

**INVESTIGATION OF OPERATIONS OF HAWK PEDESTRIAN
TREATMENT**

A Thesis

by

SIQI LI

Submitted to the Office of Graduates Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

May 2012

Major Subject: Civil Engineering

Investigation of Operations of Hawk Pedestrian Treatment

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Approved by:

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ABSTRACT

Investigation of Operations of Hawk Pedestrian Treatment.

(May 2012)

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Chair of Advisory Committee: Dr. Yunlong Zhang

High intensity Activated cross Walk (HAWK), as an innovative pedestrian-activated beacon, has become a hot topic and was introduced in 2009 Manual on Uniform Traffic Control Devices (MUTCD). According to the 2009 MUTCD, HAWK should be installed at least 100 feet from a stop-controlled intersection. This thesis first evaluates the distance between HAWK and stop-controlled intersection recommended by 2009 MUTCD. On the basis of the knowledge of HAWK operation, this thesis applies the Generalized Linear Model (GLM) to model the pedestrian delay at an HAWK location. The HAWK pedestrian delay model includes the major street arrival rate, minor street arrival rate, pedestrian arrival rate and the distance between HAWK and intersection. Four different functional forms are investigated in order to select an appropriate one that could more accurately model pedestrian delay. The minimum green time for vehicles, as an important variable in the HAWK pedestrian delay model and a peculiar element in HAWK operations, is also evaluated with VISSIM simulation based

on different vehicle and pedestrian volume combinations. The impact of the HAWK on pedestrian delay is simulated by comparing pedestrian delay in scenarios with and without HAWK.

The results indicate that the minimum distance between HAWK and stop-controlled intersection recommended in MUTCD may be inadequate for high demand situations. More distance from HAWK to stop-controlled intersection needs to be considered in order to avoid vehicle spillback to the upstream intersection. Based upon the results of training and validating datasets, it can be indicated that the HAWK pedestrian delay model developed in this study is capable of effectively evaluating the pedestrian delay with a satisfactory accuracy. The study also identifies that a minimum green time for vehicles should be considered in order to reduce the vehicular delay and different minimum green times be provide for vehicles based on different pedestrian volume and vehicle volume combinations. A model of minimum green time for vehicles is then derived from HAWK pedestrian delay model. Finally, the study results indicate that a HAWK installation may increase pedestrian delay for the stop-controlled intersection scenario when vehicle demand is low.

DEDICATION

Dedicated to

My father, Ke Li, and

My mother, Hailun Zhang

ACKNOWLEDGEMENTS

First of all I would like to thank my committee chair, Dr. Zhang, for his great effort and kind help to me with this thesis. I could have never finished it without his instruction, suggestion and help. I would also appreciate my committee members Dr. Lord and Dr. Sherman, for their guidance and helpful recommendations along the full course of this thesis.

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1. INTRODUCTION

1.1 Background

As a pedestrian-activated beacon, the **H**igh intensity **A**ctivated cross **W**alk (HAWK) device, which is consisted of a traffic signal head with a red-yellow-red lens, is primarily installed on wide, mid-to high-speed multi-lane roadways with few crossing opportunities, mainly at midblock locations. One important purpose of HAWK is to reduce the *unnecessary delay*¹ to vehicles, meanwhile, create gaps in vehicle traffic to let pedestrians cross. This is accomplished by using a beacon with yellow and red indicators, instead of a traditional green-yellow-red traffic signal. The two red signal indications are placed horizontal to one another which are above one centered yellow signal (1). The HAWK traffic signal heads are located on both a mast arm over the roadway and on the roadside (see Figure 1). Figure 2 shows the HAWK traffic signal head and the HAWK pedestrian signal head.

Note: ¹The *unnecessary delay* is measured as: ‘time taken from when all pedestrians reach the other curb until the vehicles legally resume’. It is defined as the time for which the vehicles are stopped at a signalized mid-block crossing when pedestrians have cleared the crosswalk but drivers need to remain stopped for a solid red ball according to law.

This thesis follows the style of *Transportation Research Record*.



Figure 1 HAWK Pedestrian Beacon (2)



Figure 2 HAWK Traffic Signal Head (Left) & HAWK Pedestrian Signal Head (Right) (3)

The phase sequence of the HAWK (4) is as follows shown in Figure 3. The HAWK operation steps are as follows:

1. When not activated, the HAWK traffic signal head indications remains dark, meanwhile, the HAWK pedestrian signal head displays a solid DON'T WALK (raised hand) indication, keeping the pedestrians waiting until HAWK been activated.

2. When the pedestrians press the button, the traffic signal indication will show a flashing yellow for 3-6 seconds to give the drivers a beforehand warning of pedestrians crossing.
3. The main street HAWK traffic signal indication will display a solid yellow for about 3-6 seconds to give motorists enough time to stop at the crosswalk. (Both the step 2 and 3 are for a clearance interval of vehicles).
4. After the solid yellow interval, the main street vehicle indications will show two solid red indications, and pedestrians will be given a WALK (walking person symbol) signal.
5. After a period of time (5-8 sec) and the pedestrians are into the crosswalk area, the WALK signal terminates and the two red indications flash in an alternating pattern while the pedestrians who are already in the middle of the street continue across the street (flashing DON'T WALK and the countdown timer displays become visible for the HAWK pedestrian signal). The pedestrians that have not got into the street should stop and wait until the next HAWK activation. The motorists may proceed after stopping if the pedestrians have crossed their half of the street (Note: This phase is timed for a standard pedestrian crossing time of 3.5 feet/sec in anticipation of the change to the *Manual on Uniform Traffic Control Devices* (MUTCD)(5)).

6. After the countdown time has been exhausted, the Raised Hand indication becomes a solid display indicating to the pedestrian that they must wait until the next signal cycle before proceeding to cross the roadway, meanwhile, the traffic signal indications will go dark once again until the next pedestrian actuation and motor vehicles may proceed without stopping.

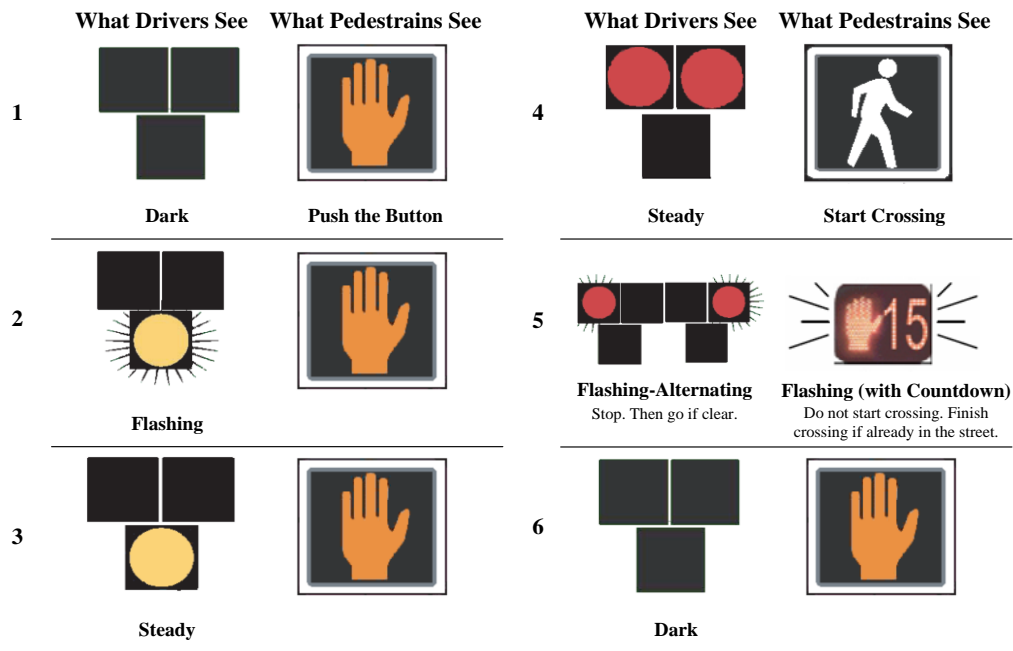


Figure 3 HAWK Beacon Phase Sequence

1.2 Problem Statement

To improve service for pedestrians, the 2009 Manual on Uniform Traffic Control Devices (MUTCD) first allowed HAWK beacon to be installed. According to the

MUTCD HAWK (called pedestrian hybrid beacon in 2009 MUTCD) should be installed at least 100 feet from a stop-controlled intersection (5).

As a kind of new pedestrian beacon, the first presentation of HAWK in 2009 MUTCD certainly provided some interesting recommendations for pedestrians, especially for those roadways with few crossing opportunities. However, very little research has been done in the area of HAWK operations. This thesis identifies the following areas of research related to HAWK operations:

1.2.1 Distance between HAWK and Stop-Controlled Intersection

As it recommended in the 2009 MUTCD, HAWK should be installed at least 100ft from stop-controlled intersection. However, when a HAWK is very close to the upstream intersection, vehicles will back up towards the upstream intersection when the HAWK is on. This could potentially lead to vehicle queue spillback into the intersection area and cause adverse impact on the operation of the upstream intersection. To avoid frequent occurrences of such spillback, an adequate distance between the HAWK and the upstream intersection should be provided. In this case, the 100 ft minimum distance between HAWK and stop-controlled intersection recommended in 2009 MUTCD should be evaluated and some new recommendations should be made if it is not adequate.

1.2.2 Pedestrian Delay Model with HAWK

As an important criterion to evaluate HAWK operations, a pedestrian delay model needs to be investigated to describe the pedestrian delay situation and estimate pedestrian delay value when a HAWK is installed. Many kinds of pedestrian delay models have been addressed in the previous studies. However, as HAWK is a newly-applied pedestrian beacon, previous studies rarely focused on pedestrian delay models when HAWK is applied. In this case, a model for pedestrian delay with HAWK should be investigated so that estimated pedestrian delay values could be provided when a HAWK is installed away from the stop-controlled intersection.

1.2.3 Minimum Green Time for Vehicles

As a type of pedestrian beacon, HAWK was designed to reduce the pedestrian delay in order to ensure the pedestrians crossing the street where there are not enough gaps due to high vehicle volume. However at the same time it may increase the vehicle delay when creating gaps for pedestrians to cross the street. Particularly, at high pedestrian demand situations vehicular delay may increase significantly. Considering the trade-off between the pedestrian demand and vehicle demand, there is a need to recommend a minimum green time for vehicles, or a minimum time between two consecutive HAWK activations. A minimum green time for vehicles can ensure the

vehicle level of service under a high pedestrian demand when HAWK applied and to balance the pedestrian level of service and vehicle level of service in order to minimize the whole network delay.

1.2.4 Impact of HAWK on Pedestrian Delay

HAWK aims at insuring the pedestrian to cross the street, meanwhile avoiding too much vehicle delay under high pedestrian demand. HAWK is a new kind of pedestrian beacon and previous research rarely investigated its effect on pedestrian delay and the whole network delay after its installation. A comprehensive study on the impact of HAWK on pedestrian delay is needed. This thesis will investigate the effect of HAWK on pedestrian delay by comparing a stop-controlled intersection with HAWK at 100ft away and a stop-controlled intersection with traditional crosswalk at the intersection.

