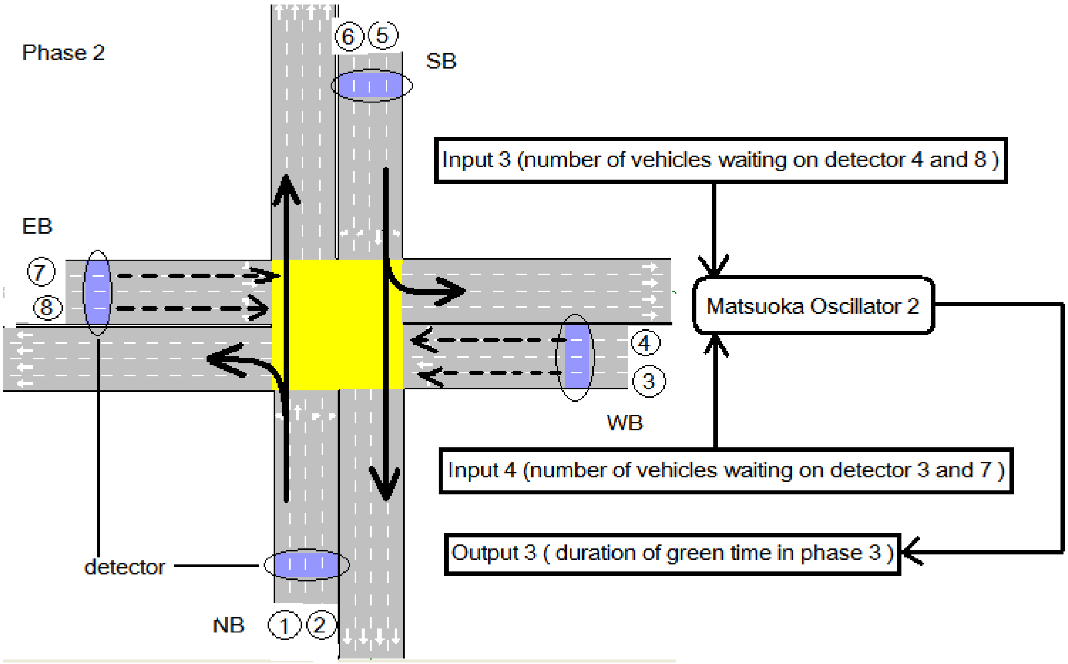


Figure 4-7 The graph of phase 2 (Matsuoka Oscillator 2 is implemented).

When the current phase is phase 2, the control system replaces the MO1 with MO2. The input 3 is the number vehicles waiting in next phase which is phase 3 (detector 4 and 8) and input 4 is the number of vehicles waiting in phase 4 (detector 4 and 8). The output 3 represents the green time in the next phase which is phase 3.

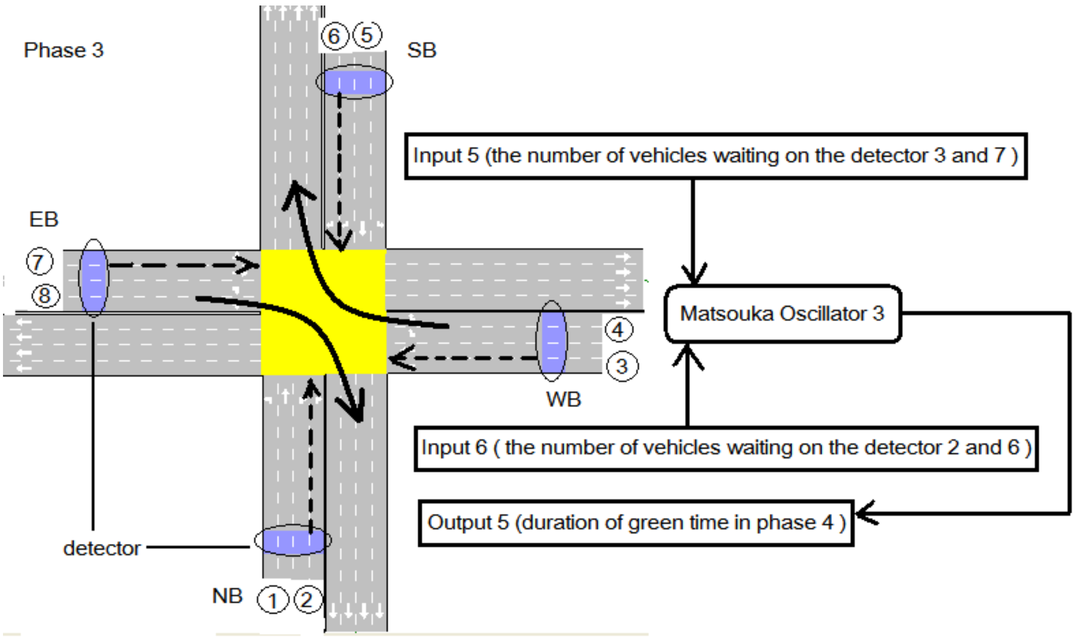


Figure 4-8 The graph of phase 3 (Matsuoka Oscillator 3 is implemented).

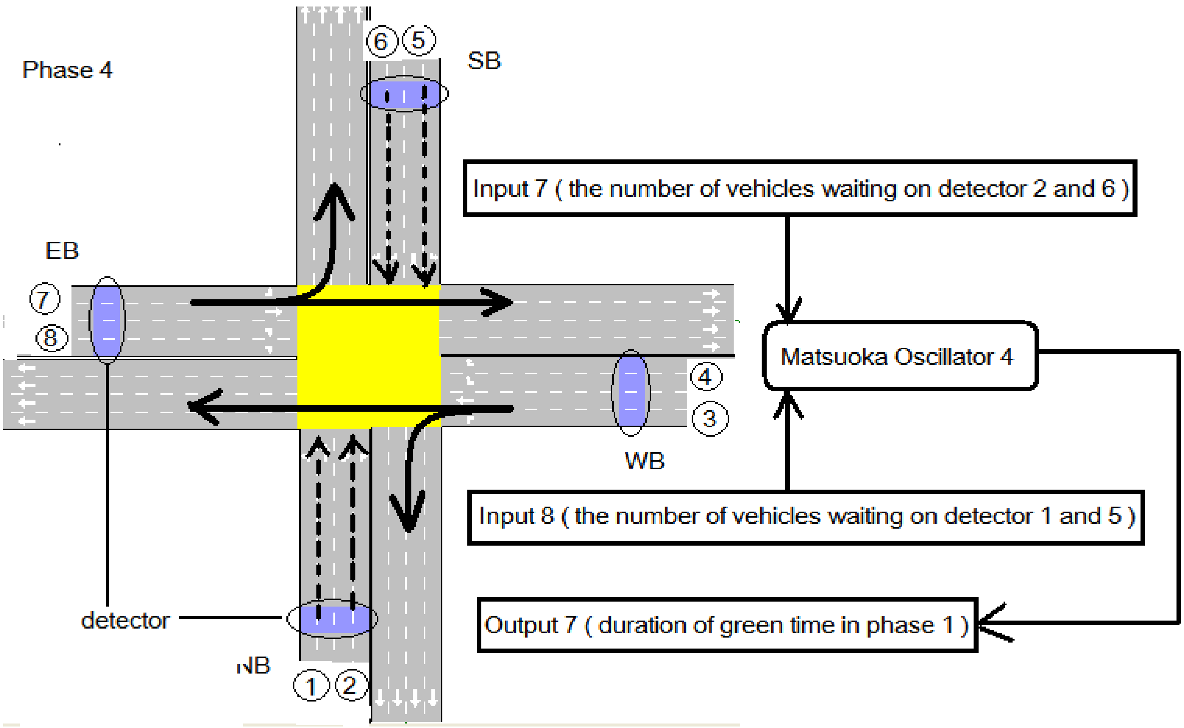


Figure 4-9 The graph of phase 4 (Matsuoka Oscillator 4 is implemented).

