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Installation Criteria for Scrambled Crosswalks Considering Both Vehicle and Pedestrian Traffic Volumes

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Abstract

Installation Criteria for Scrambled Crosswalks Considering Both Vehicle and Pedestrian Traffic Volumes

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Nowadays, interest in safety of pedestrians who are relatively weak when compared with vehicles increases and concern for pedestrian accidents on crosswalks also increases. For these reasons, scrambled crosswalks which are considered to contribute to pedestrian safety by reducing conflicts between vehicles and pedestrians are actively discussed and there are also a few intersections where they are actually installed.

However, scrambled crosswalks must include an all-red phase for all vehicle traffic flows, which inevitably leads to increase of lost time per cycle. Therefore, evaluation in terms of efficiency should be done before installation of scrambled crosswalks. This research suggests an installation criteria for scrambled crosswalks so that it is possible to judge whether installation of scrambled crosswalks is appropriate only by surveying vehicle traffic volume and pedestrian traffic volume.

This research derives optimum cycle length from signal optimization models which reflect both vehicle traffic volume and pedestrian traffic volume. From this optimum cycle length, this research compares total delay times before and after installation of scrambled crosswalks.

From analysis, two research results are derived. Firstly, there is critical traffic volume above which installation of scrambled crosswalks can not be efficient. Secondly, appropriate traffic volume areas for installation of scrambled crosswalks are different by each signal intersection or by each signal system and those differences vary. From these results, this research suggests an installation criteria for scrambled crosswalks which consist of two steps.

Keyword : Scrambled crosswalk, Vehicle traffic volume, Pedestrian traffic volume, Signal optimization, Installation criteria
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Chapter 1. Introduction

1.1. Research Background and Purpose

As society develops, interest in safety of pedestrians who are relatively weak when compared with vehicles increases. Among pedestrian traffic accidents, crosswalk-related accidents account for 64.1% of deaths and 54.2% of injured pedestrians in 2016 according to statistics of Korean National Police Agency. In this context, installation of scrambled crosswalks has been widely discussed and there are a few cases in practice. However, in a case of scrambled crosswalks, it is necessary to include an all-red phase for all vehicle traffic flows, which can cause inefficiency of signal intersection operation. Therefore, analysis of scrambled crosswalks in terms of efficiency needs to be conducted before installation of scrambled crosswalks. A purpose of this research is to present appropriate traffic volume areas for scrambled crosswalks by using delay time models which reflect both vehicle traffic volume and pedestrian traffic volume. From appropriate traffic volume areas, it is expected to determine whether installation of scrambled crosswalks is appropriate only by a traffic volume survey.

A recent signal optimization research trend is moving toward reflecting both vehicle traffic flow and pedestrian traffic flow. An existing vehicle-centered research trend can be effective to some extent when vehicle traffic volume overwhelms pedestrian traffic volume, but in an area where pedestrian traffic volume is above a certain level, it may causes inefficiency to pedestrians.

This research recognizes this limitation of the existing vehicle-centered research trend and reflects both vehicle traffic volume and pedestrian traffic volume when formulating delay time models which are bases for finding appropriate traffic volume areas for installation of scrambled crosswalks.

1.2. Research Composition

In Chapter 2, existing installation criteria for scrambled crosswalks and related research are reviewed.

In Chapter 3, scope of this research is restricted by test site selection. After test site selection, signal systems to be covered in this research are determined. Research premises are also covered in this chapter. Finally, model formulation is conducted.

In Chapter 4, signal optimization and preliminary analysis are conducted. From this, scope of analysis is restricted. Finally, main analysis is conducted. Results by signal system and results by signal intersection are explained orderly.

In Chapter 5, reasons why model verification is needed are explained, and methodology of model estimation follows. Finally, model verification is conducted. Results by model and results between models are explained orderly.

In Chapter 6, reasons for difference between an existing Korean installation criteria and results of this research are discussed. Also, comparison with overseas installation criteria is also covered in this chapter. Finally, an installation criteria for scrambled crosswalks is suggested.

In Chapter 7, main research results are covered and suggestion for an installation criteria for scrambled crosswalks is restated. Also, main different points, advantages, shortcomings and future research direction follow orderly.

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Chapter 2. Installation Criteria & Literature Review

2.1 Installation Criteria

2.1.1 Domestic Installation Criteria

According to the Traffic Signal Setting & Management Manual, a following installation criteria for scrambled crosswalks and a recommendation are suggested.

√ A place where pedestrians' diagonal crossings are needed.

√ Width of crosswalk should be more than 4 (m) and road surface should be displayed diagonally as a zebra style

√ It should be in accordance with Table 6 of the Enforcement Rules of Road Traffic Act and standard drawing.

√ Location of a crosswalk is determined by engineering judgement for a pedestrian crossing pattern, vehicle traffic volume, pedestrian traffic volume, cycle length, distance between intersections and so forth.

The First criterion and the recommendation are directly related for requirements for installation of scrambled crosswalks. However, these requirements are not specific numerically.

Recently, On September 11, 2017, The Plan to Expand the Scrambled Crosswalks for Promotion of Pedestrian Rights is authorized by the chief of Seoul Metropolitan Police Agency. In this plan, specific requirements for installation of scrambled crosswalks are suggested. A following table is requirements for installation of scrambled crosswalks.

<Table 1> Requirements for installation of scrambled crosswalks

Variables	Contents	Specific Requirements
Geometry	1. Adequate for four-way intersections 2. The number of lanes is small	1. Except three-way intersections 2. Diagonal Crosswalk is less than 30m
Signal Operation	1. Possible of unprotected left-turn operation 2. Non-signal intersection	1. At least one of two roads is possible 2. Non-signal intersection where vehicle traffic volume is very little
Vehicle Traffic Volume	Low v/c ratio	Less than 0.7 v/c ratio (less than 800 vehicle traffic volume per hour per lane)
Pedestrian Traffic Volume	High pedestrian traffic volume	More than 500 pedestrian traffic volume per hour

Also, the plan suggests a priority criteria for installation of scrambled crosswalks. A following table is a priority criteria for installation of scrambled crosswalks.

<Table 2> Priority criteria for installation of scrambled crosswalks

Division	Contents	Remarks
Accident Characteristics	The number of fatalities in recent 5 years	High
	The number of accidents (Except fatalities)	High
Geometry Characteristics	The number of lanes	Low
	Length of diagonal crosswalk	Low
Traffic Operation Characteristics	Pedestrian Traffic Volume	High
	Vehicle Traffic Volume	Low
	Left-turn Vehicle Traffic Volume	Low
	Possible of unprotected left-turn operation (engineering judgement)	o/x
	Whether a bypass road for left-turn vehicles is secured	o/x
	Lots of right-turn vehicles (engineering judgement)	o/x
Target Area Response	Response of Local Residents and so forth	o/x

In the remarks column of <Table 2>, 'High' means the larger the contents are, the higher the priority is. 'Low' means the opposite.

2.1.2 Overseas Installation Criteria

2.1.2.1 Japan Installation Criteria

Japan has a following installation criteria for scrambled crosswalks. These criteria are qualitative, not quantitative.

√ It should be installed in a station or school where a lot of pedestrians for commutation exist

√ It should be installed in a city where department stores, shopping stores, and so forth are densely packed and sufficient walking should be guaranteed

√ It should be installed in an area where it is judged that it is possible to smooth vehicle traffic flow by providing an exclusive phase for pedestrian traffic flow because lots of pedestrian traffic volume causes obstacles to right-turn of vehicle traffic flow or a safety problem for pedestrian traffic flow exists.

√ It should be installed in an area where there are many protests from residents because of frequent traffic accidents as a visible and active safety measure

√ It should be judged by other site conditions, residents tendency and so forth and should be installed according to this judgement.

2.1.2.2 Australia Installation Criteria

According to Traffic Management Guideline for Traffic Signals, a following installation criteria for scrambled crosswalks is suggested. Unlike the Japan's case, there are some quantitative criteria.

√ Crossing roads should not be main roads

√ A intersection should be in a CBDs (Central Business Districts) or commercial districts

√ Alternative roads for vehicle traffic flow that pass through roads considered should be equal or superior to the roads considered

√ A signal system prior to installation of scrambled crosswalks should consist of 2 simple phases

√ There should be 200 or more pedestrians in all directions per hour, and 400 or more 400 turning vehicle traffic volume for 4 or more hours a day during weekdays

2.2 Literature Review

As this research explores appropriate traffic volume areas for installation of scrambled crosswalks utilizing delay time models which reflect both vehicle traffic volume and pedestrian traffic volume, related research is largely divided into two parts. One part is research about installation criteria for scrambled crosswalks. The other part is signal optimization research which reflects both vehicle traffic flow and pedestrian traffic flow.