1.3 Research Objectives

The goal of the research is to provide guidance on setting HAWK operational parameters. The research objectives are:

- To evaluate the recommended minimum distance between HAWK and stop-controlled intersection in 2009 MUTCD.
- To provide a recommendation of distance between HAWK and stop-controlled

intersection.

- To find out a practical pedestrian delay model when HAWK installed away from the stop-controlled intersection.
- To investigate the minimum time between two consecutive HAWK activations (minimum green time for vehicles).
- To investigate the impact on pedestrian delay with HAWK implementation.

1.4 Research Benefits

Based on the primary guideline of pedestrian hybrid beacon included in the 2009 MUTCD, this research plans to provide a comprehensive recommendation on HAWK operational parameters. The results of this research provide new recommendations if needed, which may be beneficial to the new versions of MUTCD. This research will also provide guidance on setting HAWK operational parameters, which was rarely mentioned in the previous research. A statistical model of pedestrian delay will be provided with HAWK installed and it is a good beginning in the modeling of HAWK pedestrian delay, which could be helpful for further HAWK study. As HAWK is a new kind of pedestrian beacon, the effect of HAWK on pedestrian delay and network delay will be investigated to fully evaluate the operational benefits of HAWK.

2. LITERATURE REVIEW

2.1 Introduction

This chapter of the thesis provides basic information of High intensity Activated cross Walk (HAWK) and background information about pedestrian delay models and VISSIM. The first section provides an introduction to the previous research on High Intensity Activated cross Walk. Section 2.2 introduces the previous studies on HAWK and Section 2.3 reviews pedestrian delay models. To have a better understanding of the HAWK pedestrian delay model, section 2.3 describes the generalized linear model. Section 2.5 provides the basic knowledge of the VISSIM simulation software.

2.2 Previous Research on High Intensity Activated Cross Walk (HAWK)

In the late 1990s, HAWK was first developed and applied in the city of Tucson, Arizona in 60 locations to assist pedestrians crossing. After HAWK installation, its effect on safety was investigated by researchers.

Nassi and Barton (6) reported that although there may be some potential driver confusion, crashes involving pedestrians reduced from the year 2002 to 2006 by an average of 1.8 crashes per year at each HAWK location. With such success of HAWK

application, more governments began to consider HAWK installation in other areas and more researchers began to investigate the HAWK effect on pedestrian safety. It is concluded that pedestrian safety was improved after HAWK installation.

In 2006 Turner, Fitzpatrick, Brewer and Park (7) conducted a study on motorist yielding to pedestrians at unsignalized intersections. The study aims at evaluating different pedestrian devices at pedestrian crossings. With the selected 42 sites, which were all with different pedestrian control devices, the effective use of the pedestrian treatment were measured by motorist yielding. It was concluded that for all the study sites, HAWK makes the motorist yielding rates greater than 94% and the average compliance rate is greater than 95% which were both much higher compared with the average motorist compliance rate before HAWK application.

In the same year Fitzpatrick and Turner (8) did research on improving pedestrian safety at unsignalized crossings and had a similar conclusion that HAWK achieved a high driver compliance rate. Their research was conducted for Transit Cooperative Research Program (TCRP) and the National Cooperative Highway Research Program (NCHRP) in order to improve pedestrian safety at unsignalized crossings. Their conclusion showed that HAWK had a high driver compliance rate of 97% and the compliance rate was not affected by the number of lanes.

In the year 2010 Arhin and Noel (9) wrote a paper on evaluation of HAWK signal at Georgia Avenue and Hemlock Street NW in Washington D.C. The result of this study was consistent with the previous study in the motorist compliance part with a compliance rate up to 97.1% with the HAWK signal. However, the pedestrian HAWK was found potentially to cause some confusions and the pedestrian compliance was at a low rate of 50%-66%. Low vehicle volume might be another reason to explain this phenomenon. In this case, it was recommended HAWK should be used at unsignalized intersection to insure pedestrian crossing, especially for those intersections on a high-volume major arterials with moderate-to-high pedestrian volume. However, as the observations in this paper only lasted for three days which could not prove the conclusion sufficiently, more observations should be added in the future together with more observation sites.

Besides of the motorist compliance rate, number of crashes is another criterion to evaluate the HAWK effect on safety. In the year 2009 Fitzpatrick and Park (2) conducted a study on safety effectiveness of the HAWK pedestrian treatment. With the objective of evaluating safety effect of HAWK, the paper analyzed crash data using before and after study. In their study, two un-signalized intersections were selected and two signalized intersections were treated as reference sites for each HAWK. It was shown that HAWK beacon may improve pedestrian safety when installed as a 28%

reduction in all crashes and 58% reduction in pedestrian crashes were observed after HAWK installation.

Compared with the safety effect of HAWK, the previous research work rarely evaluated the operations aspect of HAWK. Compared with the traditional pedestrian signals (eg: pedestrian-actuated signal, pedestrian light-controlled signal, etc.), HAWK may reduce the unnecessary delay, which is the delay pedestrians cause to drivers due to the time difference between the pedestrian signal and the vehicle signal. In the year 2007 Schroeder, Roupail and Hughes (10) studied pedestrian signalization treatments at one- and two-lane roundabouts using microsimulation with VISSIM. The result indicated that HAWK signal could significantly reduce the vehicle delay compared with a conventional pedestrian-actuated signal.

In 2009, Lu and Noyce (11) did a more comprehensive study on pedestrian crosswalks at midblock locations to find out fuzzy logic solution to existing signal operations. This study found that HAWK improved vehicle operations with whatever phase timing, performed better than PA (pedestrian-actuated) and PELICAN (pedestrian light-controlled) in many aspects, such as average vehicle delay, average queue length and average number of stops.

A more specific conclusion was drawn in 2010 by Godavarthy and Russell (12). By comparing with the signalized mid-block pedestrian signal in the same city, this paper

conducted a study to find out the effectiveness of HAWK in decreasing the unnecessary delay to drivers. The result showed that according to statistical analysis, when HAWK was used the unnecessary delay was reduced significantly from 50.9% to 4.3% compared with the signalized mid-block pedestrian signal as long as the drivers understood the HAWK signal.

Besides of the HAWK effect on vehicle delay, researchers also concerned about the HAWK effect on pedestrian delay. In the year 2006 Fitzpatrick and Turner (7) did a study on improving pedestrian safety at unsignalized crossings. They concluded that with the advantage of high compliance rate, HAWK might also cause extra pedestrian delay as shown in the following Table 1 from which it could be concluded that HAWK made a great pedestrian delay compared with most other signals (the number is 1.83 bold in Table 1).

Table 1 Pedestrian Delay by Treatment (7)

Treatment	Initial Delay (s)		Median Delay (s)		Total Delay (s)		Count
	Avg	StdDev	Avg	StdDev	Avg	StdDev	
Flag	2.67	3.37	0.10	0.37	2.72	3.39	350
Half	16.88	19.78	0.69	3.04	17.06	19.70	342
Hawk	7.80	7.86	1.83	6.21	9.63	9.60	224
HiVi	1.86	4.08	0.53	2.35	2.39	4.88	606
InSt	2.09	3.67	0.09	0.86	2.15	3.78	310
Msig	26.35	27.67	0.00	0.00	26.35	27.67	393
OfPa	5.54	9.47	0.10	1.12	5.62	9.59	164
OfPb	5.44	6.61	-	-	5.44	6.61	254
Refu	5.36	10.20	3.86	11.47	9.22	16.21	512
Grand Total	8.12	15.46	1.36	6.41	9.01	16.29	3155

**Note:*

Abbreviations: Avg=average; StdDev=standard deviation; Msig=midblock signal; Half=half signal;

Hawk=HAWK signal beacon; InSt=instreet crossing signs; Flag=pedestrian crossing flags;

OfPb=overhead flashing beacons (pushbutton activation); Refu=median refuge island;

HiVi=high-visibility signs and markings; OfPa=overhead flashing beacons (passive activation)

2.3 Pedestrian Delay Models

In previous research work, researchers have developed many kinds of models in predicting pedestrian delay, mainly for signalized intersection pedestrian delay models.

In the year 1978, Braun and Roddin (13) developed the most frequently used model to estimate pedestrian delay at signalized intersections as follows in the equation 1:

$$d = \frac{(C - G)^2}{2C} = \frac{(R + A)^2}{2C} \quad (1)$$

where:

d - Average pedestrian delay,

C - Cycle length,

G - Green time,

R - Red time,

A - Clearance duration,

The model was developed under the following assumptions:

- Uniform pedestrian arrival rate;
- Complete signal compliance;
- Fixed cycle length;
- No pedestrian actuation

Later as considering that some pedestrians may violate traffic signals, another model was suggested by them in equation 2:

$$d = F \frac{(C - G)^2}{2C} \quad (2)$$

where F is the fraction of pedestrians who arrive during non-green phases and comply with traffic signals. This equation assumes that pedestrians receive no delay if they violate traffic signals.

On the basis of this model, in the year 1998 Virkler (14) conducted a study in Australia and it was noted that pedestrians who entered crosswalks during clearance phases caused most delay reductions. The following model was proposed then:

$$d = \frac{[C - (G + 0.69A)]^2}{2C} \quad (3)$$

where A is the clearance time.

Based on all the previous research result, the Highway Capacity Manual (HCM) 2000 (15) concluded that the average delay per pedestrian for a crosswalk at signalized intersection was:

$$d_p = \frac{0.5(C - g)^2}{C} \quad (4)$$

where:

d_p = average pedestrian delay (s),

g = effective green time (for pedestrians) (s), and

C = cycle length (s).

Besides of the pedestrian delay at signalized intersection, the HCM 2000 also provided the pedestrian delay at unsignalized intersection. Most unsignalized intersections are two-way stop-controlled (TWSC) intersections and the average delay per pedestrian for a crosswalk at TWSC intersection was given in equation 5:

$$d_p = \frac{1}{v} (e^{vt_G} - vt_G - 1) \quad (5)$$

where:

d_p = average pedestrian delay (s),

v = vehicular flow rate (veh/s), and

t_G = group critical gap,

$$t_G = t_c + 2(N_p - 1) \quad (6)$$

where:

t_G = group critical gap (s),

t_c = critical gap for a single pedestrian (s), and

N_p = spatial distribution of pedestrians (p).

The critical gap for a single pedestrian t_c was given in equation 7:

$$t_c = \frac{L}{S_p} + t_s \quad (7)$$

where:

t_c = critical gap for a single pedestrian (s),

S_p = average pedestrian walking speed (ft/s),

L = crosswalk length (ft), and

t_s = pedestrian start-up time and end clearance time (s).

$$N_p = INT \left[\frac{8.0(N_c - 1)}{W_E} \right] + 1 \quad (8)$$

where:

N_p = spatial distribution of pedestrians (p),

N_c = total number of pedestrians in the crossing platoon (p),

W_E = effective crosswalk width (ft), and

8.0 = default clear effective width used by a single pedestrian to avoid interference.

when passing other pedestrians,

$$N_c = \frac{v_p e^{v_p t_c} + v e^{-v t_c}}{(v_p + v) e^{(v_p - v) t_c}} \quad (9)$$

where:

N_c = size of a typical pedestrian crossing platoon (p),

v_p = pedestrian flow rate (p/s),

v = vehicular flow rate (veh/s), and

t_c = single pedestrian critical gap (s).