The other two phases (Figure 4-8 and 4-9) have the same structure as phase 1 and phase 2. Table 4-3 shows the relationship of inputs and outputs of two Matsuoka Oscillators in different phases. The input 1 in each Matsuoka Oscillator is always represented the number of vehicles waiting in next phase, and output is the green time for the next phase.

Table 4-3 The relationship of Matsuoka Oscillators operated in four phases

Current Phase				
Phase 1	MO1	Waiting Queue in Phase 2 (Input 1)	Waiting Queue in Phase 4 (Input 2)	Green Time in Phase 2 (Output 1)
Phase 2	MO2	Waiting Queue in Phase 3 (Input 3)	Waiting Queue in Phase 1 (Input 4)	Green Time in Phase 3 (Output 3)
Phase 3	MO3	Waiting Queue in Phase 4 (Input 5)	Waiting Queue in Phase 2 (Input 6)	Green Time in Phase 4 (Output 5)
Phase 4	MO4	Waiting Queue in Phase 1 (Input 7)	Waiting Queue in Phase 3 (Input 8)	Green Time in Phase 1 (Output 7)

4.5 Calibration of the traffic environment

Table 4-4 shows the data requirement of calibration in the AINSUM traffic environment. The signal information is based on the fixed time control system. The duration time of green signal in each phase will be changed depend on the number of vehicles waiting on the queue.

Table 4-4 Data requirements for calibrating the AINSUM environment

Section Information	Vehicles Information
Road type: arterial Length: 50 metres Capacity: 1800 vehicles/hr Visibility distance: 25 metres Jam Density: 200 vehicles/km Vehicle Speed in the intersection: 10km/h	Driver's reaction time: 0.5 seconds Response time to stop: 1.35 seconds The mean of length: 4 metres The mean speed of vehicle: 50 km/hour Max acceleration: 3 m/ s^2 Max deceleration: 6 m/ s^2
Detectors Information	Signals Information (fixed time)
Length: 4.5 metres Distance to exit: 35 metres	Cycle length: 102 seconds Green time in phase 1 & 3: 15 seconds Green time in phase 2 & 4: 30 seconds Yellow time: 3 seconds

4.6 Analysis

From chapter 3, the traffic control system with the Matsuoka Oscillators improves the traffic performance which is compared with fixed time control system in the high unbalanced traffic demand scenarios. The objective of this section is to analyze how the unbalanced traffic demands affect the control system with the Matsuoka Oscillator and traffic performance in the four-phase intersection. The traffic control system is simulated by AIMSUN in different scenarios with increasing traffic demands by 200 vehicles per hour on EB and WB. Section 4.6.1 discusses the relationship between inputs and outputs of four Matsuoka Oscillators in different traffic demand scenarios. The comparison of delay time on each band with Matsuoka Oscillators and fixed time control system will be discussed in section 4.6.2. Finally, the comparison of traffic performance in the entire system will be shown in section 4.6.3.

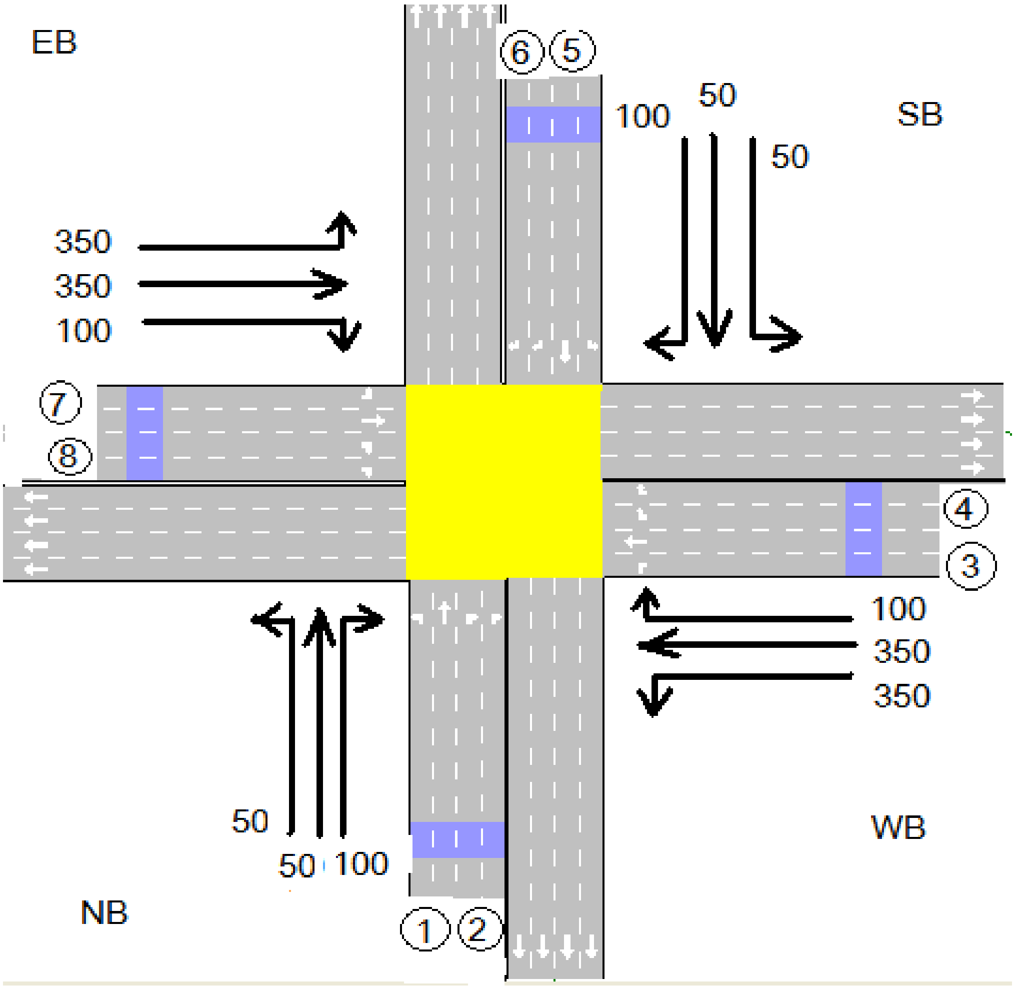


Figure 4-10 An isolated intersection with an unbalanced traffic demand scenario

Table 4-5 Unbalanced traffic demand scenarios with increasing traffic volume on EB & WB

Scenario	Movement type		Demand (vehicle/hour)	Total traffic demand
1	NB & SB	L	50	200
		TH	50	
		R	100	
	WB & EB	L	50	**200**
		TH	50	
		R	100	
2	NB & SB	L	50	200
		TH	50	
		R	100	
	WB & EB	L	150	**400**
		TH	150	
		R	100	
3	NB & SB	L	50	200
		TH	50	
		R	100	
	WB & EB	L	250	**600**
		TH	250	
		R	100	
4	NB & SB	L	50	200
		TH	50	
		R	100	
	WB & EB	L	350	**800**
		TH	350	
		R	100	
5	NB & SB	L	50	200
		TH	50	
		R	100	
	WB & EB	L	450	**1000**
		TH	450	
		R	100	
6	NB & SB	L	50	200
		TH	50	
		R	100	
	WB & EB	L	550	**1200**
		TH	550	
		R	100	
7	NB & SB	L	50	200
		TH	50	
		R	100	
	WB & EB	L	600	**1300**
		TH	600	
		R	100	

Table 4-6 shows the actual inputs and outputs of four Matsuoka Oscillators after the simulation. The inputs of the Matsuoka Oscillator represent the total number of vehicles waiting on the queue during an hour and the average represents the number of vehicles waiting on the queue in each cycle time.