2.2.1 Installation Criteria for scrambled crosswalks

Son et al. (1997) present a quantitative installation criteria for scrambled crosswalks using a vehicle delay time model and an unique pedestrian delay time model. Jang et al. (2007) analyze changes in vehicle delay times before and after installation of scrambled crosswalks. Kim and Kim (2007) use total delay time which is sum of both vehicle delay time and pedestrian delay time as an effect measure, and use the Vissim program to get total delay time. Jeon et al. (2009) use a vehicle communication aspect and a pedestrian safety aspect as effect measures. Han et al. (2011) carry out before and after study of installation of scrambled crosswalks using vehicle delay time and pedestrian crossing time which is from an unique model as effect measures. Jeong (2013) carries out benefit analysis of installation of scrambled crosswalks, reflecting a weighted vehicle communication aspect and a weighted pedestrian communication aspect. Choi (2014) compares and analyzes previous research. Tu et al. (2014) use the Paramics program to analyze difference in vehicle delay times before and after installation of scrambled crosswalks. Lee (2016) uses the Vissim program to compare total delay times before and after installation of scrambled crosswalks and from this verifies effect of ANP analysis.

As for installation criteria for scrambled crosswalks, research has been conducted actively in Republic of Korea and developed to reflect both vehicle-related indicators and pedestrian-related indicators as effect measures for analysis. However, there is a limitation in that pedestrians are not taken into account when optimizing signal cycle length which is basis of such analysis. In this research, optimum signal is obtained by delay time models reflecting both vehicle traffic volume and pedestrian traffic volume, and then appropriate traffic volume areas for installation of scrambled crosswalks are sought based on that optimum signal.

2.2.2 Signal Optimization

Sin et al. (2004) develop a signal optimization model which recognizes pedestrian traffic flow as independent traffic flow. Alhajyaseen et al. (2010) formulate a model which reflects both vehicle delay time and pedestrian delay time in an objective function, reflecting influence of a pedestrian group of the opposite side in pedestrian delay time terms. Guo et al. (2016) also formulate a model which reflects both vehicle delay time and pedestrian delay time in an objective function, dividing pedestrians into law-complying pedestrians and non-complying pedestrians when formulating pedestrian delay time models. Yu et al. (2017) also formulate a model which reflects both vehicle delay time and pedestrian delay time in an objective function, carrying out analysis for both 1-stage pedestrian crosswalks and 2-stage pedestrian crosswalks.

In Republic of Korea, there is little research on a signal optimization model which reflects both vehicle traffic flow and pedestrian traffic flow. The research of Sin et al. (2004) reflects pedestrian traffic flow during signal optimization, but it has a limitation in that pedestrian-related terms are not reflected in an objective function. On the other hand, there are much research related to a signal optimization model which reflects both vehicle traffic flow and pedestrian traffic flow on overseas, and each research is considered to have an unique point. This paper formulates models which reflect vehicle delay time and pedestrian delay time in an objective function in accordance with this trend. Based on models, difference of total delay times before and after installation of scrambled crosswalks is analyzed, which makes this research unique.

Chapter 3. Model Formulation

3.1 Scope of Research

3.1.1 Selection of Test Sites

As of July 2017, there are 94 signal intersections where scrambled crosswalks are installed in Seoul, Republic of Korea. If these signal intersections are classified in terms of the number of total lanes on a main road, results can be summarized in <Table 3>.

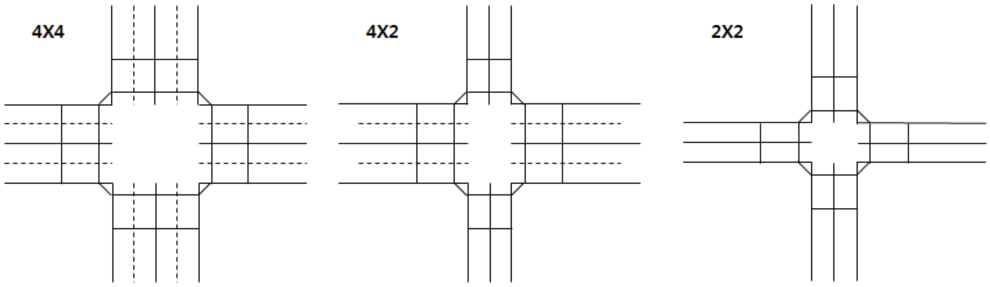
<Table 3> Classification of existing scrambled crosswalks in Seoul

The number of approach lanes + The number of exit lanes	Number
2	11
3	19
4	39
Above 5	25

Because delay time models vary according to geometry structure of intersections, it is necessary to restrict spatial scope of this research. As a result, spatial scope of this research is restricted to signal intersections where the number of total lanes on a main road is four or less, which are 69 out of 94 signal intersections where scrambled crosswalks are installed in Seoul, Republic of Korea.

Three signal intersections with geometry structures which are considered to be general in the restricted spatial scope are finally selected as test sites. An other reason for selection of these three intersections is that the number of signal systems which can be applied to each intersection is different owing to the number of approach lanes. Three intersections are selected as follows and those geometry structures are shown in <Figure 2>.

1) 4X4 signal intersection where 4 lanes are crossed by 4 lanes
2) 4X2 signal intersection where 4 lanes are crossed by 2 lanes
3) 2X2 signal intersection where 2 lanes are crossed by 2 lanes



<Figure 2> Geometry structure of test sites

3.1.2 Kinds of Signal Systems

Kinds of signal systems may vary according to a situation of each signal intersection, but four signal systems which are assumed to be general are analyzed in this research.

1) Signal system Ⅰ : Signal system consisting of 4 through movement with protected left-turn phases

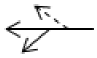
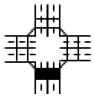
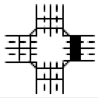
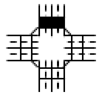
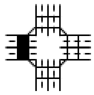
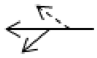
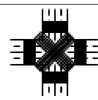
2) Signal system Ⅱ : Signal system consisting of 2 through movement phases and 2 exclusive left-turn phases

3) Signal system Ⅲ : Signal system consisting of 1 through movement with unprotected left-turn phase, 1 through movement phase and 1 exclusive left-turn phase

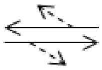
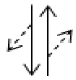
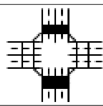
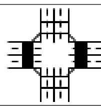
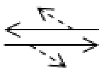
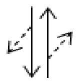
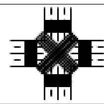
4) Signal system Ⅳ : Signal system consisting of 2 through movement with unprotected left-turn phases

<Table 4>, <Table 5>, <Table 6> and <Table 7> show composition of these four signal systems before and after installation of scrambled crosswalks.

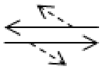
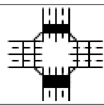
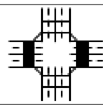
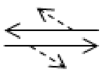
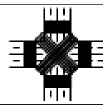
<Table 4> Composition of signal system Ⅰ

		1 phase	2 phase	3 phase	4 phase	5 phase
Before	Vehicle					-
	Pedestrian					-
After	Vehicle					-
	Pedestrian	-	-	-	-	

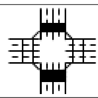
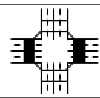
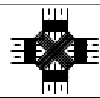
<Table 5> Composition of signal system Ⅱ

		1 phase	2 phase	3 phase	4 phase	5 phase
Before	Vehicle					-
	Pedestrian	-		-		-
After	Vehicle					-
	Pedestrian	-	-	-	-	

<Table 6> Composition of signal system Ⅲ

		1 phase	2 phase	3 phase	4 phase
Before	Vehicle				-
	Pedestrian	-			-
After	Vehicle				-
	Pedestrian	-	-	-	

<Table 7> Composition of signal system Ⅳ

		1 phase	2 phase	3 phase
Before	Vehicle			-
	Pedestrian			-
After	Vehicle			-
	Pedestrian	-	-	

3.2 Research Premise

This research has three research premises as follows. Firstly, it is assumed that test sites are signal intersections with non-saturated vehicle traffic volume. After installation of scrambled crosswalks, lost time per cycle will inevitably increases from the perspective of vehicle traffic flow. Therefore, if a signal intersection is already saturated, it can be expected that vehicle delay time will increase sharply, which makes it unrealistic to install scrambled crosswalks.

Secondly, pedestrians are supposed to obey the law. In reality, there are cases where pedestrians start to cross crosswalks in pedestrian flashing green time. However, one of the main purposes of scrambled crosswalks is safety. Therefore, it is reasonable to make all pedestrians comply with the law at intersections before considering installation of scrambled crosswalks.