2.4 Generalized Linear Model

The generalized linear model (GLM), as a flexible generalization of linear regression, was introduced by Nelder and Wedderburn (16). The generalized linear model unifies various other statistic models such as linear regression, logic regression and Poisson regression. Its core procedure is to generalize linear regression via a link function which is used to connect the linear model and the response variable. The

generalized linear model provides a crucial advantage which eliminates the assumption of a normal distribution for response variable and allows users to use any member of the exponential family of distributions comparing with the multiple regression. Therefore, it attracted more and more people's attentions, and has been widely and successfully applied in many fields (17, 18, 19, 20) today. Transpiration is a good platform to implement the generalized linear model as well.

In 1990, Said (21) applied the generalized linear model to model work trip generation rates of households for Kuwait. Finally, the relations between the dependence variable of average household work trip and factors of interest including household size, household income, the number of cars owned, nationality, etc. has been successfully established under GLM framework.

Harnen et al. (22) developed a predictive model for motorcycle crash in non-signalized intersections by the generalized linear modeling approach in 2003. After employing the motorcycle crash data collected from four districts of the state of Selangor, Malaysia, the final model demonstrated that the motorcycle crash could increase as an increase in motorcycle and non-motorcycle flows entering an non-signalized intersection occurred. Additionally, by using GLM approach, authors also found that factors such as speed, lane width, number of lanes, shoulder width significantly affect the occurrence of motorcycle crashes.

In order to explore the connection between winter maintenance and winter road safety, Usman et al. (23) developed a generalized linear model using data over three winter seasons from four maintenance routes in the province of Ontario, Canada in 2010. It was found that road surface condition is a significant factor for winter road safety. Additionally, the authors also suggested that the model could potentially be applied for evaluating the effect of alternative maintenance standards.

It should be noted that the generalized linear model has not been widely applied to the analysis of traffic and pedestrian delay yet. The potential of using GLM in the delay investigation is explored in this work.

2.5 Introduction of VISSIM Simulation Software

VISSIM is popular traffic simulation software, and is able to simulate complex nonlinear dynamic systems in Figure 4. VISSIM simulation system consists of two separate programs, which are the traffic flow model and the signal control model. Figure 4 is a block diagram of VISSIM.

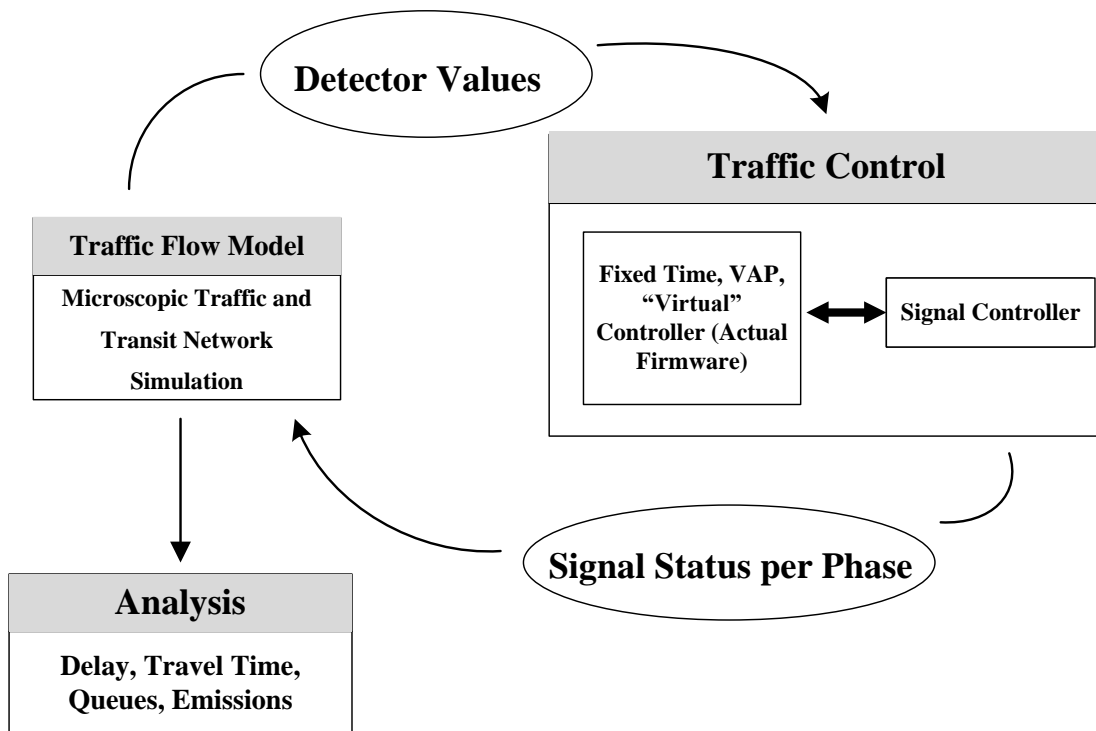


Figure 4 Block Diagram of VISSIM

In the past, VISSIM has been widely used in many traffic simulation scenarios. In the year 1994 Fellendorf (24) used VISSIM to evaluate actuated signal control including bus priority. They believed that the standardized systems can be tested by using VISSIM simulation software, which could help to assess various vehicle actuated control strategies. Besides the traffic models in the VISSIM could reflect the real world traffic situation.

Although VISSIM has many advantages in simulating the traffic, researchers conducted studies on improving the models in VISSIM for a more accurate result, which may reflect the real world traffic situation better. In the year 2001 Fellendorf and

Vortisch (25) conducted a study on validation of microscopic traffic flow model VISSIM in different real-world situations. The paper explained the car following model and investigated its ability of adapting to different driving behaviors. Two calibration efforts of the model for German and US freeway traffic were validated by comparing measured field data with simulation results. In the year 2004 Gomes and Horowitz (26) simulated the congested freeway using the microsimulation model in VISSIM. Based on the observation data, a successful calibration of the VISSIM model was carried out. It was showed that the VISSIM simulation environment suited well with the freeway conditions together with the complex interactions.

In this study, as a simulation tool VISSIM is used to simulate the operation of HAWK under different scenarios in order to estimate the pedestrian delay. With the HAWK simulation model built in VISSIM, the data such as traffic volume, vehicle speed, pedestrian volume, and pedestrian delay can be collected. All data applied to train and validate the statistical model of pedestrian delay are also conducted in VISSIM.

3. METHODOLOGY

3.1 Study Design

The study is conducted using VISSIM microscopic simulation in the scenario of a HAWK with a two-way stop-controlled intersection. It is assumed the EB and WB four-lane street as the major street and the SB and NB four-lane street as the minor one shown in Figure 5.

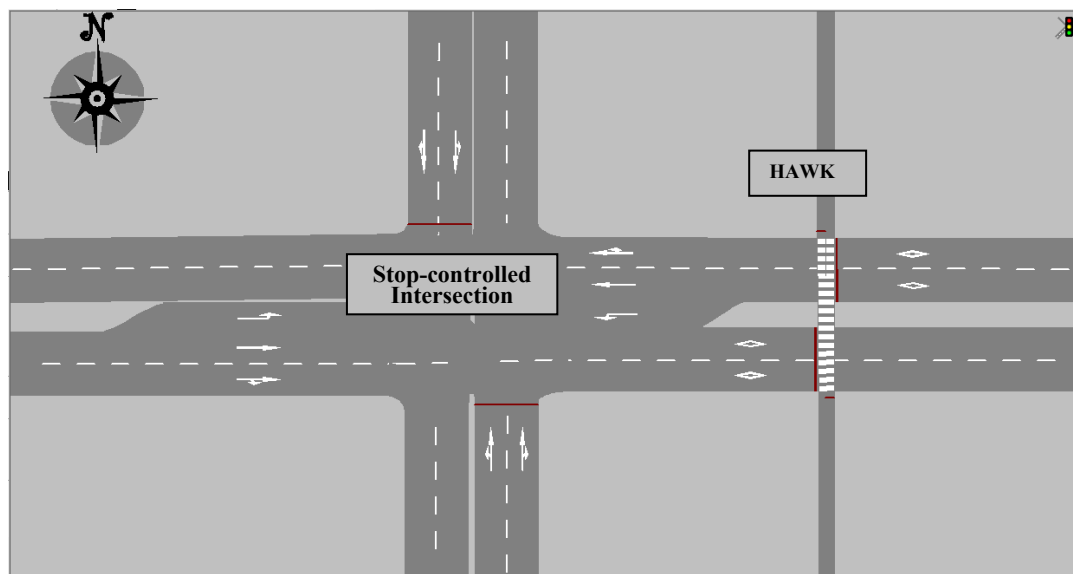


Figure 5 HAWK Simulation Model

Multiple simulation scenarios are developed considering a wide range of pedestrian and vehicle flow conditions in order to produce data for pedestrian model development. The speed of the vehicles and pedestrians is set as 40km/h and 3.5km/h, respectively. To

develop a HAWK pedestrian delay model, for the major street, the percentages of the left-turn, through, right-turn are set as 10%, 80%, 10%, respectively; meanwhile, for the SB and NB street the percentages are 25%, 50%, 25%, respectively. The pedestrian volume is defined as 20 pph, 50 pph, 100 pph, 200 pph, 300 pph and 400 pph in both NB and SB directions. As for the vehicle volume, the major street volume is defined as 750 vph, 1000 vph, 1250vph and 1500vph and minor street volume is 225 vph, 300 vph and 375 vph, 450 vph. The Travel Time Measurement function in VISSIM was used to assess the pedestrian delay (s) and the detection points provide pedestrian arrival rate (pps), major street vehicle arrival rate (vps) and minor street vehicle arrival rate (vps). The simulation time is 7200 seconds with 60 seconds as the interval, which means collecting data in every 60 seconds. For each simulation scenario, the simulation results are from the averages of five runs.

To investigate the proper minimum green time for vehicles, the minimum vehicle go-time is evaluated from 10 seconds to 60 seconds at 10 second intervals. The distance from HAWK to the stop-controlled intersection is set as 100 feet. for the major street, the percentages of the left-turn, through, right-turn are set as 10%, 80%, 10%, respectively; meanwhile, for the SB and NB street the percentages are 25%, 50%, 25%, respectively. The pedestrian volume is defined as 50 pph, 100 pph, 200 pph, 300 pph and 400 pph in both NB and SB directions. As for the vehicle volume, the major street

volume is defined as 1000 vph, 1500vph and 2000vph and minor street volume is 300 vph, 450 vph and 600 vph. The Travel Time Measurement function in VISSIM was used to assess the pedestrian delay (s) and vehicle delay (s). The simulation time is 7200 seconds with 60 seconds as the interval. For each simulation scenario, the simulation results are from the averages of five runs.