Table 4-6 The table of inputs and outputs in the Matsuoka model in unbalanced traffic demand scenarios after the simulation. (Continued in the next page)

Scenario	Input = (total vehicles/hour) Average = (average vehicles/cycle)					Output (seconds)		
1	MO1	Input1	142	Average	4	Output 1	Phase 2 average green time	15.4
		Input2	103	Average	2			
	MO2	Input3	161	Average	4	Output 3	Phase 3 average green time	31.0
		Input4	93	Average	2			
	MO3	Input5	124	Average	3	Output 5	Phase 4 average green time	15.4
		Input6	92	Average	2			
	MO4	Input7	185	Average	4	Output 7	Phase 1 average green time	31.0
		Input8	103	Average	3			
2	MO1	Input1	122	Average	3	Output 1	Phase 2 average green time	15.5
		Input2	167	Average	4			
	MO2	Input3	273	Average	8	Output 3	Phase 3 average green time	30.7
		Input4	198	Average	5			
	MO3	Input5	269	Average	7	Output 5	Phase 4 average green time	15.9
		Input6	96	Average	2			
	MO4	Input7	162	Average	4	Output 7	Phase 1 average green time	32.6
		Input8	93	Average	2			
3	MO1	Input1	124	Average	3	Output 1	Phase 2 average green time	15.5
		Input2	248	Average	7			
	MO2	Input3	387	Average	11	Output 3	Phase 3 average green time	29.9
		Input4	312	Average	9			

	MO3	Input5	436	Average	13	Output 5	Phase 4 average green time	15.9
		Input6	94	Average	2			
	MO4	Input7	164	Average	5	Output 7	Phase 1 average green time	36.6
		Input8	94	Average	3			
4	MO1	Input1	142	Average	4	Output 1	Phase 2 average green time	15.8
		Input2	330	Average	10			
	MO2	Input3	499	Average	16	Output 3	Phase 3 average green time	29.2
		Input4	417	Average	13			
	MO3	Input5	583	Average	18	Output 5	Phase 4 average green time	16.0
		Input6	80	Average	2			
	MO4	Input7	162	Average	5	Output 7	Phase 1 average green time	42.6
		Input8	101	Average	3			
5	MO1	Input1	145	Average	4	Output 1	Phase 2 average green time	15.6
		Input2	440	Average	14			
	MO2	Input3	602	Average	20	Output 3	Phase 3 average green time	28.5
		Input4	487	Average	16			
	MO3	Input5	671	Average	22	Output 5	Phase 4 average green time	16.3
		Input6	82	Average	2			
	MO4	Input7	177	Average	5	Output 7	Phase 1 average green time	47.0
		Input8	108	Average	3			
6	MO1	Input1	146	Average	4	Output 1	Phase 2 average green time	15.6
		Input2	554	Average	18			
	MO2	Input3	730	Average	24	Output 3	Phase 3 average green time	28.4
		Input4	582	Average	19			
	MO3	Input5	717	Average	24	Output 5	Phase 4 average green time	16.0
		Input6	72	Average	3			
	MO4	Input7	162	Average	5	Output 7	Phase 1 average green time	50.3
		Input8	113	Average	3			

Table 4-6 The table of inputs and outputs in the Matsuoka model in unbalanced traffic demand scenarios after the simulation. (Continued from previous page).

7	MO1	Input1	142	Average	4	Output 1	Phase 2 average green time	15.5
		Input2	610	Average	24			
	MO2	Input3	761	Average	26	Output 3	Phase 3 average green time	28.3
		Input4	615	Average	21			
	MO3	Input5	746	Average	25	Output 5	Phase 4 average green time	15.9
		Input6	76	Average	2			
	MO4	Input7	160	Average	5	Output 7	Phase 1 average green time	51.0
		Input8	107	Average	3			

4.6.1 Input & output analysis

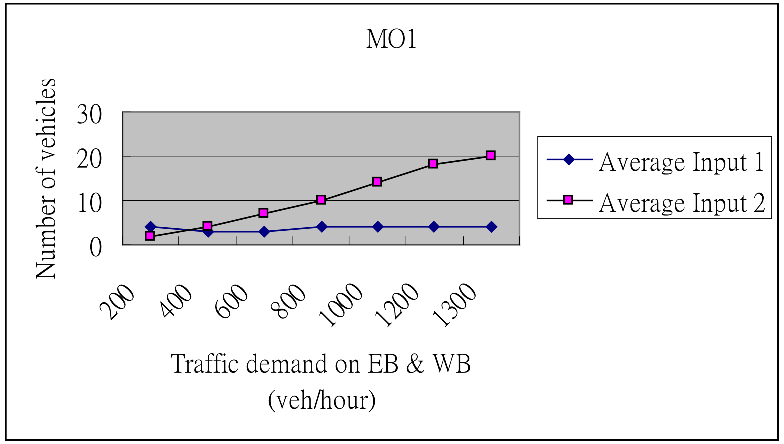


Figure 4-11 The average input 1 and input 2 in MO1.

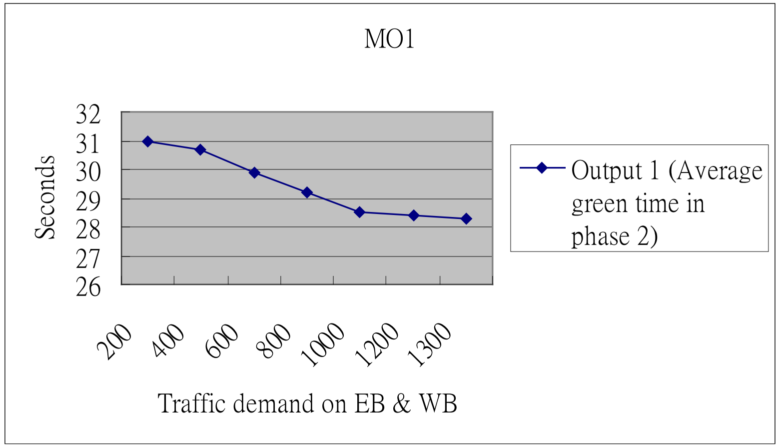


Figure 4-12 The average output 1 in MO1.

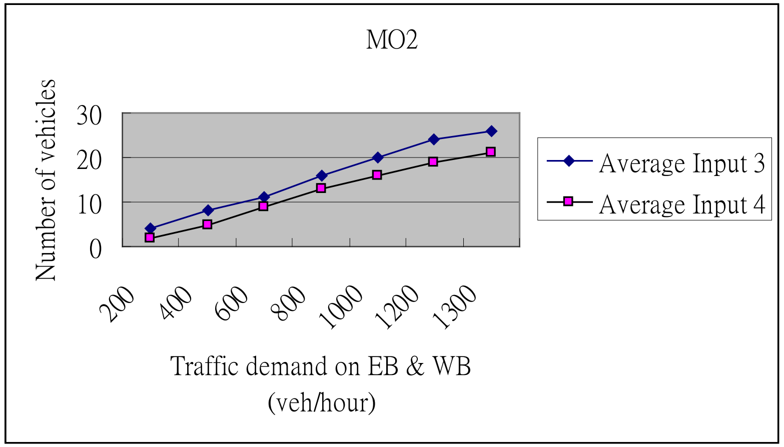


Figure 4-13 The average input 3 and input 4 in MO2.

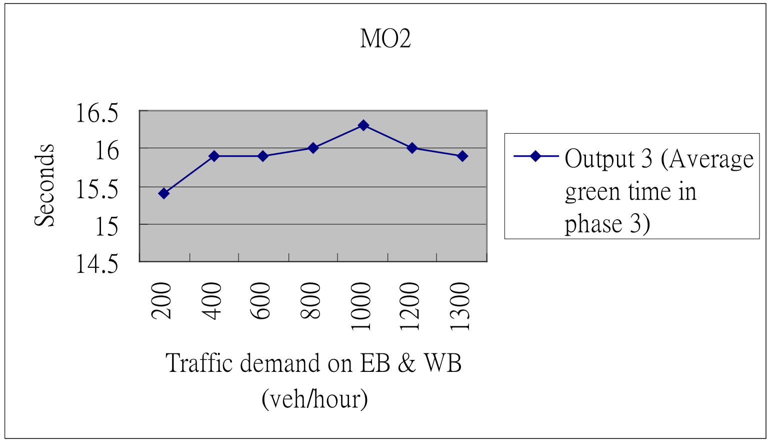


Figure 4-14 The average output 3 in MO2.