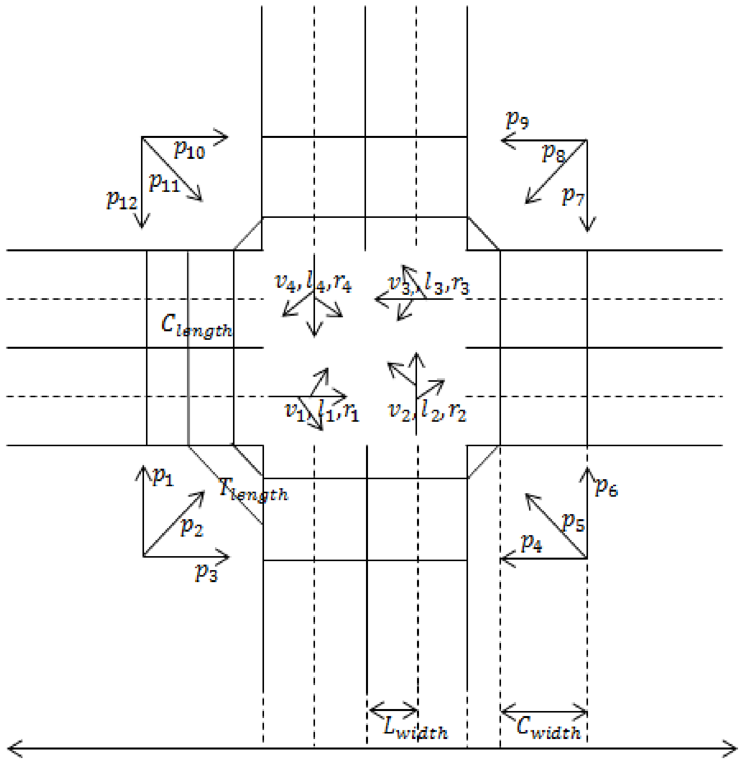
Thirdly, it is assumed that pedestrians have knowledge of shortest path. In reality, there are cases where pedestrians do not have the knowledge of shortest path, which makes unnecessary delay. However, in terms of signal optimization, it is reasonable to exclude such unnecessary delay.

Although the second and third premises may be different from reality, these can be realized by regulating non-obeying pedestrians and providing information to pedestrians.

3.3 Delay Time Model

Delay time models include total delay time which is sum of vehicle delay time and pedestrian delay time in an objective function, basically based on the Webster's uniform delay time model.

Before model explanation, some parameters which are used in the models are expressed in <Figure 3> where 4X4 signal intersection is expressed.



<Figure 3> Geometry Structure of 4X4 signal intersection

<Table 8> shows decision variables, input parameters and traffic parameters which are used in the models.

A 'Value' column gives information about a value of traffic parameters. '-' notation means a value varies by each signal intersection or by each signal system. 'eq' notation means a value is calculated by equations which are explained later.

<Table 8> Variables and Parameters

Decision Variables		
x_i	Vehicle green time of phase i	
C	Cycle length	
Input Parameters		
v_i	Vehicle traffic volume of vehicle traffic flow i (n/sec)	
p_i	Pedestrian traffic volume of pedestrian traffic flow i (n/sec)	
l_i	Ratio of left-turn vehicles to vehicle traffic flow i	
Traffic Parameters		Value
β	Weighting factor (Average vehicle occupancy in this study)	1.8
s	Saturation flow rate per lane (n/sec)	0.5
L_{width}	Lane width (m)	3.5
C_{width}	Crosswalk width (m)	6
$S_{\min}$	Minimum shoulder width (m)	0.6
SV_D	Pedestrian flow rate of service D (n/sec)	1
G	Pedestrian green time (sec)	5
pss	Pedestrian safety speed (m/s)	1
pas	Pedestrian average speed (m/s)	1.3
PHF	Peak hour factor	1
v/c	Target v/c ratio	0.9
$Buffer$	A value set to give enough time for vehicle traffic flow to be under an unsaturated condition (sec)	1
l^1	Start-up lost time (sec)	2
e	Encroachment of vehicles into yellow and all-red time (sec)	2
y_i	Vehicle yellow time of phase i (sec)	3
r_i	Ratio of right-turn vehicles to vehicle traffic flow i	0.2
T_{length}	Length which is needed for pedestrians who cross diagonally to move from end of a former crosswalk to front of a latter crosswalk (m)	7
L_n^i	The number of lanes for pedestrian traffic flows of phase i to cross (n)	-
V_n^i	The number of lanes for vehicle traffic flow i (n)	-
T_n^i	The number of lanes for through movement vehicles of vehicle traffic flow i (n)	-
P_n	The number of phases of a cycle (n)	-
D_{length}	Length which is needed to cross diagonally in scrambled crosswalks	-
L	Total lost time per cycle (sec)	eq
ps	Pedestrian saturation flow rate (n/sec)	eq
h	Headway (sec)	eq
FDW_i	Pedestrian flashing green time of phase i (sec)	eq
AR	Pedestrian all-red time (sec)	eq
C_{length}^i	Crosswalk length for pedestrian traffic flows of phase i (m)	eq
$C_{\min}$	Minimum cycle length (sec)	eq
C_{des}	Desirable cycle length (sec)	eq
C_{ped}	Cycle length which is needed to satisfy phase of corresponding pedestrian traffic flows (sec)	eq
l^2	Clearance lost time (sec)	eq
N_{length}^i	Length which is needed for pedestrian traffic flow $3i-1$ to cross diagonally in normal crosswalks	eq
α	Calibration parameter of right-turn on red	eq
V_c	Sum of critical lane volumes	eq

β is based on the Domestic Vehicle Occupancy Characteristics. s is based on the Korean Highway Capacity Manual. L_{width} is based on the Article 10 of the Road Traffic Act of Republic of Korea. C_{width}, $S_{\min}$ and SV_D are based on the Sidewalk Installation and Management Instruction. G and pss are based on the Traffic Signal Installation and Management Manual. pas is based on the Transportation Operation System Advancement Research. l^1 and e are based on the book by Roess et al. (2010).

PHF is set to be 1 because this research assumes arrival of vehicles is uniform. v/c is set to be 0.9 and $Buffer$ is set to be 1 to give enough time for each vehicle traffic flow to be under an unsaturated state.

In a case of p_i, for $i=12m+n(1 \le n \le 12)$ where m is an integer and n is a positive integer, $i=n$ is finally used in models. In a case of x_i, y_i and FDW_i, for $i=4m+n(1 \le n \le 4)$ where m is an integer and n is a positive integer, $i=n$ is finally used in a model before installation. In a case of C^i_{length}, for $i=4m+n(1 \le n \le 4)$ where m is an integer and n is a positive integer, $i=n$ is finally used in a model after installation.

Following delay time models are applicable to signal system Ⅰ. Delay time models for signal system Ⅱ, Ⅲ and Ⅳ need some variations.

3.3.1 Before Installation

$$\min\left(\beta\sum_{i=1}^{4}(V_n^i \times D_i^{veh}) + \sum_{i=1}^{8} D_i^{ped}\right)/C \quad (1)$$

$$\text{subject to} \quad x_i + y_i \geq G + FDW_i + AR,\ i = 1,2,3,4 \quad (2)$$

$$x_i \geq v_i \times C \times h + Buffer,\ i = 1,2,3,4 \quad (3)$$

$$\sum_{i=1}^{4}(x_i + y_i) = C \quad (4)$$

$$C \geq C_{\min} \quad (5)$$

where, β = weighting factor, C = cycle length, V_n^i = the number of lanes for vehicle traffic flow, x_i = vehicle green time of phase i, y_i = vehicle yellow time of phase i, G = pedestrian green time, FDW_i = pedestrian flashing green time of phase i, AR = pedestrian all-red time, v_i = vehicle traffic volume of vehicle traffic flow i, h = headway

$$FDW_i = C_{length}^i / pss \quad (6)$$

$$AR = T_{length} / pss \quad (7)$$

$$h = 1/s \quad (8)$$

where, C_{length}^i = crosswalk length for pedestrian traffic flows of phase i, T_{length} = length which is needed for pedestrians who cross diagonally to move from end of a former crosswalk to front of a latter crosswalk. pss = pedestrian safety speed, s = saturation flow rate per lane

$$C_{length}^i = 3.5 \times L_n^i \quad (9)$$

where, L_n^i = the number of lanes for pedestrian traffic flows of phase i to cross

Equation 1 is an objective function and a numerator of the function is divided into vehicle delay time terms and pedestrian delay time terms. Equation 2 is a constraint that sum of green time and yellow time of a vehicle traffic flow must be greater than sum of green time, flashing green time and all-red time of corresponding pedestrian traffic flows. Equation 3 is a constraint to keep vehicle traffic flow in an unsaturated state. Equation 4 is an equality constraint that sum of sum of green time and yellow time of each phase for vehicle traffic flow is cycle length. Equation 5 is a constraint that cycle length is greater than minimum cycle length.

The terms that constitute the objective function will be explained in detail below.

D_i^{veh} is delay time of vehicle traffic flow which is given green time in phase i. D_i^{veh} can be expressed by a following equation and is equal to the area shown in <Figure 4>.