The dataset for pedestrian delay model in this study was collected in VISSIM, which has a total sample size of 5670. The dataset, which was divided into two sub-datasets, includes 3780 training data points and 1890 validation data points. The data collected in VISSIM included the pedestrian delay(sec), the vehicle delay(sec), the minimum green time for vehicles(sec), the pedestrian arrival rate(pps), the distance from HAWK to intersection(ft), the major street vehicle arrival rate(vps) and the minor street vehicle arrival rate(vps). Three distances from HAWK to intersection data were randomly selected from the normal distribution $N(200, 50)$ within the range from 100 to 300. The length of minimum green time for vehicles, which means the minimum HAWK's "off" duration between two activations, impacts the pedestrian delay and the vehicle delay significantly (27). Five minimum green time for vehicles data were randomly selected from the normal distribution $N(40, 10)$ within the range from 10 to 70. It is assumed that the pedestrian delay at HAWK is affected by minimum green time for vehicles and pedestrian arrival rate.

3.2 Investigation of the Recommended Distance in 2009 MUTCD

When a HAWK is very close to the upstream intersection, vehicles will back up towards the upstream direction. This could potentially lead to spillback into the intersection area and cause adverse impact on the operation of the upstream intersection. To avoid frequent occurrences of such spillback, an adequate distance between the HAWK and the upstream intersection should be provided. According to the 2009 MUTCD, HAWK should be installed at least 100 feet from a stop-controlled intersection. To evaluate this distance, some calculations need to be made.

Based on the HAWK operations mentioned in the previous section, the “on” period of HAWK is composed of the clearance interval of vehicles (step 2 and 3 in previous section) and the pedestrian-walking period (step 4 and 5 in the previous section). Normally, the clearance interval of vehicles is at least set as 8 seconds. To calculate the pedestrian-walking period, we have the following assumptions:

- Lane width=12 ft,
- Four-lane street,
- Pedestrian walking speed=3 ft/s (3.0 fps total walking speed is adopted considering the elder people).

Based on the above assumptions, the “on” period of HAWK is calculated to be $12\text{ft} \cdot 4\text{lanes} / 3 + 8\text{sce} = 24\text{sec}$. Assuming there is an arriving vehicle platoon during the “on” period of the HAWK, the waiting vehicles at the HAWK will accumulate to 12 per lane assuming a 2 second headway between vehicles in the arriving platoon. Assuming a 25 ft spacing between two consecutive vehicles in the queue, the queue behind the HAWK can grow to a length of 300ft if there is enough upstream vehicular demand. Considering the fact that it takes some time to clear the queue once the HAWK activation is over, more distance should be provided if the vehicular demand is high. Based on this assumption, for a stop-controlled intersection 100 feet is certainly not enough for accommodating the queue if there are platoon arrivals and may cause adverse impact on the operation of the upstream stop-controlled intersection. It also should be noticed that obviously arrivals in a dense platoon are unlikely from a stop-controlled intersection. However, a 100 ft distance can only accommodate 4 vehicles in the queue, with an arrival rate of 600vphpl, spillback will likely to occur with uniform/random arrivals.

3.3 Pedestrian Delay Model with HAWK

3.3.1 Preliminary Data Analysis

It is necessary to explore the distribution of simulated HAWK pedestrian delays as a preliminary analysis before modeling in order to determine the pedestrian delay model. Distributions including Normal, Log-normal, Weibull, Gamma and Beta were investigated and summarized as shown in Figure 6.

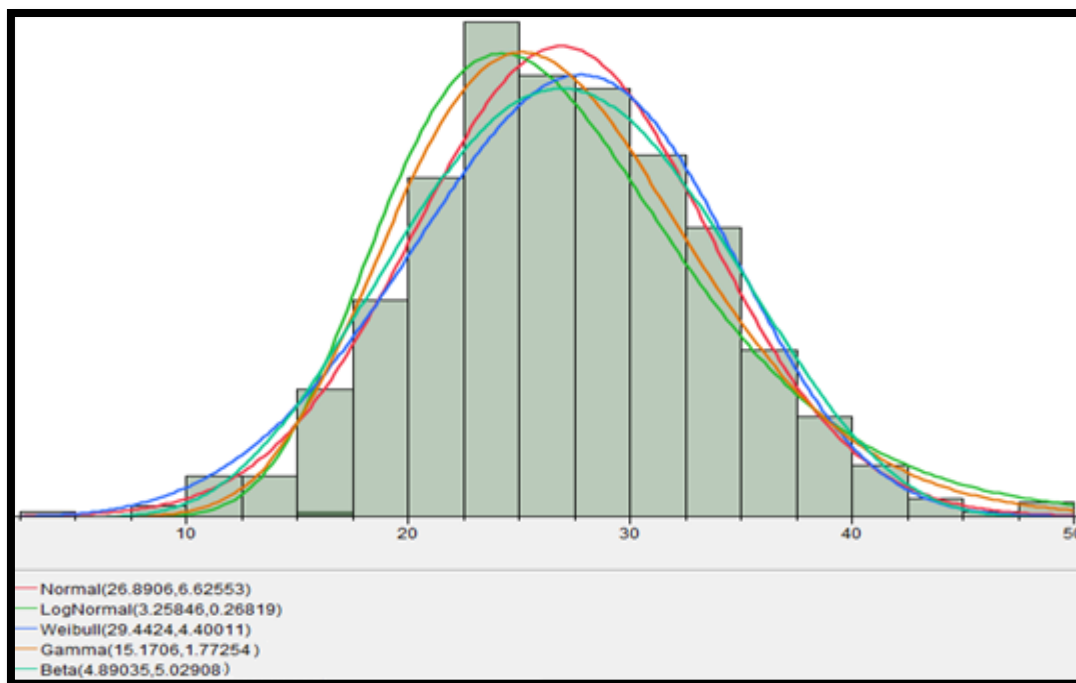


Figure 6 Fitting Distributions for Simulated HAWK Pedestrian Delays

Based on the visual inspection, all distributions performed similarly and it is very difficult to determine which distribution the HAWK pedestrian delay possesses. In order

to determine the best fitted distribution, the goodness of fit by the Chi-square test was conducted and the results are summarized in Table 2.

Table 2 Goodness of Fit for Tested Distributions

Distribution	Probability Density Function	Estimated Parameters	P-value
<i>Normal</i>	$f(x) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$	$\mu=26.89$ $\sigma=6.63$	0.1312
<i>Log-Normal</i>	$f(x; \mu, \sigma) = \frac{1}{x\sigma\sqrt{2\pi}} e^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}$	$\mu=3.26$ $\sigma=0.27$	<0.01
<i>Weibull</i>	$f(x; \lambda, k) = \begin{cases} \frac{k}{\lambda} \left(\frac{x}{\lambda}\right)^{k-1} e^{-\left(\frac{x}{\lambda}\right)^k}, & x \geq 0 \\ 0, & x < 0 \end{cases}$	$\lambda=29.44$ $k=4.4$	<0.01
<i>Gamma</i>	$f(x; k, \theta) = x^{k-1} \frac{e^{-\frac{x}{\theta}}}{\theta^k \Gamma(k)} \quad x \geq 0, k, \theta > 0$	$k=15.17$ $\theta=1.77$	<0.01
<i>Beta</i>	$f(x; \alpha, \beta) = \frac{\Gamma(\alpha + \beta)}{\Gamma(\alpha)\Gamma(\beta)} x^{\alpha-1} (1-x)^\beta$	$\sigma=4.89$ $\beta=5.03$	<0.01

According to Table 2, it is obvious that normal distribution has the highest p-value over 0.05, which means the hypothesis that the pedestrian delay is derived from the

normal distribution cannot be rejected. Besides of that, all the other p-values are less than 0.05 and their corresponding hypothesis are rejected. Based on the preliminary result, the pedestrian delay is derived from the normal distribution. Basically speaking, the linear regression model can be used to model the HAWK pedestrian delay. However, the linear regression model can only deal with the response variable which has a linear relation with factors but the generalized linear model (GLM) is capable to deal with the response variable which has a non-linear relation with factors. The linear regression model is included in the GLM as a specific example when specifying the identity link function under a normal distribution. In this study we assume the pedestrian delay is non-linear with factors. Therefore the normal generalized linear model is finally selected to model the HAWK pedestrian delay.

3.3.2 Generalized Linear Model

The generalized linear model (GLM) introduced by Nelder and Wedderburn (13) is a statistical regression model integrating linear regression, logistic regression and Poisson regression. Generalized linear model conducts linear regression by connecting the linear model with the related response variable through a link function as a flexible generalization of ordinary least squares regression. Maximum-likelihood estimation, a

widely used method to produce the estimation, is usually adopted to estimate parameters in the generalized linear model.

In the generalized linear model, the dependent variable Y denoted by observations $\{y_1, y_2, \dots, y_n\}$ as the outcome is assumed to be derived from a particular distribution in the exponential family including the normal, exponential, gamma, chi-square, beta, binomial, Bernoulli, Poisson and many others. The mean of the dependent variable Y can be expressed by the independent variables $X = \{x_1, x_2, \dots, x_n\}$. The general framework of GLM can be demonstrated as follows:

$$E(Y) = \mu = g^{-1}(X\beta) = g^{-1}\left(\beta_0 + \sum_{i=1}^n \beta_i x_i\right) \quad (10)$$

$$\eta = g(\mu) = X\beta \quad (11)$$

where $E(Y)$ is the expected value (mean) of the outcome Y , η is the linear predictor, β_i is a linear combination parameter, and g is the link function. The link function provides the relationship between the expected value of the dependent variable Y and the systematic component of the model. There are a lot of link functions commonly used in the modeling. According to the preliminary data analysis above, the HAWK pedestrian delay is assumed to have a normal distribution with mean μ and variance σ^2 denoted by $Y \sim N(\mu, \sigma^2)$. The probability density function is defined as:

$$f(y) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(y-\mu)^2}{2\sigma^2}} \quad (12)$$

The combination parameters β_i are typically estimated by the maximum likelihood estimation using an iteratively reweighted least squares in this study. When determining parameters by maximum likelihood estimation, it is usually easier to work with the log likelihood function. Based on quantities such as μ , η , X , and β introduced above, the working dependent variable can be calculated:

$$t = \hat{\eta} + (y_i - \hat{\mu}) \frac{d\eta}{d\mu} \quad (13)$$

where $\hat{\eta}$ is the estimated linear predictor using a trial estimate of parameters $\hat{\beta}$, and $\hat{\mu}$ is the fitted value equal to $g^{-1}(\hat{\eta})$. Therefore, according to the work conducted by Chartrand and Yin (14), the iterative weight is calculated by:

$$\omega = \frac{1}{\left[\frac{\sigma^2}{\phi} \left(\frac{d\eta}{d\mu} \right)^2 \right]} \quad (14)$$

where ϕ is one of the parameters of the distribution for observations named as the proportionality factor. This weight is inversely proportional to the variance of the working dependent variable with the proportionality factor. Finally, the estimated parameters $\hat{\beta}$ can be determined by the following equation:

$$\hat{\beta} = (X'WX)^{-1}X'T \quad (15)$$

where W is a diagonal matrix of weights with entries ω , and T is a response vector with entries t . This process is repeated until the difference between two successive estimated parameters is lower than a specific threshold value.