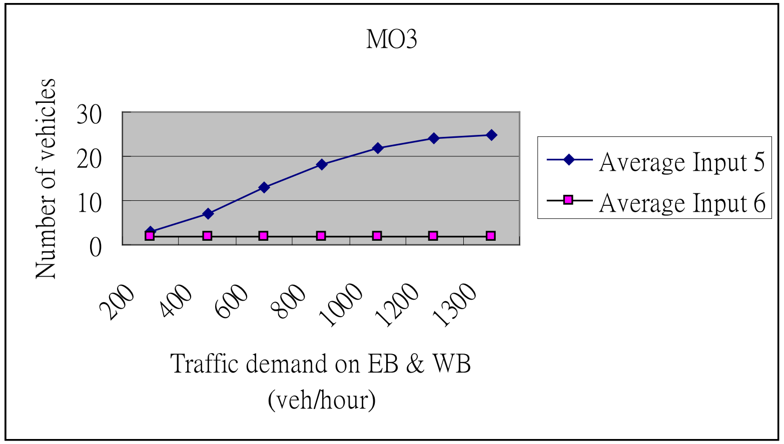


Figure 4-15 The average input 5 and input 6 in MO3.

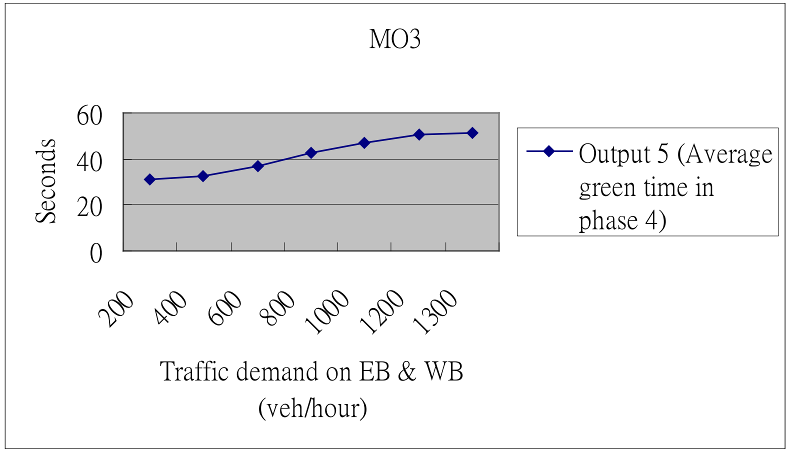


Figure 4-16 The average output 5 in MO3.

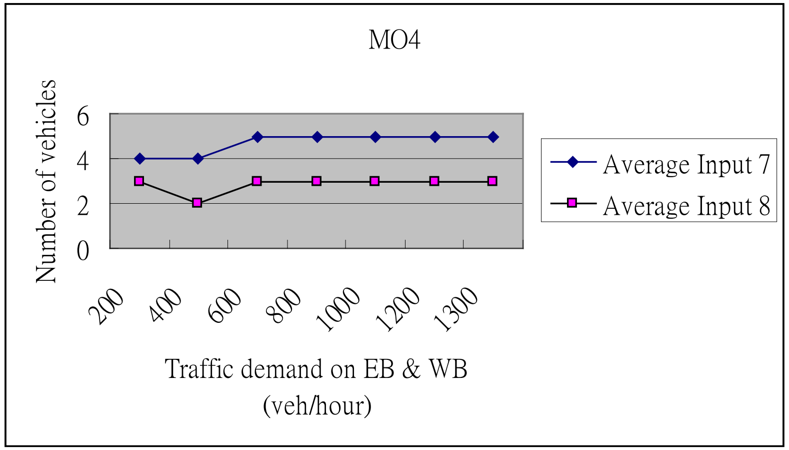


Figure 4-17 The average input 7 and input 8 in MO4.

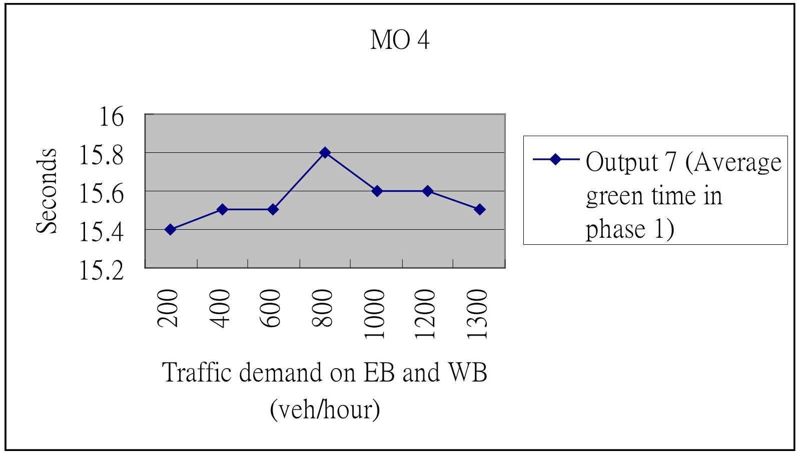


Figure 4-18 The average output 7 in MO4.

Table 4-6 shows the actual inputs and outputs of four Matsuoka Oscillators after the simulation. According to the description of section 4.4, the two inputs of each oscillator represent the number of vehicles waiting on the queue in next two phases. The method of these unbalanced traffic demand scenarios is to increase the traffic volume on EB and WB, and therefore the number of vehicles waiting on EB and WB will be increased. In the aspect of a Matsuoka Oscillator, four inputs increase in these scenarios which are input 2, input 3, input 4 and input 5.

The relationships between inputs and outputs in each Matsuoka Oscillator are shown from Figure 4-11 to 4-18. Firstly, the input 2 increases from 2 to 20 and input 1 remains around constant 4. The output 1 decreases from 31s to minimum green time 28s.

In the Matsuoka Oscillator 2, both of input 3 and input 4 have the same increasing rate. The difference of these two inputs is almost constant. So the output 3 remains less than 16.5s. Figure 4-17 shows the difference rate between input 7 and input 8 is almost the same. The output 7 of Matsuoka Oscillator 4 also remains less than 16.5s.

In the Matsuoka Oscillator 4, the input 5 increases from 3 to 25 and input 6 remains constant value 2. The output 5 increases from 31 to 51s because of increasing difference between input 5 and input 6.

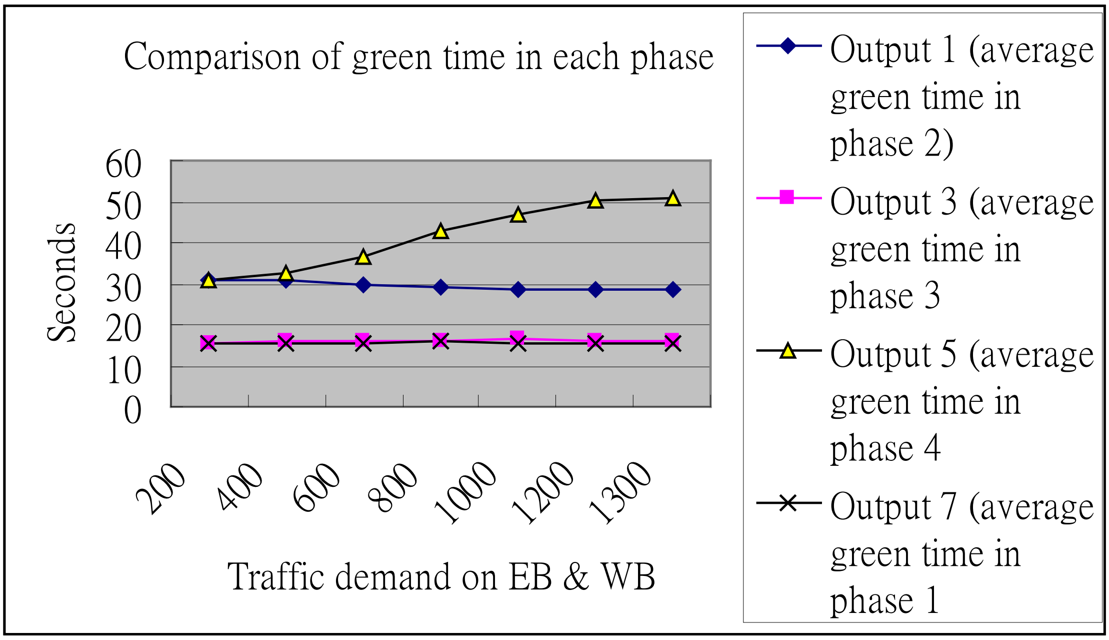


Figure 4-19 The comparison of green time in each phase.