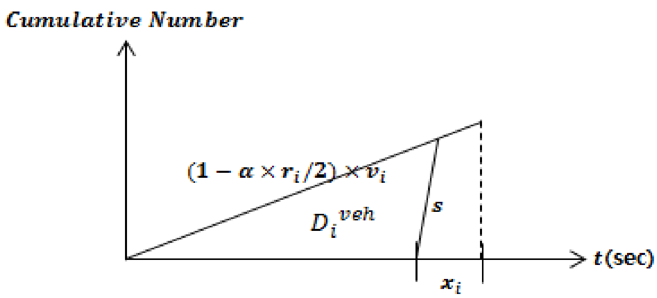
$$D_i^{veh} = \frac{1}{2} \times \frac{s \times (1-\alpha \times r_i/2) \times v_i \times (C - x_i)^2}{s-(1-\alpha \times r_i/2) \times v_i} \quad (10)$$

where, s = saturation flow rate, α = calibration parameter of right-turn on red, r_i = ratio of right-turn vehicles to vehicle traffic flow i, v_i = vehicle traffic volume of vehicle traffic flow i, C = cycle length, x_i = vehicle green time of phase i

$$\alpha = \begin{cases} 0 & T_n^i = 1 \\ 1 & T_n^i = 2 \end{cases} \quad (11)$$

where, T_n^i = the number of lanes for through movement vehicles of vehicle traffic flow i

About calibration of RTOR(right-turn on red), it is assumed that if the number of lanes for through movement vehicles of vehicle traffic flow i is 2, then half of right-turn vehicles can pass an intersection without delay time.



<Figure 4> Graphical expression of D_i^{veh}

D_i^{ped} is pedestrian delay time and divided into two terms, D_{2i-1}^{ped} and D_{2i}^{ped}. D_{2i-1}^{ped} is delay time of pedestrian traffic flows which are given green time in phase i and cross counterclockwise and D_{2i}^{ped} is delay time of pedestrian traffic flows which are given green time in phase i and cross clockwise.

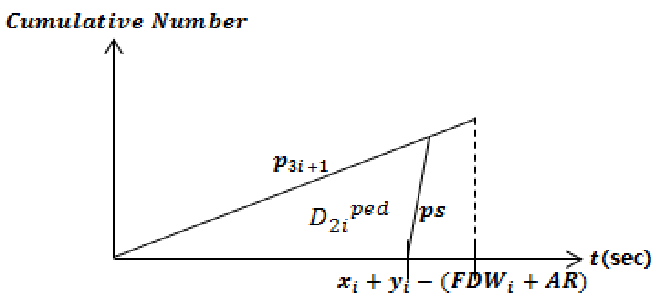
D_{2i}^{ped} has a shape similar to D_i^{veh} because it is not affected by pedestrians crossing diagonally. D_{2i}^{ped} can be expressed by a following equation and is equal to the area shown in <Figure 5>.

$$D_{2i}^{ped} = \frac{1}{2} \times \frac{ps \times p_{3i+1} \times (C - (x_i + y_i - (FDW_i + AR)))^2}{ps - p_{3i+1}} \quad (12)$$

where, ps = pedestrian saturation flow rate, p_i = pedestrian traffic volume of pedestrian traffic flow i, C = cycle length, x_i = vehicle green time of phase i, y_i = vehicle yellow time of phase $i FDW_i$ = pedestrian flashing green time of phase i, AR = pedestrian all-red time

$$ps = \frac{C_{width}}{S_{\min}} \times SV_D \quad (13)$$

where, C_{width} = crosswalk width, $S_{\min}$ = minimum shoulder width, SV_D = pedestrian flow rate of service D



<Figure 5> Graphical expression of D_{2i}^{ped}

In a case of D_{2i-1}^{ped}, real value can not be obtained. The reason is that it is affected by pedestrians crossing diagonally in the former phase who are affected by pedestrians crossing diagonally in the former phase and a cycle of signal systems has cyclic characteristics. To solve this problem, maximum value and minimum value can be obtained. Maximum value of D_{2i-1}^{ped}, $D_{2i-1}^{ped-\max}$ can be expressed by a following equation and is equal to the area shown in the bottom graph of <Figure 6>.

$$
\begin{aligned}
D_{2i-1}^{ped-\max} = & \int_0^{(C-(x_i+y_i+x_{i-1}+y_{i-1}-(FDW_{i-1}+AR)/pas-(FDW_i+AR)))} F^1 + \int_0^{A_i} F^2 \quad (14) \\
& + \int_0^{x_{i-1}+y_{i-1}-(FDW_{i-1}+AR)-A_i} F^3 + \int_0^{(pas-1)\times(FDW_{i-1}+AR)/pas} F^4 \\
& + 1/2 \times F^4_{x=(pas-1)\times(FDW_{i-1}+AR)/pas} \times B_i
\end{aligned}
$$

where, pas = pedestrian average speed

$A_i = (C-(x_{i-1}+y_{i-1}-(FDW_{i-1}+AR))) \times (p_{3(i-1)-1}+p_{3(i-1)})/(ps-(p_{3(i-1)-1}+p_{3(i-1)}))$

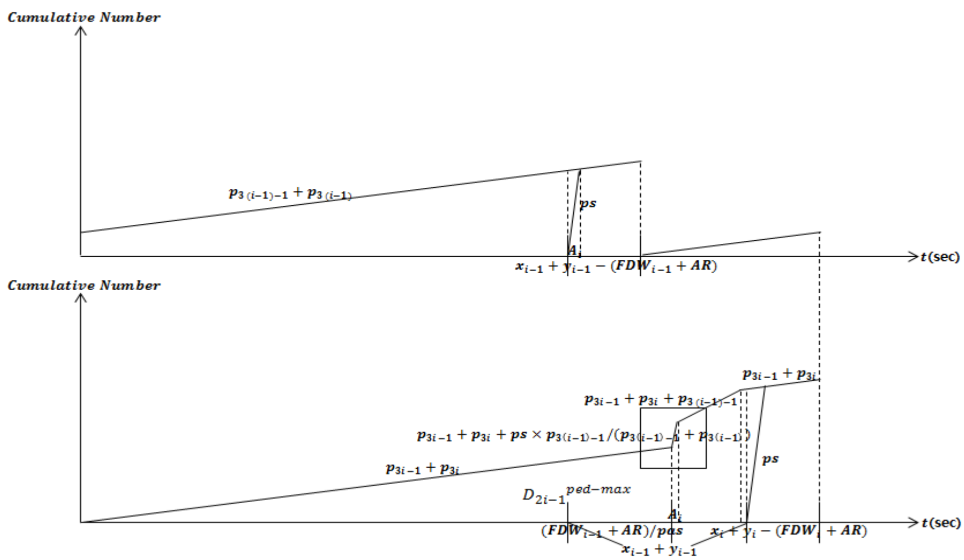
$B_i = (F^4_{x=(pas-1)\times(FDW_{i-1}+AR)/pas})/(ps-(p_{3i-1}+p_{3i}))$

$F^1 = (p_{3i-1}+p_{3i}) \times x$

$$
\begin{aligned}
F^2 = & (p_{3i-1}+p_{3i}+ps \times p_{3(i-1)-1}/(p_{3(i-1)-1}+p_{3(i-1)})) \times x \\
& + F^1_{x=(C-(x_i+y_i+x_{i-1}+y_{i-1}-(FDW_{i-1}+AR)/pas-(FDW_i+AR)))}
\end{aligned}
$$

$F^3 = (p_{3i-1}+p_{3i}+p_{3(i-1)-1}) \times x + F^2_{x=A_i}$

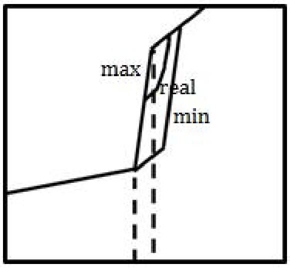
$F^4 = (p_{3i-1}+p_{3i}) \times x + F^3_{x=x_{i-1}+y_{i-1}-(FDW_{i-1}+AR)-A_i}$



<Figure 6> Graphical expression of $D_{2i-1}^{ped-\max}$

As can be seen from <Figure 6>, pedestrians in a phase are affected by pedestrians in the former phase.

Relationship between maximum value, real value, and minimum value of D_{2i-1}^{ped} can be shown in the square area of <Figure 6>, which is shown in <Figure 7>.