For demonstration purposes, four functional forms were selected for linking the HAWK pedestrian delay with affected factors. These functional forms are very frequently used and are described as follows:

1) Classical Linear:

$$\mu = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n \quad (16)$$

2) Multiplicative:

$$\mu = \beta_0 x_1^{\beta_1} x_2^{\beta_2} \dots x_n^{\beta_n} \quad (17)$$

3) Reciprocal:

$$\mu = \beta_0 + \beta_1 \left(\frac{1}{x_1}\right) + \beta_2 \left(\frac{1}{x_2}\right) + \dots + \beta_n \left(\frac{1}{x_n}\right) \quad (18)$$

4) Semi-log:

$$\ln \mu = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_n x_n \quad (19)$$

where:

μ = the mean of HAWK pedestrian delays

x_1, x_2, \dots, x_n = factors affecting the HAWK pedestrian delay;

$\beta_0, \beta_1, \dots, \beta_n$ = estimated coefficients.

3.3.3 HAWK Pedestrian Delay Model

As mentioned in the simulation study design, the minimum green time for vehicles as an important and special factor significantly affected both of pedestrian delay and

vehicle delay. Before the modeling, it should be emphasized that the HAWK pedestrian delay has nothing to do with the volumes of traffic since the minimum green time for vehicles would be operated after activation of HAWK by pedestrians every time, even when there is no vehicles. According to statements in terms of the generalized linear model, the HAWK pedestrian delay model can be defined as:

$$D_p = f_1(x_1, x_2, \dots, x_n, T_{min}) \quad (20)$$

where D_p is the pedestrian delay, T_{min} is the minimum green time for vehicles, and x_1, x_2, \dots, x_n are other factors affecting the delay.

As the same concept, the vehicle delay can be proved that is derived from the normal distribution and can be generalized by GLM as well based upon the same assumption stated previously, which can be described as:

$$D_v = f_2(x_1, x_2, \dots, x_n, T_{min}) \quad (21)$$

where D_v is the vehicle delay, and x_1, x_2, \dots, x_n are factors affecting the vehicle delay, which could be different from the factors in the HAWK pedestrian delay.

The network delay can be demonstrated by the equation as follows:

$$\begin{aligned} D_N &= \frac{k * D_p * \gamma_p + D_v * \lambda_v}{k * \gamma_p + \lambda_v} \\ &= \frac{k * f_1(x_1, \dots, x_n, T_{min}) * \gamma_p + f_2(x_1, \dots, x_n, T_{min}) * \lambda_v}{k * \gamma_p + \lambda_v} \end{aligned} \quad (22)$$

where D_N is the weighted network delay, γ_p is the mean arrival rate of pedestrian, λ_v is the mean arrival rate of vehicles, and k is the weighting coefficient of pedestrian

since one pedestrian cannot be considered as the same as a vehicle in the network delay calculation.

Based on the study conducted by Li and Zhang (12), the optimized minimum green time for vehicles is the one which could minimize the network delay with certain volume combination of vehicles and pedestrians. Hence, let the derivative of the network delay with respect to the minimum green time for vehicles equal to zero, which is illustrated as the following equation:

$$\frac{dD_N}{dT_{min}} = \frac{k * f_1'(x_1, \dots, x_n, T_{min}) * \gamma_p + f_2'(x_1, \dots, x_n, T_{min}) * \lambda_v}{k * \gamma_p + \lambda_v} = 0 \quad (23)$$

Based on the equation above, we have:

$$T_{min} = g(x_1, x_2, \dots, x_n, k) \quad (24)$$

After substituting the minimum green time for vehicles into Equation 20, the final form of the HAWK pedestrian delay model can be re-expressed as follows:

$$D_p = f_1(x_1, x_2, \dots, x_n, g(x_1, x_2, \dots, x_n, k)) \quad (25)$$

This pedestrian delay corresponds to the T_{min} value that minimizes the total network delay.

3.3.4 Performance Measure

All models with different functional forms were estimated by the following methods for the model selection and the goodness of fit (GOF) of the models. The methods used in this study are summarized as follows:

Akaike Information Criterion (AIC)

AIC is the Akaike information criterion grounded in the concept of information theory as a measure of the relative goodness of fit of a statistical model. It is widely adopted in the model selection dependent upon the AIC values. Generally, AIC is defined as:

$$AIC = 2k - 2l n(L) \quad (26)$$

where k is the number of parameters of the model and L is the maximized value of the likelihood function for the estimated model. The preferred model is the one with the minimum AIC value comparing with those of others.

Mean Absolute Deviance (MAD)

MAD is the mean absolute deviation from the mean used to commonly measure the average mis-prediction of the model. It is determined by the following equation:

$$MAD = \frac{1}{n} \sum_{i=1}^n |\hat{y}_i - y_i| \quad (27)$$

where \hat{y}_i is the predictive value, y_i is the observation value, and n is the number of samples.

Mean Squared Predictive Error (MSPE)

MSPE is the mean square predictive error typically used to quantify the difference between the predictive values and corresponding true values with a validation or external dataset. It can be expressed as following:

$$MSPE = \frac{1}{n} \sum_{i=1}^n (\hat{y}_i - y_i)^2 \quad (28)$$

3.4 Minimum Green Time for Vehicles

To determine a minimum green time for vehicles, neither of pedestrian delay nor vehicle delay is a proper criterion as small minimum vehicle go-time can reduce pedestrian delay while increasing vehicle delay, and vice versa. Considering the trade-off between pedestrian delay and vehicle delay, the “minimum weighted network delay” is proposed to define the minimum vehicle go-time. In this case, we define the weighted network delay as follows in equation 1. It should be noticed that the weighting coefficient of pedestrian k is multiplied by the pedestrian delay as 1 second of pedestrian delay is of greater concern than 1 second of vehicle delay. The reason is that the vehicle number is much larger than the pedestrian number in the whole network, and

more importantly, a HAWK is a pedestrian treatment giving pedestrians higher priority. If the weightings of the vehicle and the pedestrian are treated equally, the result of the network delay will be affected much more by the vehicle delay which is not reasonable.

$$D_N = \frac{N_P * D_P * k + N_V * D_V}{N_P * k + N_V} \quad (29)$$

where:

D_N = weighted network delay,

D_P = pedestrian delay,

N_P = pedestrian volume,

N_V = vehicle volume,

k = weighting coefficient of pedestrian, assumed to be 2 in the subsequent analysis,

D_V = vehicle delay.

By comparing the weighted network delay of different minimum vehicle go-time with the same volume combination, an optimized minimum vehicle go-time can be found for each particular volume combination.

3.5 Impact of HAWK on Pedestrian Delay and Network Delay

The pedestrian delay impact from a HAWK is assessed by comparing the pedestrian delay in two scenarios (see Figure 8).

- a) Pedestrians cross the street at the HAWK location
- b) Pedestrians cross at the marked crosswalk at the intersection without a HAWK

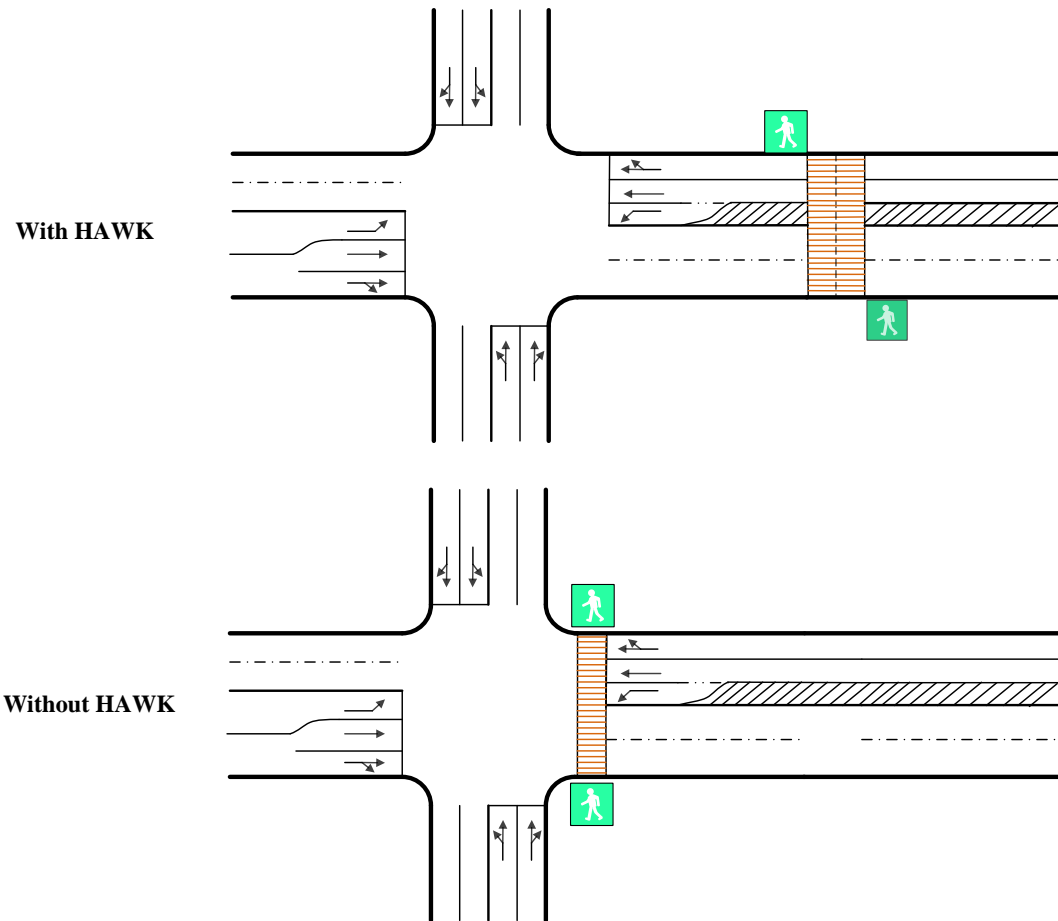


Figure 7 Simulation Model with HAWK and without HAWK

Since HAWK is a new type of pedestrian signal in recent years, assessing its impact on pedestrian delay can be meaningful for its future application. With different minimum vehicle go-times set from 10 sec to 60 sec with a 10 sec interval and different pedestrian volume and vehicle volume combinations, HAWK's impact on pedestrian delay is

investigated by comparing pedestrian delay in two scenarios, with HAWK and without HAWK. The distance to the stop-controlled intersection is set as 100ft following the recommendation in 2009 MUTCD.