4.6.2 Comparison of delay time on each band

Table 4-7 shows the comparison of delay time (vehicle/second) on each band between the Matsuoka model and fixed time control system in the different traffic demand scenarios.

Table 4-7 The comparison of average delay time (vehicle/second) on each band between the Matsuoka model and fixed time control system.

#	Scenarios	Band	Delay time (vehicles/second) in Matsuoka Model	Delay time (vehicles/second) in Fixed time control
1	WB & EB (200veh/hour)	NB	27.92	26.52
		WB	25.27	26.82
		SB	25.98	24.44
		EB	25.48	26.82
2	WB & EB (400veh/hour)	NB	29.88	25.74
		WB	26.10	26.76
		SB	30.35	24.45
		EB	25.92	28.20
3	WB & EB (600veh/hour)	NB	28.50	26.48
		WB	27.95	29.50
		SB	31.60	25.03
		EB	29.59	29.31
4	WB & EB (800veh/hour)	NB	35.59	26.48
		WB	30.03	31.97
		SB	31.25	25.02
		EB	29.36	36.57
5	WB & EB (10000veh/hour)	NB	37.22	26.48
		WB	33.75	39.94
		SB	35.54	26.71
		EB	33.09	40.02
6	WB & EB (1200veh/hour)	NB	31.33	26.48
		WB	35.84	54.14
		SB	31.72	26.71
		EB	37.51	53.08
7	WB & EB (1300veh/hour)	NB	34.36	26.48
		WB	39.97	64.36
		SB	32.92	26.17
		EB	43.60	68.89

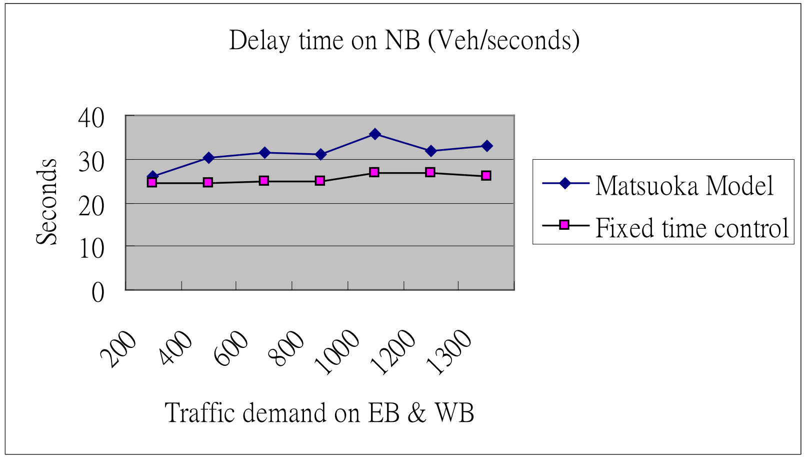


Figure 4-20 Matsuoka v.s. fixed time (Delay time on NB).

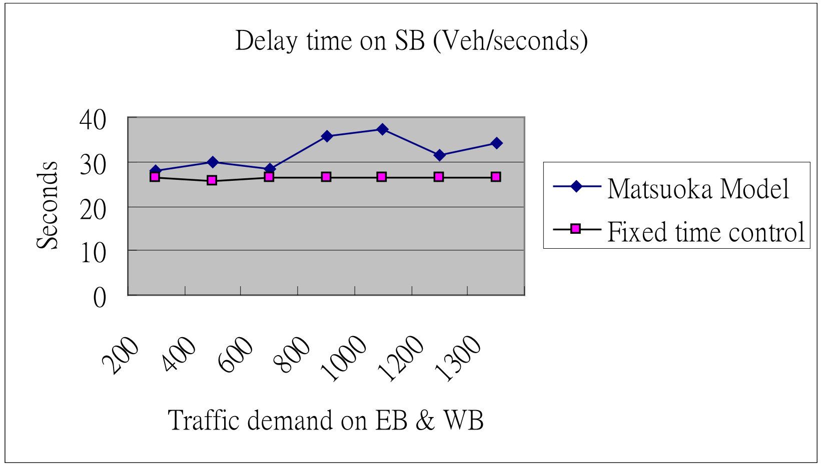


Figure 4-21 Matsuoka v.s. fixed time (Delay time on SB).

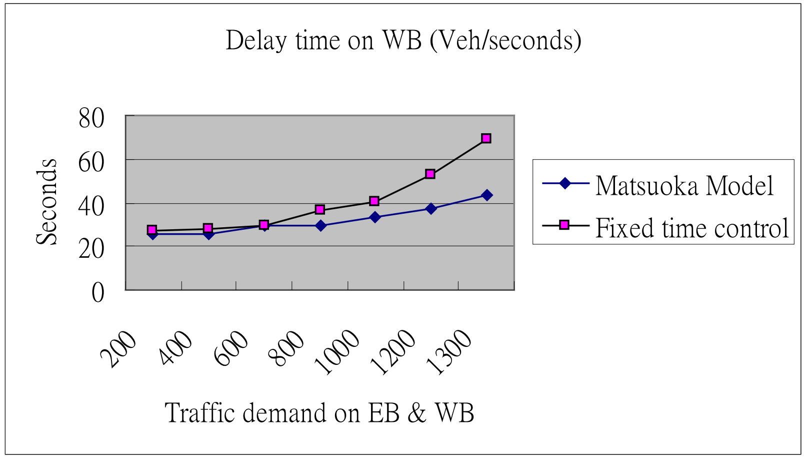


Figure 4-22 Matsuoka v.s. fixed time (Delay time on WB).

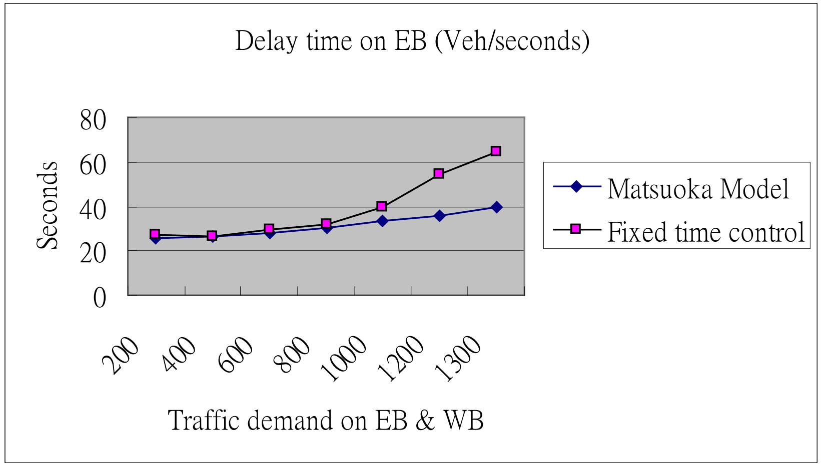


Figure 4-23 Matsuoka v.s. fixed time (Delay time on EB).

The objective of this section is to compare the delay time on each band by using fixed time control system and the Matsuoka model. Firstly, figure 4-20 and 4-21 shows the delay time of Matsuoka model is larger than the fixed time control from traffic demand on both EB and WB is 400vehicles/hour. The largest delay of the Matsuoka model is 37.22 vehicles/seconds which occur when traffic demand on EB and WB are 1200 vehicles/hour. The fixed time control system keeps the delay time on EB and WB around 26.5vehicles/second. The Matsuoka model has the same delay time as fixed time control system when traffic demand on both EB and WB are 200vehicles/hour.