<Figure 7> Relation between max, real, min value of D_{2i-1}^{ped}

Minimum value of D_{2i-1}^{ped}, $D_{2i-1}^{ped-\min}$ can be expressed by a following equation.

$$\begin{aligned} D_{2i-1}^{ped-\min} = D_{2i-1}^{ped-\max} - (B_{i-1} - B_{i-1} \times (p_{3i-1} + p_{3i} + p_{3(i-1)-1}) \\ / (p_{3i-1} + p_{3i} + ps \times p_{3(i-1)-1} / (p_{3(i-1)-1} + p_{3(i-1)}))) \\ \times A_i \times (p_{3i-1} + p_{3i} + ps \times p_{3(i-1)-1} / (p_{3(i-1)-1} + p_{3(i-1)})) \end{aligned} \quad (15)$$

In the model, average value of $D_{2i-1}^{ped-\max}$ and $D_{2i-1}^{ped-\min}$, $D_{2i-1}^{ped-avg}$ is used as D_{2i-1}^{ped} and can be expressed by a following equation.

$$D_{2i-1}^{ped-avg} = (D_{2i-1}^{ped-\max} + D_{2i-1}^{ped-\min})/2 \quad (16)$$

Since $C_{\min}$ is possible minimum value, $C_{\min}$ is maximum value between C_{des} and C_{ped}. C_{des} is minimum value which satisfies the condition that vehicle traffic flow is in an unsaturated state and is influenced by v_i. C_{ped} is minimum value which satisfies the condition that sum of green time and yellow time of each phase for a vehicle traffic flow is greater than sum of green time, flashing green time and all-red time of corresponding pedestrian traffic flows. C_{des} is based on the book by Roess et al. (2010) and can be expressed by a following equation.

$$C_{des} = \frac{L}{1 - \left[\frac{V_c}{\frac{3600}{h} \times PHF \times (v/c)} \right]} \quad (17)$$

where, L = total lost time per cycle, V_c = sum of critical lane volumes, h = headway, PHF = peak hour factor, v/c = target v/c ratio

$$L = \sum_i (l^1 + l^2) \quad (18)$$

$$V_c = \sum_i (v_i \times 3600) \quad (19)$$

where l^1 = start-up lost time, l^2 = clearance lost time, v_i = vehicle traffic volume of vehicle traffic flow i

$$l^2 = y_i - e \quad (20)$$

where, e= encroachment of vehicles into yellow and all-red time, y_i = vehicle yellow time of phase i

C_{ped} is affected by pedestrian flashing green time and all-red time and can be expressed by a following equation.

$$C_{ped} = \sum_i (G + FDW_i + AR) \quad (21)$$

where, G = pedestrian green time, FDW_i = pedestrian flashing green time of phase i, AR = pedestrian all-red time

As mentioned above, $C_{\min}$ is minimum cycle length and can be expressed by a following equation.

$$C_{\min} = \max(C_{des}, C_{ped}) \quad (22)$$

3.3.2 After Installation

$$\min\left(\beta\sum_{i=1}^{4} D_i^{veh} + \sum_{i=1}^{12} D_i^{ped} - \sum_{i=1}^{4} B_i^{ped}\right)/C \quad (23)$$

$$\text{subject to } x_i \geq v_i \times C \times h + Buffer,\ i = 1,2,3,4 \quad (24)$$

$$\sum_{i=1}^{4}(x_i + y_i) + G + FDW_i = C \quad (25)$$

$$C \geq C_{\min} \quad (26)$$

where, β = weighting factor, C = cycle length, x_i = vehicle green time of phase i, v_i = vehicle traffic volume of vehicle traffic flow i, h = headway, y_i = vehicle yellow time of phase i, G = pedestrian green time, FDW_i = pedestrian flashing green time of phase i

$$FDW_i = D_{length}/pss \quad (27)$$

where, D_{length} = length which is needed to cross diagonally in scrambled crosswalks, pss = pedestrian safety speed

Equation 23 is an objective function and a numerator of the equation is divided into vehicle delay time terms, pedestrian delay time terms and benefit time terms. Equation 24 is a constraint to keep vehicle traffic flow in an unsaturated state. Equation 25 is equality constraint that sum of sum of green time and yellow time of each phase for vehicle traffic flow and sum of green time and flashing green time of pedestrian traffic flow is a cycle length. Equation 26 is a constraint that cycle length is greater than minimum cycle length.

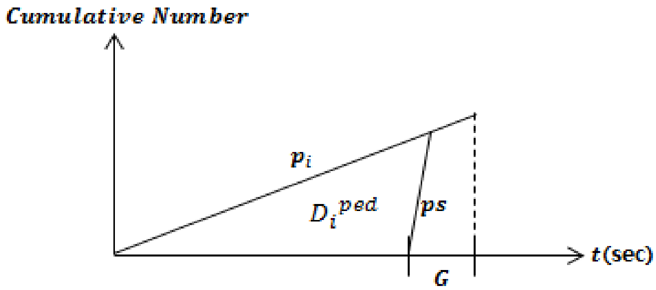
The terms that constitute the objective function will be described in detail below.

D_i^{veh} is delay time of vehicle traffic flow which is given green time in phase i and can be expressed by equation 10.

D_i^{ped} is delay time of each pedestrian traffic flow i and can be expressed by a single term because pedestrian traffic flows does not affect each other unlike the case of intersections before installation of scrambled crosswalks. D_i^{ped} can be expressed by a following equation and is equal to the area shown in <Figure 8>.

$$D_i^{ped} = \frac{1}{2} \times \frac{ps \times p_i \times (C - G)^2}{s - p_i} \quad (28)$$

where, ps = pedestrian saturation flow rate, p_i = pedestrian traffic volume of pedestrian traffic flow i, C = cycle length, G = pedestrian green time



<Figure 8> Graphical expression of D_i^{ped}

B_i^{ped} is benefit time of installation of scrambled crosswalks for pedestrians who cross diagonally due to shorter time in walk and can be expressed by a following equation.

$$B_i^{ped} = p_{3i-1} \times C \times (N_{length}^i - D_{length}) / pas \quad (29)$$

where, p_i = pedestrian traffic volume of pedestrian traffic flow i, C = cycle length, N_{length}^i = length which is needed for pedestrian traffic flow $3i-1$ to cross diagonally in normal crosswalks, D_{length} = length which is needed to cross diagonally in scrambled crosswalks, pas = pedestrian average speed

$$N_{length}^i = C_{length}^i + T_{length} + C_{length}^{i+1} \quad (30)$$

where, C_{length}^i = crosswalk length for pedestrian traffic flows of phase i, T_{length} = length which is needed for pedestrians who cross diagonally to move from end of a former crosswalk to front of a latter crosswalk

When determining minimum cycle length, it is sufficient to obtain C_{des} since cycle used in the model is not affected by minimum green time of pedestrian traffic flow. Therefore, $C_{\min}$ can be expressed by a following equation.

$$C_{\min} = C_{des} = \frac{L}{1 - \left[\dfrac{V_c}{\dfrac{3600}{h} \times PHF \times (v/c)} \right]} + P_n \times Buffer \quad (31)$$

where, C_{des} = desirable cycle length, L = total lost time per cycle, V_c = sum of critical lane volumes, h = headway, v/c = target v/c ratio for the critical movements in the intersections, P_n = the number of phases of a cycle

$$L = \sum_i (l^1 + l^2) + (G + FDW_5) \quad (32)$$

where l^1 = start-up lost time, l^2 = clearance lost time, G = pedestrian green time, FDW_5 = pedestrian flashing green time of phase 5

Equation 32 differs from Equation 18 because sum of green time and flashing green time of pedestrian traffic flow is taken to be lost time.

Chapter 4. Analysis

4.1 Methodology

v_i, p_i and l_i are assumed to be equal for every i. In signal system Ⅰ and Ⅳ, l_i does not affect results. However, l_i does affect results in signal system Ⅱ and Ⅲ because l_i affects minimum cycle length of those signal systems.

A process of analysis is as follows. Firstly, signal optimization based on delay time models are implemented. Since delay time models before and after installation of scrambled crosswalks contain a nonlinear objective function with linear constraints, the fmincon function which is used to find a minimum value of a nonlinear multi-variable function constrained in the Matlab program is used for signal optimization.

Secondly, from results of signal optimization, scope of analysis can be restricted to a traffic volume area where vehicle traffic volume is under 270 vehicles per vehicle traffic flow per lane per hour by preliminary analysis. From the preliminary analysis, it is revealed that over 250 vehicles, installation of scrambled crosswalks is not efficient for all combinations of signal intersection and signal system. Pedestrian traffic volume is also restricted under 270 pedestrians per pedestrian traffic flow per hour as vehicle traffic volume. l_i is restricted to 0.2, 0.3 or 0.4.

Thirdly, based on the restriction, main analysis is conducted on 729 combinations of vehicle traffic volume and pedestrian traffic volume for each combination of signal intersection and signal system. 729 combinations means there are 27 cases of vehicle traffic volumes whose gap is equally 10 and 27 cases of pedestrian traffic volumes whose gap is also equally 10, and each of the former case group are connected to all of the latter case group. A minimum value of 27 cases is 10 and a maximum value is 270.

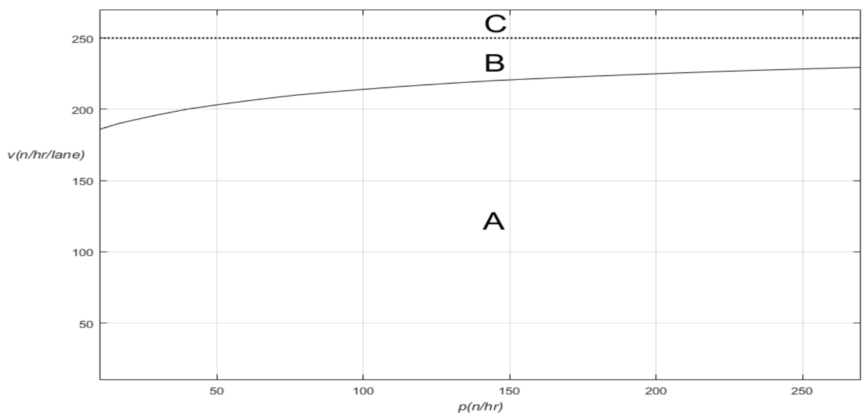
The analysis is implemented by subtracting total delay time per second of a case after installation from total delay time per second of a case before installation. Total delay time per second is calculated by the fmincon function mentioned above.