4. RESULTS AND ANALYSIS

4.1 Pedestrian Delay under HAWK

As it clarified in the previous chapter, the dataset for pedestrian delay model in this study was collected in VISSIM, which has a total sample size of 5670. The dataset, which was divided into two sub-datasets, includes 3780 training data points and 1890 validation data points. The minimum green time for vehicles and the mean of pedestrian arrival rate as the independent variables x_1 and x_2 would be firstly used to model the HAWK pedestrian delay by the generalized linear model. The parameter estimation of selected function forms for pedestrian delay is demonstrated in the Table 3. Based on the result of the significant test shown in Table 3, the minimum green time for vehicles (T_{min}) and the pedestrian arrival rate (γ_p) are significant for pedestrian delay (D_p). Table 4 summarizes the statistical output of four functional forms. Based on the goodness of fit statistics, this table demonstrates that the multiplicative function form performs better than others. This result was expected since the fact that the multiplicative function could capture more variance in the datasets. Therefore, the HAWK pedestrian delay can be conducted as:

$$D_p = 38.983 * T_{min}^{0.2384} * \gamma_p^{0.5818} \quad (30)$$

Table 3 Parameter Estimation of Selected Functional Forms for Pedestrian Delay

Functional Form	Coefficients			Standard Errors			Prob>Chi-Square		
	β_0	β_1	β_2	β_0	β_1	β_2	β_0	β_1	β_2
<i>Classical Linear</i>	6.185	0.4969	7.170	0.9228	0.0208	3.1312	<0.0001	<0.0001	0.0222
<i>Multiplicative</i>	38.983	0.2384	0.5818	2.0372	0.0079	0.2237	<0.0001	<0.0001	0.0193
<i>Reciprocal</i>	46.91	-732.6	-0.0772	2.8680	30.9073	0.0235	<0.0001	<0.0001	0.0011
<i>Semi-log</i>	2.447	0.0188	0.5012	0.0386	0.0008	0.1308	<0.0001	<0.0001	0.0010

Table 4 Statistical Output of Selected Functional Forms for Pedestrian Delay

Functional Form	Coefficients			Pearson Chi-Square			MAD	MSPE	AIC
	β_0	β_1	β_2	DF	Value	Value/DF			
<i>Classical Linear</i>	6.185	0.4969	7.170	3777	9740.26	2.579	8.254	102.3	4812.67
<i>Multiplicative</i>	38.983	0.2384	0.5818	3777	3044.50	0.8061	7.349	80.59	1351.23
<i>Reciprocal</i>	46.91	-732.6	-0.0772	3777	15802.89	4.184	12.548	133.5	5814.96
<i>Semi-log</i>	2.447	0.0188	0.5012	3777	4944.92	1.309	7.954	90.55	1895.48

As the same concept stated previously, the vehicle delay was modeled with the factors which are the minimum green time for vehicles, denoted as x_1 , the mean of vehicle arrival rate for the major approach x_2 , the mean of vehicle arrival rate for the

minor approach x_3 , and the distance between HAWK and the intersection x_4 . The same four function forms were evaluated in order to select the best one for the generalized linear model. Based on the result of the significant test shown in Table 5, the minimum green time for vehicles (T_{min}), the major street vehicle arrival rate (λ_{Maj}), the minor street vehicle arrival rate (λ_{min}) and the distance from HAWK to stop-controlled intersection (d) are significant for vehicle delay (D_v). The estimated coefficients, the Pearson Chi-Square values, the MAD, MSPE and AIC are summarized in Table 6. It is obvious that the multiplicative functional form has better performance than other forms. Therefore, the HAWK vehicle delay can be modeled as:

$$D_v = 119.1 * T_{min}^{-0.0958} * \lambda_{Maj}^{3.514} * \lambda_{Min}^{-0.2185} * d^{-0.0659} \quad (31)$$

where λ_{Maj} is the vehicle arrival rate for the major approach, λ_{Min} is the vehicle arrival rate for the minor approach, and d is the distance between the HAWK and the intersection.

Table 5 Parameter Estimation of Selected Functional Forms for Vehicle Delay

Functional Form		Classical Linear	Multiplicative	Reciprocal	Semi-log
<i>Coefficients</i>	β_0	19.24	119.1	118.7	-0.0481
	β_1	-0.0394	-0.0958	63.46	-0.0024
	β_2	134.8	3.514	-60.84	5.139
	β_3	-41.68	-0.2185	0.7219	-1.458
	β_4	-0.0081	-0.0659	248.3	-0.0035
<i>Standard Errors</i>	β_0	1.2924	2.311	3.5896	0.0174
	β_1	0.0068	0.0076	10.859	0.0001
	β_2	2.8409	0.0582	1.2526	0.0861
	β_3	8.4348	0.0308	0.2216	0.0346
	β_4	0.0048	0.0263	89.61	0.0001
<i>Prob>Chi-Square</i>	β_0	<0.0001	<0.0001	<0.0001	0.4795
	β_1	0.0723	0.033	0.1021	0.0673
	β_2	<0.0001	<0.0001	<0.0001	<0.0001
	β_3	<0.0001	<0.0001	<0.0001	<0.0001
	β_4	0.1191	0.0193	0.3084	0.0259

Table 6 Statistical Output of Selected Functional Forms for Vehicle Delay

Functional Form		Classical Linear	Multiplicative	Reciprocal	Semi-log
Coefficients	β_0	19.24	119.1	118.7	-0.0481
	β_1	-0.0394	-0.0958	63.46	-0.0024
	β_2	134.8	3.514	-60.84	5.139
	β_3	-41.68	-0.2185	0.7219	-1.458
	β_4	-0.0081	-0.0659	248.3	-0.0035
Pearson Chi-Square	DF	3775	3775	3775	3775
	Value	17186	8513	16932	9542
	Val. /DF	4.55	2.25	4.48	2.53
MAD		<0.0001	20.66	11.22	17.35
MSPE		0.0723	863.2	236.8	758.1
AIC		<0.0001	18501.64	6613.276	12417.23

Given a minimum green time for vehicles, pedestrian and vehicle delay can be determined by Equation 30 and 31. As mentioned in the methodology, based on the results above, the network delay can be determined as following:

$$\begin{aligned}
 D_N &= \frac{k * D_p * \gamma_p + D_v * \lambda_v}{k * \gamma_p + \lambda_v} \\
 &= \frac{k * 38.983 * T_{min}^{0.2384} * \gamma_p^{1.5818}}{k * \gamma_p + \lambda_{Maj} + \lambda_{Min}} \\
 &+ \frac{119.1 * T_{min}^{-0.0958} * \lambda_{Maj}^{3.514} * \lambda_{Min}^{-0.2185} * d^{-0.0659} * (\lambda_{Maj} + \lambda_{Min})}{k * \gamma_p + \lambda_{Maj} + \lambda_{Min}} \quad (32)
 \end{aligned}$$

And then, after taking the derivative of the network delay with respect to the minimum green time for vehicles, as shown in Equation 32, the minimum green time for vehicles, which minimizes the network delay, can be calculated as following:

$$T_{min} = \frac{1.228 * \lambda_{Maj}^{3.514} * \lambda_{Min}^{-0.2185} * d^{-0.0659} * (\lambda_{Maj} + \lambda_{Min})}{k * \gamma_p^{1.5818}} \quad (33)$$

After substitute Equation (33) into Equation (31), the final form of the HAWK pedestrian delay corresponding to the optimal network delay is produced as following:

$$\begin{aligned} D_p &= 40.94 * \frac{(\lambda_{Maj}^{1.076} * \lambda_{Min}^{-0.0521} + \lambda_{Maj}^{0.8377} * \lambda_{Min}^{0.1863}) * \gamma_p^{0.2046}}{k * d^{0.0157}} \\ &= 40.94 * \frac{(\lambda_{Maj}^{1.076} + \lambda_{Maj}^{0.8377} * \lambda_{Min}^{0.2384}) * \gamma_p^{0.2046}}{k * d^{0.0157} * \lambda_{Min}^{0.0521}} \end{aligned} \quad (34)$$

Based on the HAWK pedestrian delay model, it is obvious that the HAWK pedestrian delay model is an increasingly monotonic function with respect to the major street vehicle arrival rate, the minor street vehicle arrival rate and the pedestrian arrival rate. Meanwhile the HAWK pedestrian delay model is a decreasingly monotonic function with respect to the distance from HAWK to the stop-controlled intersection and the weighting coefficient of pedestrian k . It should be noted that the weighting coefficient of pedestrian k is supposed to be determined by agencies based upon their different emphasis for pedestrian safety.

A total of 1890 samples were applied to validate the performance of the developed HAWK pedestrian delay model. Table 7 summarized the statistical results for the

validation. It can be seen that the developed HAWK pedestrian delay model performed well with a low MAD of 6.79 and a MSPE of 65.8 considering the VISSIM simulation HAWK pedestrian delay as the ground truth value.

Table 7 Performance of the Developed Model in the Validation

HAWK Pedestrian Delay	Min.	Max.	Average	Std.	MAD	MSPE
<i>Simulation</i>	8.3	40.67	27.06	4.81	-	-
<i>Developed Model</i>	6.7	41.51	30.54	5.22	6.79	65.8

4.2 Minimum Green Time for Vehicles

The minimum vehicle go-time is evaluated from 10 seconds to 60 seconds at 10 second intervals. The distance from HAWK to the stop-controlled intersection is set as 100 feet. The minimum vehicle go-time is determined by weighted network delay calculated with equation 24. Table 6 summarizes minimum vehicle go-time for all vehicle/pedestrian combinations. The delay components and the weighted network delay are also presented in the table. The results show that when the vehicle volume is fixed, higher pedestrian volume favors smaller minimum go-time; when pedestrian volume is fixed, higher vehicle volume favors larger minimum go-time.

The results show that there is no “perfect” vehicle go-time suitable for all cases. Different minimum vehicle go-time should be used based on different volume

combinations. Figure 7, developed from the results of Table 8, shows that when a minimum vehicle go-time decreases from 20 sec, the weighted network delay goes higher sharply; when the minimum vehicle go-time increases from 20 sec, the weighted network delay tends to go up slightly smoothly. This phenomenon indicates that 20 sec is likely a reasonable practical minimum for the vehicle/pedestrian volume combinations evaluated in this study.

The weighted network delay largely depends on the weighting coefficient of pedestrian k . With the increase of k , the minimum weighted network delay decreases and the minimum vehicle go-time decreases as pedestrians will have more effect on the whole network. It should also be noted that we only provide a theoretical way to determine the best value for minimum vehicle go-time. In practice, a likely procedure is to set a value to avoid overly long queue in front of the queue or spillback towards upstream intersection. This value can be determined rather quickly in a simple approach based on arriving vehicle flow rate.