Figure 4-22 and 4-23 shows the delay time on EB and WB are same in the first three scenarios (200,400, and 600 vehicles/hour on EB and WB) by using the Matsuoka model and fixed time control system. The delay time of fixed time control system increases rapidly from about 31 to 65 vehicles/second from both EB and WB are 800vehicles/hour. In the same scenarios, Matsuoka model has better delay time on EB and WB. The delay time of the Matsuoka model increases slowly from about 30 to 40vehicles/second.

4.6.3 Comparison of traffic performance

Table 3-11 shows the comparison of entire traffic performance (total travel time, delay time, and flow) between control system with the Matsuoka Oscillator and fixed time control system in unbalanced traffic demand scenarios.

Table 4-8 The comparison of traffic performance between control system with the Matsuoka Oscillator and fixed time control system

Scenario	Total travel time (hours)		Improvement % change	Delay time (seconds/km)		Improvement % change	Flow (vehicles/hour)		Improvement % change
	Matsuoka	Fixed		Matsuoka	Fixed		Matsuoka	Fixed	
1. EB&WB (200veh/hour)	8.89	9.11	+2.5%	266.51	267.23	+0.3%	777	793	-0.2%
2 .EB&WB (400veh/hour)	13.23	14.85	+12.2%	265.10	266.85	+0.3%	1170	1184	-1.2%
3. EB&WB (600veh/hour)	18.52	18.53	0%	277.48	282.18	+1.7%	1588	1574	+0.8%
4. EB&WB (800veh/hour)	24.24	24.28	+0.2%	295.28	297.78	+0.8%	1978	1972	+0.3%
5. EB&WB (1000veh/hour)	31.49	32.24	+2.4%	327.73	341.59	+4.2%	2368	2376	-0.3%
6. EB&WB (1200veh/hour)	40.70	46.37	+13.9%	369.85	435.97	+17.9%	2762	2746	+0.5%
7. EB&WB (1300veh/hour)	46.49	58.56	+25.9%	403.21	522.94	+29.7%	2937	2960	-0.8%

The performance of total travel time does not have much difference when the traffic demand on EB and WB are less than 1000 vehicles/hour except in the scenario 2 (400 vehicles/hour on EB and WB) which has 12.2% improvement percentage by using the Matsuoka model (400 vehicles/hour on EB and WB).

The traffic control system with the Matsuoka Oscillator improves the total travel time when traffic demand on EB and WB are larger then 1000 vehicles/hour. The total travel time of the Matsuoka model is decreased from 46.37 to 40.70 hours which compared with fixed time control system when traffic demand on EB and WB are 1200 vehicles/hour. The Matsuoka model improves the total travel time by 25.9% when the traffic demand on WB and EB are 1300 vehicles/hour.

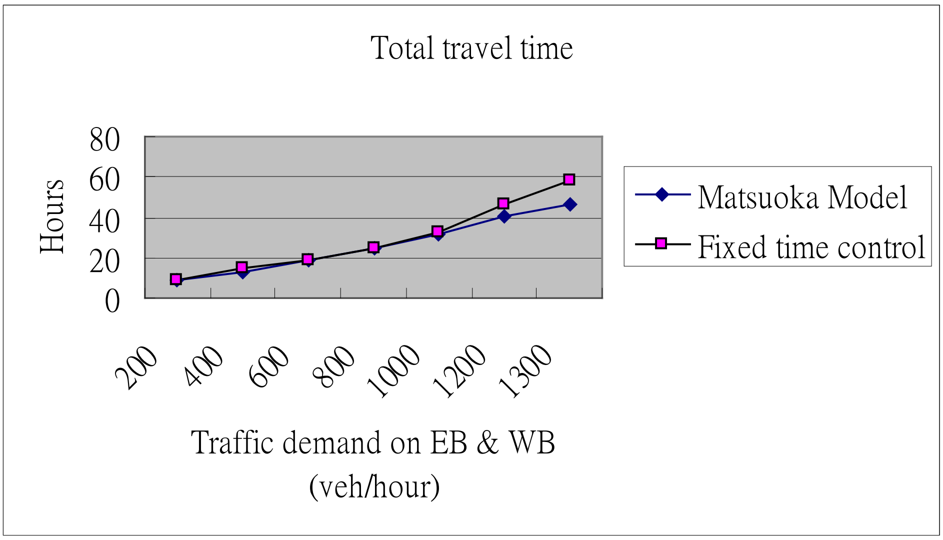


Figure 4-24 Comparison of total travel time (Matsuoka model v.s. Fixed time control).

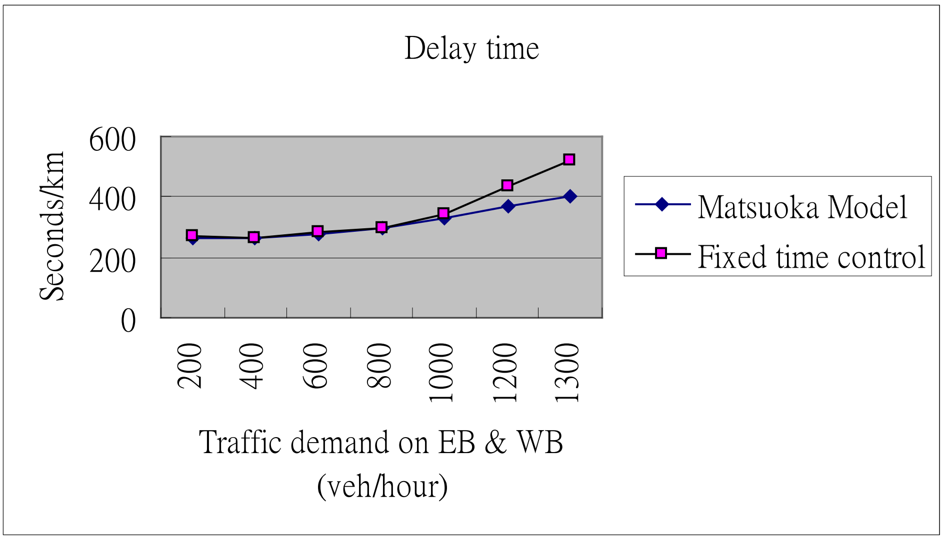


Figure 4-25 Comparison of delay time (Matsuoka model v.s. Fixed time control).

The situation of delay time performance is similar to the performance of total delay time. The delay time performance between the Matsuoka model and fixed time control system does not have much difference when the traffic demand on EB and WB are less than 1000 vehicles/hour. The improvement percentages of delay time by using Matsuoka model are 4.2%, 17.9%, and 29.7% respectively (1000, 1200, and 1300 vehicles/hour on EB and WB). Figure 4-26 shows that there are no difference of flow performance between Matsuoka model and fixed time control.

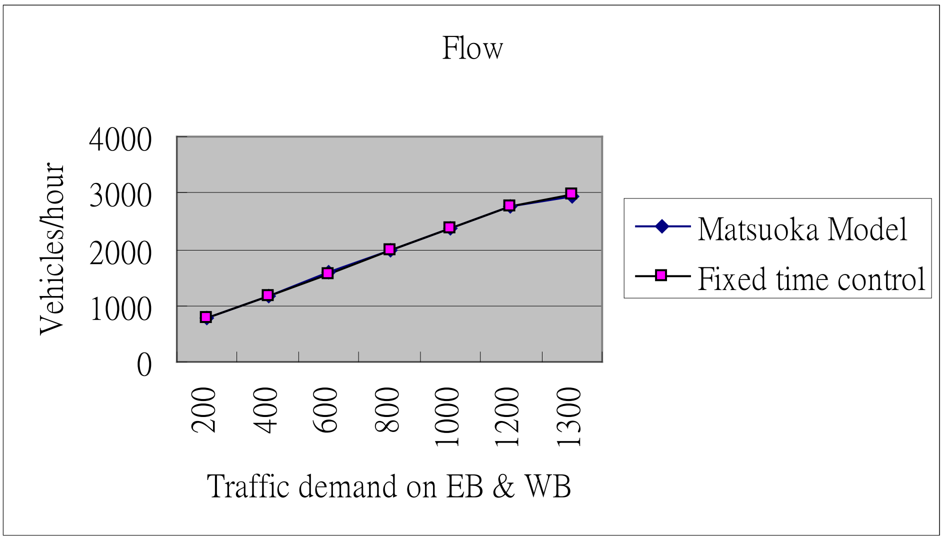


Figure 4-26 Comparison of flow (Matsuoka model v.s. Fixed time control).