Fourthly, from results of the analysis, the contour function of the Matlab program gives result graphs. The contour function of the Matlab program can give a curve which connects dots whose values are same. In case of together depicting more than two combinations of signal intersection and signal system, l_i is set to be 0.3 for comparison with other combinations.

4.2 Results by Signal System

4.2.1 4X4 Signal Intersection

4.2.1.1 Signal System Ⅰ



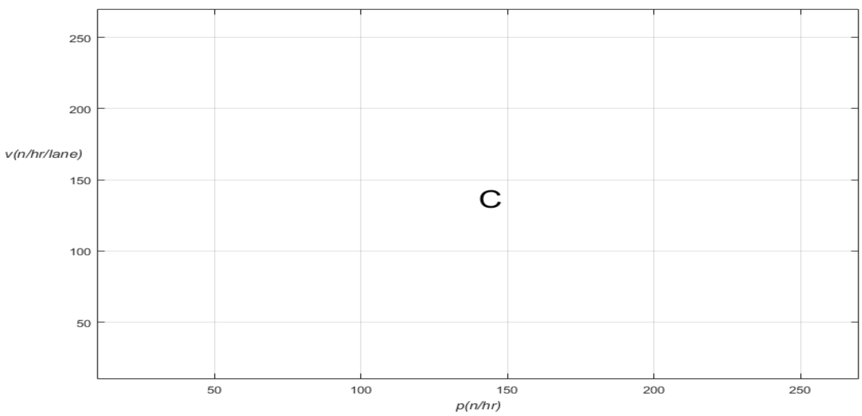
<Figure 9> 4X4 signal intersection where signal system Ⅰ is applied

The x-axis in <Figure 9> represents the number of pedestrians per pedestrian traffic flow per hour and the y-axis represents the number of vehicles per vehicle traffic flow per lane per hour. The real line curve drawn on the x-y axis plane connects dots where total delay times per second before and after installation of scrambled crosswalks are same.

The area under the real line curve, 'A', represents an area where total delay time per second decreases after installation of scrambled crosswalks, in other words, an area where efficiency increases after installation of scrambled crosswalks. The areas over the real line curve, 'B' and 'C', represent areas where total delay time per second increases after installation of scrambled crosswalks, in other words, areas where efficiency decreases after installation of scrambled crosswalks. Especially, the area over the dotted line, 'C', represents an area where a gap between total delay times per second before and after installation of scrambled crosswalks becomes wider as pedestrian traffic volume increases, which means that increase of pedestrians can not make installation of scrambled crosswalks efficient.

Installation of scrambled crosswalks is found to be effective in terms of efficiency in cases of 185 vehicle traffic volume or less. Between 185 and 250 vehicle traffic volume, whether or not installation of scrambled crosswalks is efficient is dependent on pedestrian traffic volume. Over 250 vehicle traffic volume, installation of scrambled crosswalks is not efficient.

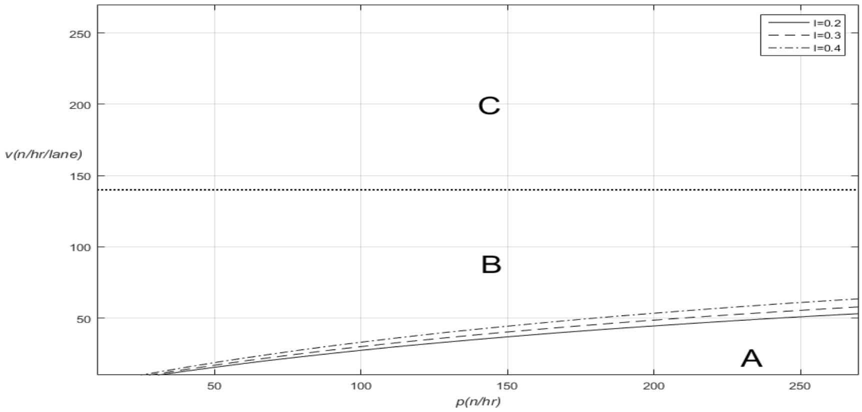
4.2.1.2 Signal System Ⅱ



<Figure 10> 4X4 signal intersection where signal system Ⅱ is applied

The area 'C' encompasses the x-y plane whole, which means that under signal system Ⅱ, installation of scrambled crosswalks is not efficient.

4.2.1.3 Signal System Ⅲ



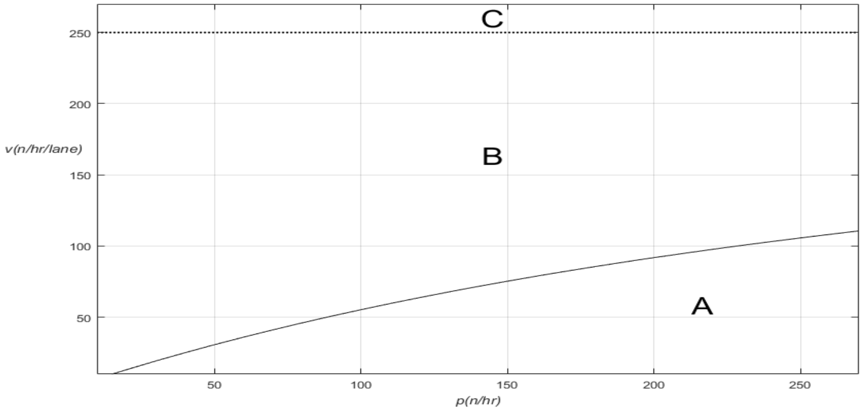
<Figure 11> 4X4 signal intersection where signal system Ⅲ is applied

The real line means a case where l_i is 0.2. The dashed line means a case where l_i is 0.3. The dot-and-dash line means a case where l_i is 0.4.

Between 0 and 140 vehicle traffic volume, whether or not installation of scrambled crosswalks is efficient is dependent on pedestrian traffic volume. Over 140 vehicle traffic volume, installation of scrambled crosswalks is not efficient.

As ratio of left-turn vehicles to vehicle traffic flow, l_i, increases, the appropriate area increases. The reason is that l_i increases cycle lengths of the model before installation, which makes benefit of shorter cycle length for the model after installation larger.

4.2.1.4 Signal System Ⅳ

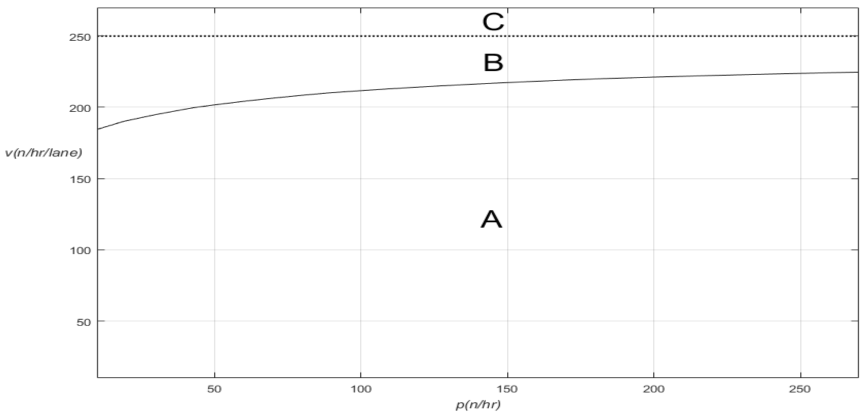


<Figure 12> 4X4 signal intersection where signal system Ⅳ is applied

Between 0 and 250 vehicle traffic volume, whether or not installation of scrambled crosswalks is efficient is dependent on pedestrian traffic volume. Over 250 vehicle traffic volume, installation of scrambled crosswalks is not efficient.

4.2.2 4X2 Signal Intersection

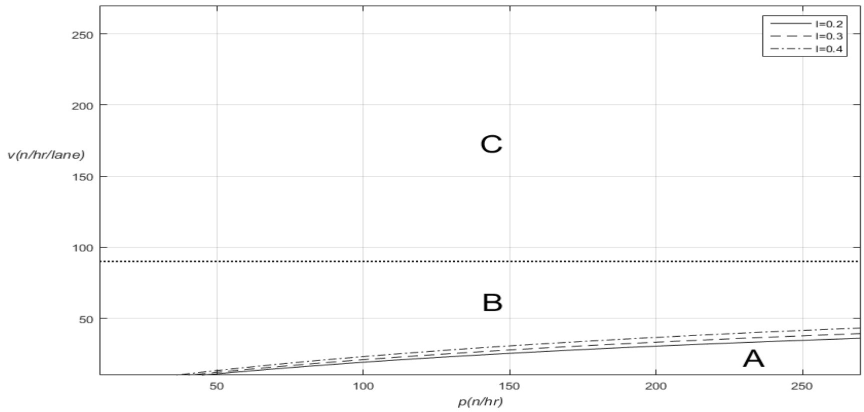
4.2.2.1 Signal System Ⅰ



<Figure 13> 4X2 signal intersection where signal system Ⅰ is applied

Installation of scrambled crosswalks is found to be efficient in cases of 185 vehicle traffic volume or less. Between 185 and 250 vehicle traffic volume, whether or not installation of scrambled crosswalks is efficient is dependent on pedestrian traffic volume. Over 250 vehicle traffic volume, installation of scrambled crosswalks is not efficient.