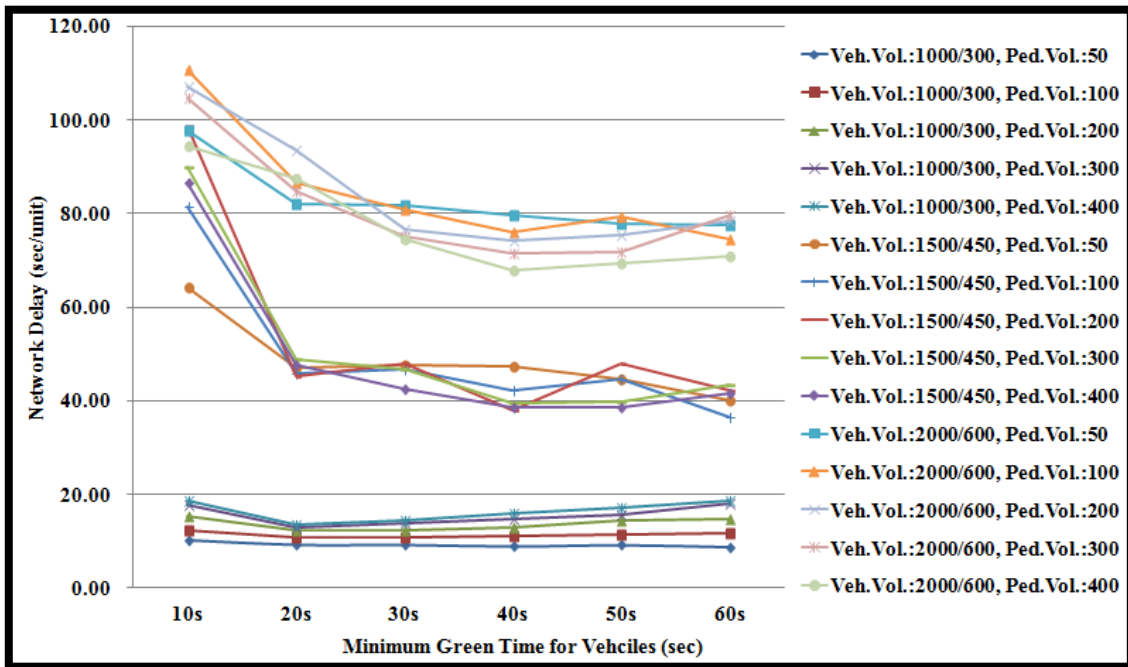


Figure 8 Weighted Network Delay for Stop-Controlled Intersection

Table 8 Optimization Result of Stop-Controlled Intersection Based on Weighted Network Delay

Minimum Weighted Network Delay (sec/unit), Corresponding Pedestrian Delay (sec/person), Corresponding Vehicle Delay (sec/veh)										Minimum Vehicle Go-Time (sec)			
M/N P	1000/300			1500/450			2000/600			M/N P	1000/ 300	1500/ 450	2000/ 600
	D_P	D_V	D_N	D_P	D_V	D_N	D_P	D_V	D_N		P		
50	23.4	7.8	8.9	33.4	40.4	40.0	45.3	79.6	77.7	50	40	60	60
100	21.1	9.1	10.7	37.4	36.3	36.5	45.3	77.7	74.5	100	30	60	60
200	17.2	10.6	12.2	26.1	40.7	38.0	36.5	82.8	74.3	200	20	40	40
300	17.3	10.9	13.1	26.8	43.8	39.4	34.7	84.5	71.6	300	20	40	40
400	16.5	11.8	13.6	31.2	41.9	38.5	33.0	82.8	67.8	400	20	50	40

Note:

M - One Direction Total Volume (two lanes) of the Major Street (vph);

N - One Direction Total Volume (two lanes) of the Minor Street (vph);

P - One Direction Total Volume of Pedestrian (pph);

D_P – Pedestrian Delay (sec/person);

D_V – Vehicle Delay (sec/veh);

D_N – Minimum Weighted Network Delay (sec/unit);

The previous study provided a general idea of the minimum green time for vehicles by comparing the weighted network delay with a different combination of pedestrian

volume and vehicle volume. It was assumed that with the proper minimum green time for vehicles the whole network delay should be minimized which may provide the most benefit to the whole network operations. However, this assumption may have some limitations at the same time. Firstly as HAWK is a newly-applied pedestrian beacon, its effect on the pedestrian delay needs to be paid more attention so that the vehicle delay and the pedestrian delay should not be considered at the same level. In this case, the weighting coefficient of pedestrian k needs to be discussed according to different situations. For example when the vehicle volume is much larger than the pedestrian volume, the weighting coefficient of pedestrian k should be set larger. On the contrary when the vehicle volume is not too much larger than the pedestrian volume, the weighting coefficient of pedestrian k should be set smaller. Based on this consideration, it is difficult to set the weighting coefficient of pedestrian k as generally it is based on the experience as there is no specific criterion of k . However without a value of k , the minimum green time for vehicles cannot be determined. Secondly although the previous study selected and listed several typical scenarios of different vehicle volume and pedestrian volume combinations, it is difficult to include all the real world scenarios and has some limitations. Also the minimum green time for vehicles selected are from 10 seconds to 60 seconds at 10 second intervals, which are only some rough estimations and cannot describe all the real world situations.

Due to all these considerations, a model of the minimum green time for vehicles needs to be developed in order to describe the real world situations and provide a more specific value of the minimum green time for vehicles. Based on the previous data and process of developing the pedestrian delay model, it can be found that the model of the minimum green time for vehicles can be developed in the process of developing the pedestrian delay model as the minimum green time for vehicles T_{min} is an important variable in the pedestrian delay model. According to the previous study of the pedestrian delay model, the model of minimum green time for vehicles can be developed as follows:

$$T_{min} = \frac{1.228 * \lambda_{Maj}^{3.514} * \lambda_{Min}^{-0.2185} * d^{-0.0659} * (\lambda_{Maj} + \lambda_{Min})}{k * \gamma_p^{1.5818}} \quad (35)$$

where T_{min} is the minimum green time for vehicles, γ_p is the mean arrival rate of pedestrian, λ_{Maj} is the vehicle arrival rate for the major approach, λ_{Min} is the vehicle arrival rate for the minor approach, d is the distance between the HAWK and the intersection, and k is the weighting coefficient of pedestrian. It should be noted that the weighting coefficient of pedestrian k is supposed to be determined based on the specific real world situation by agencies upon their different emphasis for pedestrian safety.

4.3 Impact of HAWK on Delay

Figure 9 shows the pedestrian delay with HAWK under different volume combinations and different minimum vehicle go-times. The key findings are:

- With the increasing of the minimum vehicle go-time, the pedestrian delay increases accordingly.
- Vehicle volume does not appear to affect pedestrian delay with a given minimum vehicle go-time.
- With a certain vehicle volume, when the minimum vehicle go-time is higher than 50 sec, no matter how the pedestrian volume changes, the pedestrian delay tends to be flat.

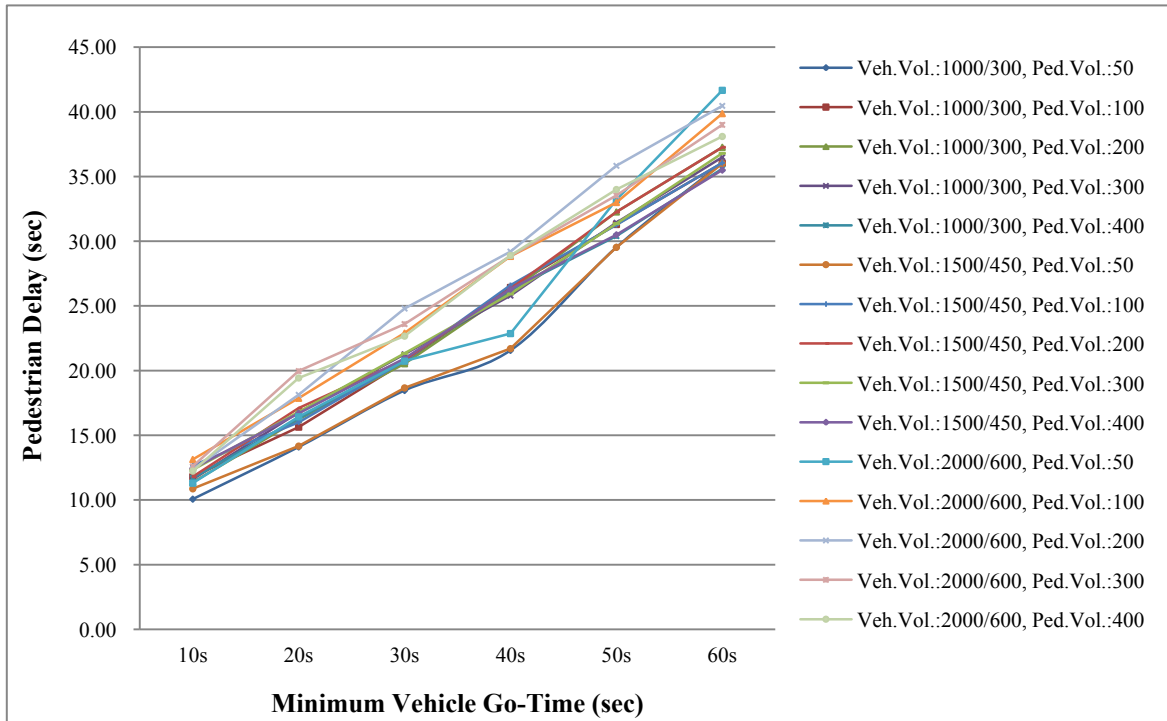


Figure 9 Pedestrian Delays for Stop-Controlled Intersection with Different Minimum Vehicle Go-Time

Figure 10 demonstrates the percent change of the pedestrian delay between with HAWK and without HAWK scenarios under different volume combinations as the minimum vehicle go-time increases. The change of the pedestrian delay C_{pd} is given in equation 36.

$$C_{pd} = \frac{D_P - D_0}{D_0} * 100\% \quad (36)$$

where C_{pd} is the change percentage of the pedestrian delay, D_P is the pedestrian delay with HAWK. D_0 is the pedestrian delay without HAWK. The key findings are:

- At high vehicle demand, HAWK reduces pedestrian delay significantly. This reduction can be as high as 50% with a small minimum vehicle go-time.

- With a low vehicle volume, it appears no matter how the pedestrian volume changes, pedestrian delay increases with a HAWK. This phenomenon appears as when the vehicle volume is low, pedestrians are likely to cross the street without much waiting at marked crosswalk at a stop-controlled intersection while HAWK may cause extra delay when there is no vehicle as long as a minimum vehicle go-time is adopted.
- With a high vehicle volume, as the pedestrian volume decreases, the minimum green time for vehicles should increase to ensure that HAWK does not cause additional vehicle delay.