4.7 Summary

The objective of Chapter 4 was to implement Matsuoka Oscillators in traffic control system for a four-phase intersection in order to balance the traffic condition with unbalanced traffic demand. According to the section of inputs and outputs analysis, the proportional relationship is shown between the difference of traffic demand and extension green time.

By comparing the delay time on each band with Matsuoka model and fixed time control system, the Matsuoka model increases the delay time on the band which has lower traffic demand and reduces the delay time on the band with higher traffic demand when the difference of traffic demand reaches a certain range.

From the aspect of entire traffic performance, the traffic control system with Matsuoka Oscillators balance the traffic condition by allocating more green time on the road with higher traffic demand. The traffic performance of the Matsuoka model is no difference when compared with the fixed time control system since the difference of traffic demand between major street (EB or WB) and minor street (NB or SB) is less than 800 vehicles/hour. The Matsuoka model has better improvement percentage of performance of total travel time (13.9% and 25.9%) and delay time (17.9% and 29.7%) when the difference of traffic demand between major street and minor street is larger than 1000 vehicles/hour.

Chapter 5 Summary and recommendations for the future work

5.1 Summary of the thesis

The objective of this thesis was to implement Matsuoka Oscillators into the traffic control system at the two-phase and four-phase isolated intersections. This thesis used the characteristic of a Matsuoka Oscillator to control the traffic signals depending on the dynamic traffic demand in each phase. These Matsuoka Oscillators were calibrated based on the 30 and 15 seconds fixed green time and implemented into the two-phase and four-phase isolated intersections. The traffic control system with Matsuoka Oscillators was simulated by AIMSUN software with unbalanced traffic demand scenarios. There are some conclusions for the achievement and analysis that could be summarized as follows:

- The Matsuoka Oscillators were designed and calibrated based on 30 and 15 seconds fixed green signals. The relationship of inputs and outputs of Matsuoka Oscillators were analyzed and connected with the parameters in the traffic environment such as numbers of vehicles and the duration of green time.

- The limitation and characteristic of this Matsuoka Oscillator in the traffic control system has been analyzed in this paper. There was a proportional relationship between the differences within two inputs and the differences within outputs.

- The algorithm Matsuoka Oscillator was coded in C++ language and dynamically linked to the AIMSUN. In Chapter 3, two independent Matsuoka Oscillators controlling two signals implemented in a two-phase intersection. Two external inputs of a Matsuoka Oscillator are the number of vehicles waiting on the queue in next phase and the number vehicles passing through the intersection in the current phase. The output represents the duration of green time in the next phase.

- In Chapter 3, the traffic control system with the Matsuoka Oscillators is stable which has been tested and analyzed with the same traffic volume in each phase but different total traffic demand scenarios. The maximum difference between two average green times is less than 3.8 seconds. The traffic performance of the Matsuoka model remains same as fixed time control when the total traffic demand is less than 4000 vehicles/hour.

- In Chapter 4, the Matsuoka Oscillators controlled four signals in a four-phase intersection. The two external inputs of Matsuoka Oscillator represents by the number of vehicles waiting on the queue in next two phases.

- In the unbalanced traffic demand scenarios, the Matsuoka model reduces the delay time for the road with higher traffic demand and increases the delay time for the road with lower traffic demand in order to balance the traffic condition. Therefore, the Matsuoka model improves the entire traffic performance of delay time and total travel time only when the difference of traffic demand is going high.

5.2 Discussion

According to the previous chapters of this thesis, some problems and further research could be discussed for adaptive signal control system with the Matsuoka Oscillators is summarized as follows:

The concept of designing this adaptive system control with the Matsuoka Oscillator is to compare the differences of number of vehicles on the current phase or next phase in order to allocate the suitable green time on next phase. This adaptive control system allocates more green time to the phase with higher traffic volumes and keeps the green as minimum green time for the phase with lower traffic volumes. The advantage of this adaptive system is to reduce the delay time on the phase with higher traffic volumes because the control system allocates more green time on it. From previous analysis, the proportional relationship has been shown between the difference number of vehicles on each phase and duration of green time on next phase. On the other hand, the disadvantage of this system is the higher delay time on the phase with lower traffic volumes.

In Chapter 3, the Matsuoka Oscillators control only two signals at an isolated intersection. The traffic control system allocates the green time on next phase immediately depending on the traffic demand on each phase. The entire traffic system has better performances when the differences of traffic demands are larger.

In Chapter 4, there are four Matsuoka Oscillators working independently on each phase. This adaptive system allocates more green time on the phase with higher traffic volumes but also increases the red time on the phase with lower traffic volumes. There are four signals at this isolated intersection. If the traffic system allocates more green time on the higher traffic demands phase, that means the other three phases have longer red signal time. So that could be the reason the traffic system keeps the isolated intersection balance when the differences of traffic demand between major streets and minor streets are not too large. The performance of the entire traffic becomes better when compared with a fixed time control system only when the differences of traffic demand are extreme large.

5.3 Further research

1. The external inputs of a Matsuoka Oscillator in this adaptive control system represent by the number of vehicles waiting on the queue or passing through the intersection. Some other concepts or algorithms could be used to determine the arrivals in order to make more recent real-time data continuously such as projection horizon concept (Gartner, 1983).

2. The structure of the adaptive control system with the Matsuoka Oscillators could be simplified. It is suggested to use one Matsuoka Oscillator based on the one fixed green time signal. This suggestion could simplify the C++ codes and make the structure of this adaptive control system simple.

3. In this thesis, the two external inputs of a Matsuoka Oscillator are number of vehicles on different phases. The current adaptive signal system use independent Matsuoka Oscillators to control the signals on each phase. It is suggested to study other possible traffic variables such as density of traffic that can substitute into the inputs of oscillator in order to make the adaptive signal system more effective. This suggestion could make

the structure of adaptive signal system simpler and easier to design. It may also reduce the delay time or total travel time of the entire traffic system rather than just balance the unbalance traffic conditions.

4. In this thesis, the Matsuoka Oscillators are implemented into two-phase and four-phase intersection with fixed sequence. The control system needs to be extended to include every possible phases in the isolated intersection. It is suggested to study the Matsuoka Oscillator to be used in the multiple intersections or diamond interchanges.

References

Anthony, A. S., G., Anandalingam, and Nicholas, J. G. "Traffic Signal Timing at Isolated Intersections Using Simulation Optimization." Proceedings of the 1986 Winter Simulation Conference, 795-801.

Bell, M.G. H., "A probability approach to the optimization of traffic signal systems in discrete time", Transportation And Traffic Theory, Elsevier, London, 1990, pp.619-633.

Bhargava, R. C., Chantan, J., and Yuqi, F., "Adaptive Controller II", Department of Civil and Environmental Engineering University of Utah Traffic Lab, Salt Lake City, pp7-15, 2003.

Bouhet, P. H., Cambonie, P., and Nicolotto, C., "Humanoid Robotic Chewing – Neuronal Oscillator Based Generation and Adaptation of Central Pattern of Mastication", Massey University Institute of Technology and Engineering, Auckland, New Zealand, 2007.

Carl, S. P., "Traffic signal detector locations proper positioning increases efficiency & safety", University of British Columbia Department of Civil Engineering, pp4-6, 1995.

David, B., "Advice Leaflet 1: The "SCOOT" Urban Traffic Control System", Peek Traffic Limited, Siemens Traffic Controls and TRL Limited, pp1-8, 2000-2008.