4.2.2.2 Signal System Ⅲ

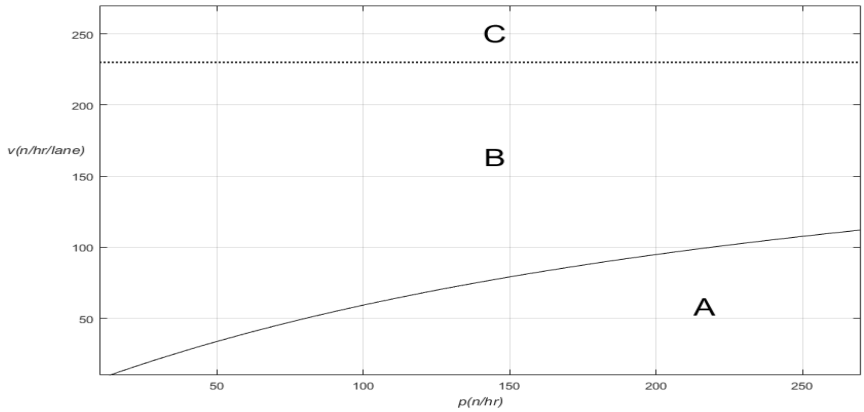


<Figure 14> 4X2 signal intersection where signal system Ⅲ is applied

Between 0 and 90 vehicle traffic volume, whether or not installation of scrambled crosswalks is efficient is dependent on pedestrian traffic volume. Over 90 vehicle traffic volume, installation of scrambled crosswalks is not efficient.

As ratio of left-turn vehicles to vehicle traffic flow, l_i, increases, the appropriate area increases owing to the same reason mentioned in 4.2.1.3.

4.2.2.3 Signal System Ⅳ

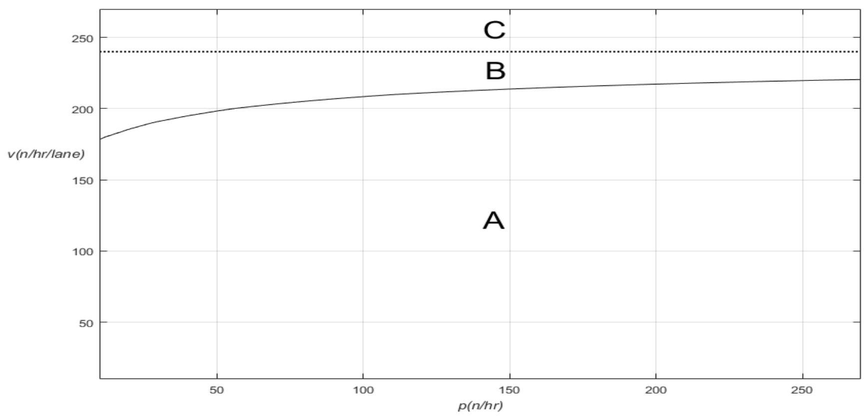


<Figure 15> 4X2 signal intersection where signal system Ⅳ is applied

Between 0 and 230 vehicle traffic volume, whether or not installation of scrambled crosswalks is efficient is dependent on pedestrian traffic volume. Over 230 vehicle traffic volume, installation of scrambled crosswalks is not efficient.

4.2.3 2X2 Signal Intersection

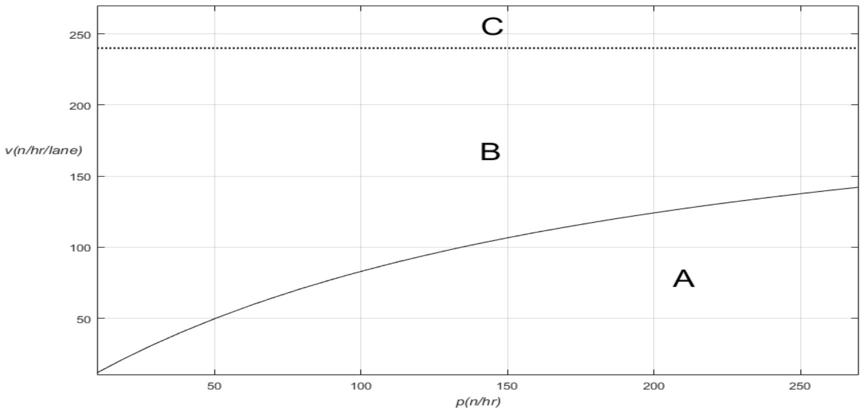
4.2.3.1 Signal System Ⅰ



<Figure 16> 2X2 signal intersection where signal system Ⅰ is applied

Installation of scrambled crosswalks is found to be efficient in cases of 180 vehicle traffic volume or less. Between 180 and 240 vehicle traffic volume, whether or not installation of scrambled crosswalks is efficient is dependent on pedestrian traffic volume. Over 240 vehicle traffic volume, installation of scrambled crosswalks is not efficient.

4.2.3.2 Signal System Ⅳ

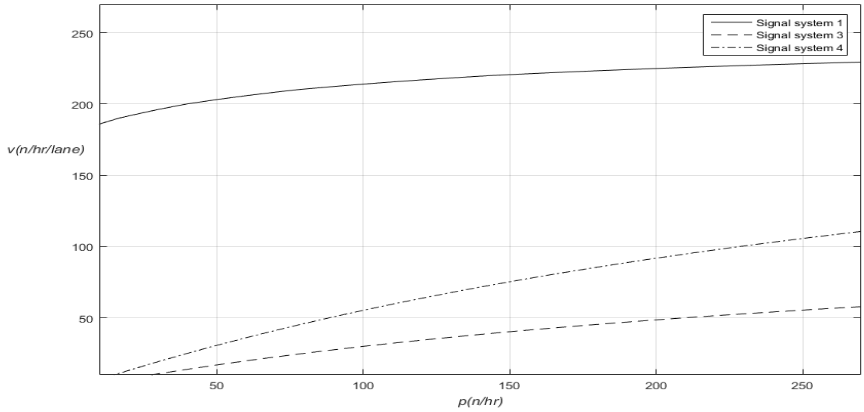


<Figure 17> 2X2 signal intersection where signal system Ⅳ is applied

Installation of scrambled crosswalks is found to be efficient in cases of 10 vehicle traffic volume or less. Between 10 and 240 vehicle traffic volume, whether or not installation of scrambled crosswalks is efficient is dependent on pedestrian traffic volume. Over 240 vehicle traffic volume, installation of scrambled crosswalks is not efficient.

4.2.4 Comparison

4.2.4.1 4X4 Signal Intersection

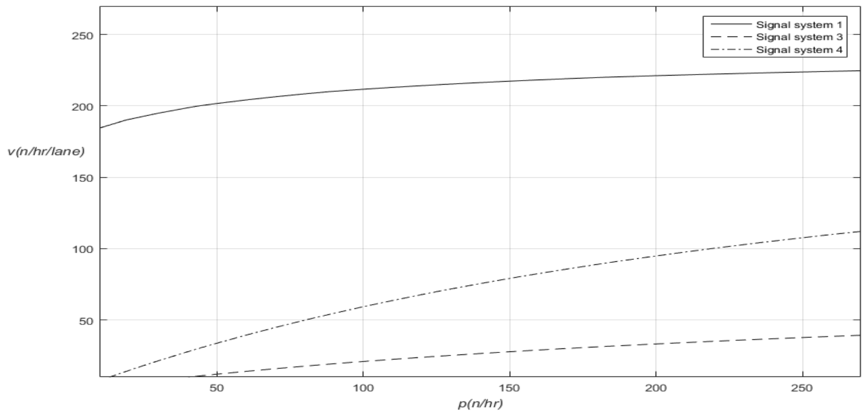


<Figure 18> 4X4 signal intersection

The real line, the dashed line and the dot-and-dash line mean under that line, installation of scrambled crosswalks is efficient. The real line means a case of signal system Ⅰ. The dashed line means a case of signal system Ⅲ. The dot-and-dash line means a case of signal system Ⅳ. Mentioned above, under signal system Ⅱ, there is no appropriate area for installation of scrambled crosswalks.

As can be seen from <Figure 18>, the appropriate areas of signal system Ⅰ, signal system Ⅳ, signal system Ⅲ, signal system Ⅱ are from largest to smallest due to difference of benefit of cycle length which can be obtained after installation of scrambled crosswalks of each signal system to some extent and difference of the number of phases where pedestrians which are intended to cross diagonally can start crossing to some extent.