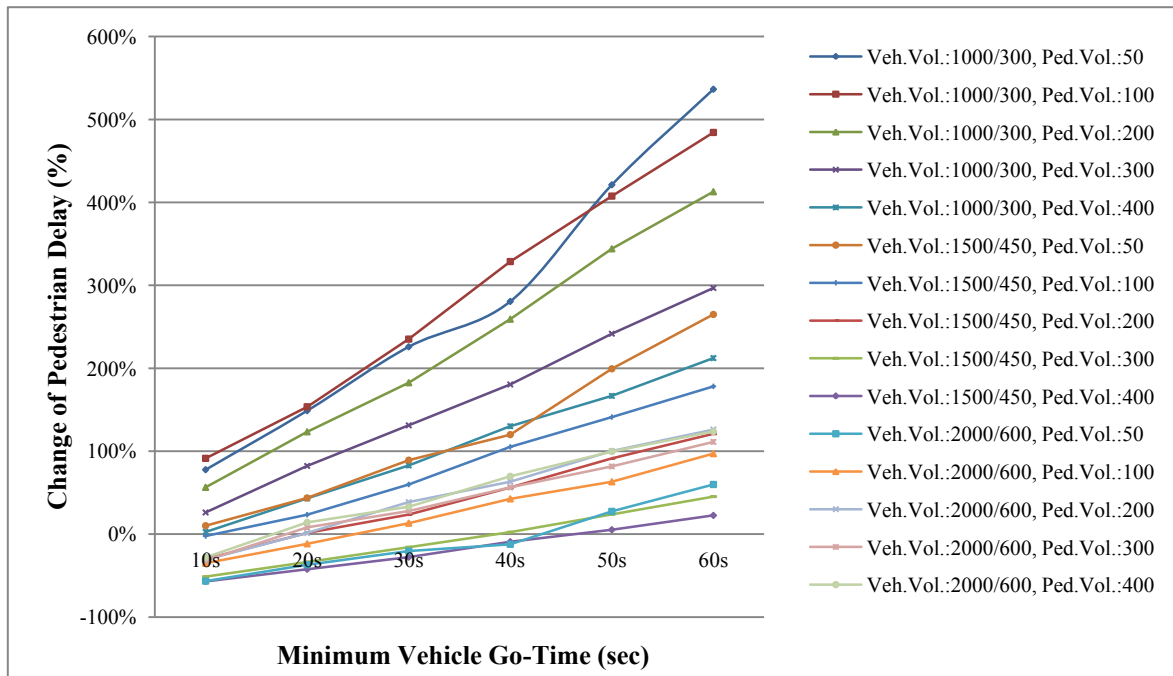


Figure 10 Percent Change of Pedestrian Delay between With HAWK and Without HAWK for Stop-Controlled Intersection

5. CONCLUSIONS AND FUTURE WORK

5.1 Conclusions

As a new kind of pedestrian beacon, HAWK was first mentioned in the 2009 MUTCD. HAWK aims at creating gaps in vehicle traffic to let pedestrians cross meanwhile reducing the unnecessary delay of vehicles. The application of HAWK aroused curiosity of researchers and was proved that HAWK may increase the pedestrian safety. This study focused on investigating the operations of HAWK pedestrian beacon.

Based on the knowledge of HAWK pedestrian beacon phase sequence, it was revealed that the minimum distances from HAWK to a stop-controlled intersection recommended by the MUTCD which was 100 feet may not be adequate. This was estimated by calculating the length of the vehicles accumulation when there was a traffic platoon during “on” time of HAWK. By comparing the vehicles accumulation length and the minimum distance from HAWK to stop-controlled intersection, it was obviously that with a traffic platoon 100 feet may not be adequate for vehicles accumulation and may cause spillback toward the upstream intersection. Besides of that, considering the fact that it takes some time to clear the queue once the HAWK activation is over, more distance should be provided if the vehicular demand is high.

Besides of evaluating the existing recommendations in 2009 MUTCD, as an important part of this thesis this study also developed the HAWK pedestrian delay models to describe the pedestrian delay with HAWK pedestrian beacon. The generalized liner model was applied to analyze the pedestrian delay at a HAWK location. The vehicle arrival rate at the major approach, the vehicle arrival rate at the minor approach, the pedestrian arrival rate, and the distance between HAWK and the intersection were investigated as input factors affecting the pedestrian delay. The dataset was generated in simulation scenarios produced by VISSIM and was divided into two parts for training and validation. After evaluating four different functional forms, based on the results of the goodness of fit test, the multiplicative functional performed better than others with lower AIC, MAD, and MSPE in the HAWK pedestrian delay model. Finally by using the validation dataset, the results showed that the HAWK pedestrian delay model developed in this study was capable of describing the variance of the pedestrian delay with satisfactory MAD and MSPE.

Based on knowledge of HAWK pedestrian beacon operations, as a particular element and an important variable of the HAWK pedestrian delay model, the minimum green time for vehicles was studied in this thesis. Based on the assumption that the delay of the whole network can be minimized with the minimum green time for vehicles, a recommendation of the minimum green time for vehicles was given with different

pedestrian volume and vehicle volume combinations. It was found that the minimum green time for vehicles may vary with different volume combinations. Typically, the minimum green time for vehicles of 20 sec is considered to be a practical minimum and this value goes up as the vehicle demand increases. To give a better description of the minimum green time for vehicles, the model describing the minimum green time for vehicles that minimize combined vehicle and pedestrian delay is derived based on the developed pedestrian delay models.

Finally the impact of HAWK on pedestrian delay was investigated by comparing the pedestrian delay with HAWK installed at 100 feet from the upstream stop-controlled intersection and without HAWK but with the pedestrians cross at the marked crosswalk at the stop-controlled intersection. Different volume combinations and minimum green time for vehicles were considered in the compilation. It showed that at high vehicle demand, HAWK reduces pedestrian delay significantly. However HAWK may cause pedestrian delay increase when vehicle demand is low for the stop controlled intersection.

5.2 Future Work

Although this study provided an effective model for the pedestrian delay at a HAWK location, additional studies are needed to add more factors, such as different

turning movement combinations or lane configurations, into this model to make it more accurate and comprehensive. Additionally, data from the real world are desirable for the validation of the developed model. Also needs noting is the fact that we did not consider ODs of pedestrians when evaluating the pedestrian delay impact by HAWK.

REFERENCES

1. Houten, R. V. and J. E. L. Malenfant. *An Analysis of the Efficacy of Rectangular-shaped Rapid-Flash LED Beacons to Increase Yielding to Pedestrians Using Crosswalks on Multilane Roadways in the City of St. Petersburg, FL*. Center for Education and Research in Safety.
2. Fitzpatrick, K., and E. S. Park. Safety effectiveness of the HAWK pedestrian treatment. In *Transportation Research Record: Journal of Transportation Research Board*. Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 214-223.
3. *Hybrid Beacon Signal Head*. <http://www.spotdevices.com/sb440.html>
4. Furst A. T. *Request for Permission to Experiment with HAWK Pedestrian Hybrid Signal Beacon*. Office of Transportation Operations, 2009.
5. *Manual on Uniform Traffic Control Devices*. FHWA, U.S. Department of Transportation, Washington, D.C., 2003.
6. Nassi, R. B., and M. J. Barton. New Traffic Control for an Old Pedestrian Crossing Safety Problem. In *Transportation Research Record: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington, D.C., 2008, pp. 44–49.
7. Turner, S., K. Fitzpatrick , M. Brewer, and E. S. Park. Motorist Yielding to Pedestrians at Unsignalized Intersections. In *Transportation Research Record: Journal of Transportation Research Board*. Transportation Research Board of the National Academies, Washington, D.C., 2006, pp. 1-12.
8. Fitzpatrick, K., S. Turner, M. Brewer, P. Carlson, B. Ullman, N. Trout, E. S. Park, J. Whitacre, N. Lalani, and D. Lord. *Improving Pedestrian Safety at Unsignalized Crossings*. Publication TCRP Report 112/NCHRP Report 562, Transportation Research Board of the National Academies, Washington, D.C, 2006.
9. Arhin, S., and E. C. Noel. *Evaluation of Hawk Signal at Georgia Avenue and Hemlock Street*. Report No. DDOT-PPSA-HAWK-001, District Department of

Transportation 2010

10. Schroeder, B. J., N. M. Roupail, and R. Hughes, Exploratory Analysis of Pedestrian Signalization Treatments at One- and Two-Lane Roundabouts Using Microsimulation. In *Transportation Research Record: Journal of Transportation Research Board*. Transportation Research Board of the National Academies, Washington, D.C., 2007, pp. 21-25.
11. Lu, G. and D. A. Noyce. Pedestrian Crosswalks at Midblock Locations: Fuzzy Logic Solution to Existing Signal Operations. In *Transportation Research Record: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington, D.C., 2009, pp. 63–78.
12. Godavarthy, R. P., and E. R. Russell, Effectiveness of a HAWK Beacon Signal at Mid-Block Pedestrian Crossings in Decreasing Unnecessary Delay to the Drivers. Presented at 89rd Annual Meeting of the Transportation Research Board, Washington, D.C., 2010.
13. Braun, R.R. and M.F. Roddin. HRP Report 189: Quantifying the Benefits of Separating Pedestrians and Vehicles. In *Transportation Research Record: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington, D.C., 1978, pp. 127.
14. Virkler, M. R. Pedestrian compliance effects on signal delay. In *Transportation Research Record: Journal of the Transportation Research Board*, Transportation Research Board of the National Academies, Washington, D.C., 1998, pp. 88-91.
15. *Highway Capacity Manual 2000*. TRB, National Research Board, Washington, D.C., 2000, page 18-7.
16. Nelder, J., R.W., Wedderburn, Generalized linear models. *Journal of the Royal Statistical Society Series A*, Vol. 135, 1972, pp. 370–384.
17. Brockman, M. J., and Wright, T. S. Statistical model rating: making effective use of your data. *Journal of the Institute of Actuaries*, Vol. 119, No. 3, 1992, pp. 457-543.

18. Haberman, S., and Renshaw, A. E. Actuarial applications of generalized linear models. *Statistics in Finance*, 1998.
19. De Jong P. and G. Z. Heller. Generalized Linear Models for Insurance Data. New York: *Cambridge University Press*, 2008.
20. Ohlsson, E. and B. Johansson. Non-Life Insurance Pricing with Generalized Linear Models (EAA Series). *New York: Springer*, 2010.
21. Said, G. M. Work Trip Rates and the Socio-Economic Characteristics of Households in Kuwait, *Australian Road Research*, 20(1), 1990
22. Sulistio, H., R.S. Radin Umar, S.V. Wong and W.I. Wan Hashim. Motorcycle Crash Prediction Model for Non-Signalized Intersections. *IATSS Research*, 27 (2). 2003, pp. 58-65.
23. Usman, T., L. Fu, and Luis F. Miranda-Moreno. Quantifying Safety Benefit of Winter Road Maintenance: Accident frequency modeling. *Accident Analysis and Prevention* 42(6). 2010, pp 1878-1887
24. Fellendorf, M. VISSIM: A Microscopic Simulation Tool to Evaluate Actuated Signal Control Including Bus Priority. Presented at 64th Institute of Transportation Engineers Annual Meeting, October 1994.
25. Fellendorf, M., and P. Vortisch. Validation of Microscopic Traffic Flow Model VISSIM in Different Real-World Situations. Presented at 80th Annual Meeting of the Transportation Research Board, Washington, D.C., 2001.
26. Gomes, G., A. May, and R. Horowitz. Congested Freeway Microsimulation Model Using VISSIM. In *Transportation Research Record: Journal of the Transportation Research Board*, No. 1876, Transportation Research Board of the National Academies, Washington, D.C., 2004, pp. 71–81.
27. Li, S., and Y. Zhang. Pedestrian Delay and HAWK Pedestrian Treatment. Presented at 90th Transportation Research Board Annual Meeting, Washington, D.C., 2011.

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