Dell'Olmo, P., and P. B. Mirchandani, "A model for real-time traffic co-ordination using simulation based optimization", Advanced Methods in Transportation Analysis (ed. L. Bianco and P. Toth) Springer-Verlag, Germany. pp525-546, 1996.

Dell'Olmo, P., and P. B. Mirchandani, REALBAND: An approach for real-time coordination of traffic flows on networks, Transportation Research Record 1494, National Research Council, Washington, D.C., 1995.

Evan, H. Pelc, Monica, A. Daley, and Daniel, P. Ferris., "Resonant hopping of a robot controlled by artificial neural oscillator", IOP Publishing Ltd, pp1-11, 2008.

Fang, F., "Optimal Adaptive Signal Control for Diamond Interchanges Using Dynamic Programming." College of Engineering, Pennsylvania State University, pp9, 16-17, 2004.

Gartner N. H., "OPAC: A Demand-Responsive Strategy for Traffic Signal Control", Transportation Research Record (906), Transportation Research Board, Washington, DC, 1983, pp. 75-81

Gazis, D. C. & Potts, R. B., "The oversaturated intersection" Yorktown Heights, N.Y.: International Business Machines Corporation. Thomas J. Watson Research Center, 1963.

Haijun, G., Lingxi, L., Rui, L., and Feiyue, W., **"**Changeable phases signal control of an isolated intersection", Systems, Man and Cybernetics, 2002 IEEE International Conference on Volume 5, Issue , 6-9 Oct. 2002 Page(s): 4 pp. vol.5.

Head, K.L., "Event-Based Short-Term Traffic Flow Prediction Model", Transportation Research Record (1510), Transportation Research Board, Washington, D.C., pp.45-52,1995.

Hooper, Scott L. "Central Pattern Generators", Embryonic ELS at http://www.els.net/elsonline/figpage/I0000206.html, 1999.

K. Matsuoka, "Sustained oscillations generated by mutually inhibiting neurons with adaptation", Biological Cybernetics 56, pp367-376, 1985.

Kuo, Arthur D. "The relative roles of feed forward and feedback in the control of rhythmic movements." *Motor Control* (2002): 6, 129-145.

Lin, F.B, and Vijayayumar, S., "Adaptive signal control at isolated intersections", ASCE Journal of Transportation Engineering, Vol. 114, No. 5, September 1988, pp.555-573

Lowrie, P.R., SCATS: The Sydney Co-ordinated Adaptive Traffic System. Paper presented at the IEE International conference on road traffic signaling at London, U.K., 1982.

Martin, P.T., and L. M. Hockaday., SCOOT - an update. ITE Journal 65, pp44-48, 1995.

Matthew, M. W. (1999) “Designing Rhythmic Motions using Neural Oscillators” Proceedings of the 1999 IEEE/RSJ International Conference on Intelligent Robots and Systems, 494-500.

Miller, A.J., "A Computer Control System for Traffic Networks", 1963, pp. 200-220.

Sen, S., and K. L. Head., “Controlled Optimization of Phases at an Intersection”, Transportation Science 31, pp5-17, 1997.

Taga, G.,“A model of the neuro-musculo-skeletal system fro human locomotion I. Emergence of basic gait”, Biological Cybernetics 73, pp97-111, 1995.

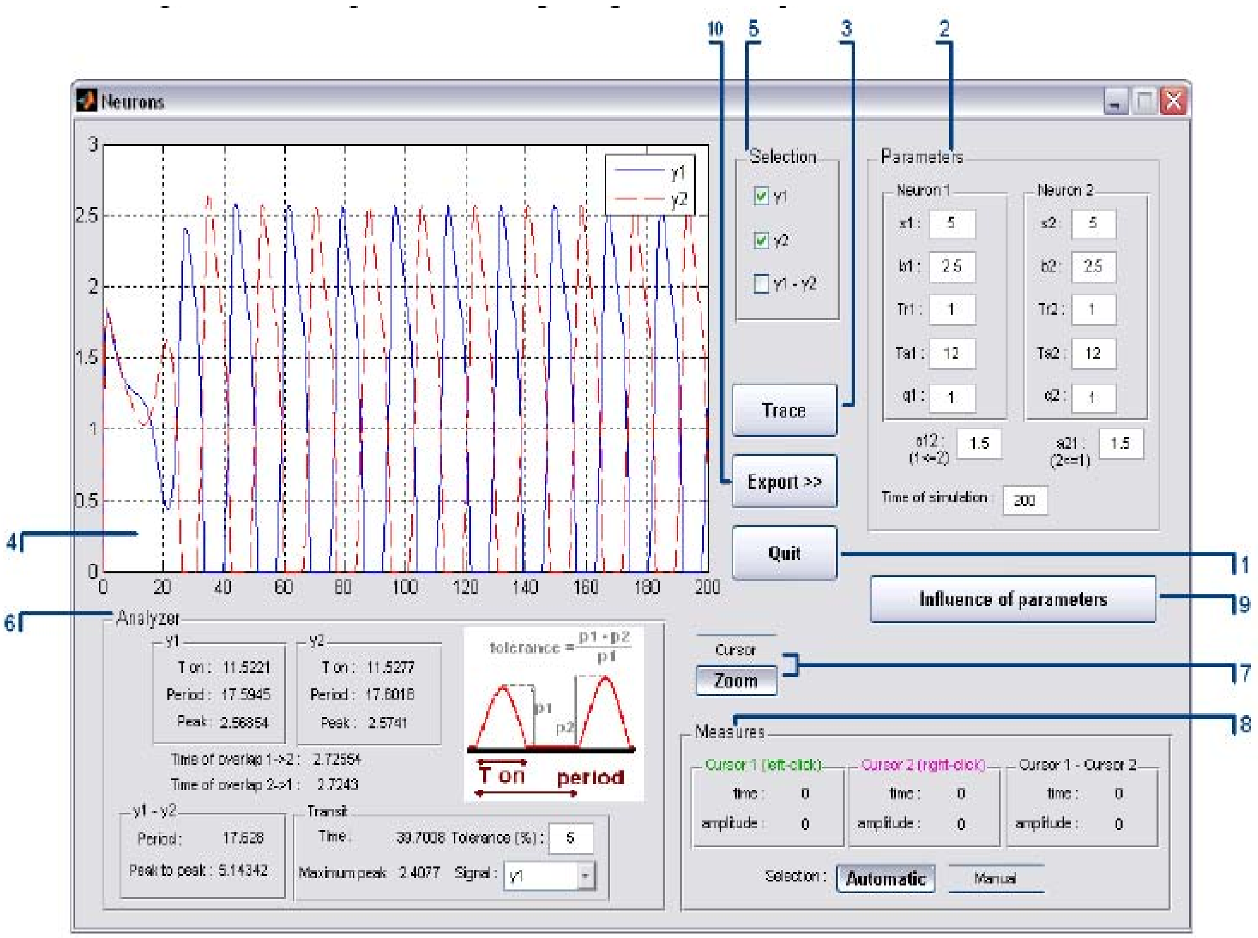
TSS-Transportation Simulation System, “Aimsun Microsimulator API Manual Draft Version”, Barcelona, Spain, 2008.

Vincent, R.A., and C. P. Young., “Self-Optimizing Traffic Signal Control Using Microprocessors the TRRL 'MOVA' Strategy for Isolated Intersections”, Traffic Engineering and Control 27, no. 7-8, Jul-Aug, pp385-387, 1986.

Wann, M.W., “Applications of Linear Systems Controller to A Cycle-based Traffic Signal Control” IEEE Intelligent Transportation Systems Conference Proceedings – Oakland (CA), USA, pp179-184, 2001.

Appendix A

Graphic User Interface



1: Button to close the window

2: Panel to set the values of each parameter and the time of the simulation

3: Button to launch the plot of the curves

4: Chart of the outputs

5: Panel to select the displayed curves

6: Panel of characteristic measures

7: Buttons to select the mode of the chart

8: Panel of values of the cursors

9: Button to opening the window of influence

10: Button to export the curves

APPENDIX B C++ CODE OF MATSUOKA OSCILLATOR