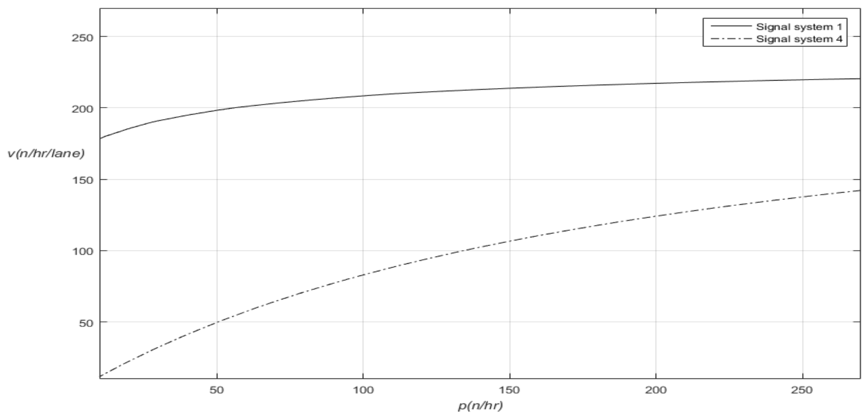
4.2.4.2 4X2 Signal Intersection



<Figure 19> 4X2 signal intersection

As can be seen from <Figure 19>, the appropriate areas of signal system Ⅰ, signal system Ⅳ, signal system Ⅲ are from largest to smallest due to the reason which is mentioned in 4.2.4.1.

4.2.4.3 2X2 Signal Intersection



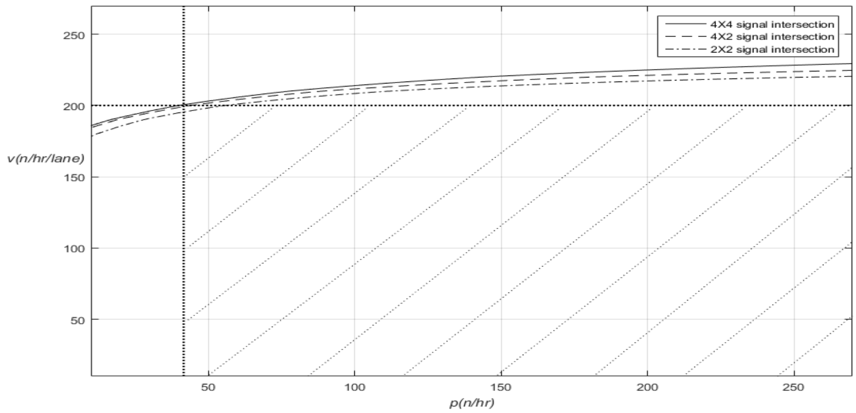
<Figure 20> 2X2 signal intersection

As can be seen from <Figure 20>, the appropriate areas of signal system Ⅰ, signal system Ⅳ are from largest to smallest due to the reason which is mentioned in 4.2.4.1.

4.3 Results by Intersection

In this part, addition to results of analysis by intersection, comparison with an existing Korean installation criteria for scrambled crosswalks is dealt with.

4.3.1 Signal System Ⅰ



<Figure 21> Signal system Ⅰ

In <Figure 21>, the area which is displayed by dotted lines where vehicle traffic volume per vehicle traffic flow per lane per hour is under 200 and pedestrian traffic volume per pedestrian traffic flow per hour is over about 42 is the appropriate area according to requirements of Seoul Metropolitan Police Agency for installation of scrambled crosswalks.

The Real line, the dashed line and the dot-and-dash line mean under that line, installation of scrambled crosswalks is efficient. The real line means a case of 4X4 signal intersection. The dashed line means a case of 4X2 signal intersection. A dot-and-dash line means a case of 2X2 signal intersection.

As can be seen from <Figure 21>, the appropriate area for installation of scrambled crosswalks does not change much depending on kinds of signal intersections.

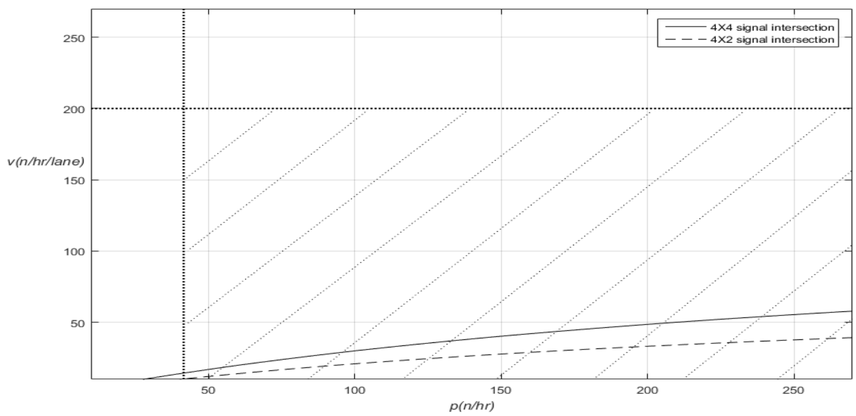
The appropriate areas of 4X4 signal intersection, 4X2 signal intersection, 2X2 signal intersection, the existing criteria are from largest to smallest.

On the one hand, as size of an intersection increases, benefit of installation of scrambled crosswalks in terms of cycle length increases. The benefit is expressed by a ratio of difference between cycle lengths before and after installation to cycle length before installation. On the other hand, as size of an intersection increases, pedestrian flashing green time after installation also increases, which makes benefit of scrambled crosswalks decrease, increasing lost time per cycle for vehicle traffic flow. In signal system Ⅰ, the former effect is more than the latter, which makes the result that as size of an intersection increases, the appropriate area also increases.

4.3.2 Signal System Ⅱ

Under signal system Ⅱ, it is confirmed that installation of scrambled crosswalks is not efficient under all of combinations of vehicle traffic volume and pedestrian traffic volume.

4.3.3 Signal System Ⅲ



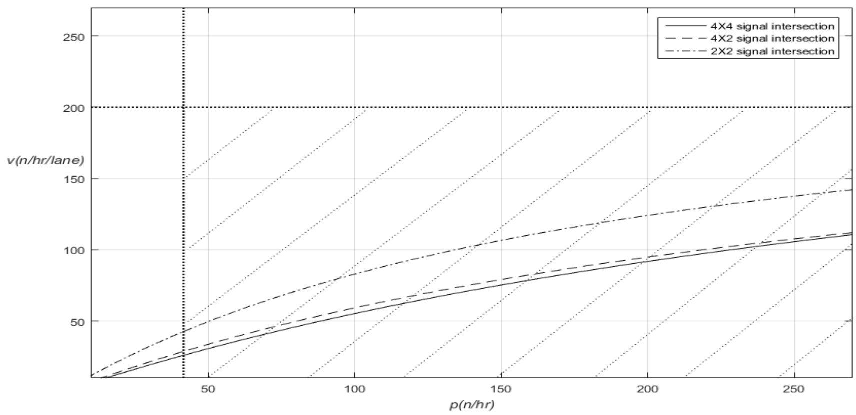
<Figure 22> Signal system Ⅲ

As can be seen from <Figure 22>, the appropriate area for installation of scrambled crosswalks changes depending on kinds of signal intersections much more than signal system Ⅰ.

The appropriate areas of the existing criteria, 4x4 signal intersection, 4X2 signal intersection are from largest to smallest.

In signal system Ⅲ, as size of an intersection increases, the appropriate area also increases, which can be explained by same reasons in 4.3.1.

4.3.4 Signal System Ⅳ



<Figure 23> Signal system Ⅳ

As can be seen from <Figure 23>, the appropriate area for installation of scrambled crosswalks changes depending on kinds of signal intersections much more than signal system Ⅰ. Especially, 2X2 signal intersection has much more appropriate area for scrambled crosswalks than 4X4 signal intersection and 4X2 signal intersection.

The appropriate areas of the existing criteria, 2X2 signal intersection, 4X2 signal intersection, 4X4 signal intersection are from largest to smallest.

In signal system Ⅳ. difference by signal intersection can not be explained by same reasons in 4.3.1. Between 4X4 signal intersection and 4X2 signal intersection, the latter effect among two effects which are explained in 4.3.1 is more than the former, which makes the appropriate area of 4x2 signal intersection is more than that of 4X4 signal intersection. Between 4X2 signal intersection and 2X2 signal intersection, 2X2 signal intersection is more beneficial in terms of cycle length and less inefficient in terms of lost time, which makes the appropriate area of 2X2 signal intersection is more than that of 4X2 signal intersection.

Chapter 5. Model Verification

5.1 Methodology

As the models of this research assume that arrival distribution of vehicles and pedestrians is uniform, there is a limitation in the models in that it can be different from reality. Also, the models can not reflect conflicts between unprotected right-turn vehicles and pedestrians that increase delay time in reality. Furthermore, as real values of pedestrian delay time before installation of scrambled crosswalks can not be obtained, the model uses average values of pedestrian delay time. In addition to this, the models consider RTOR(Right-turn on red) only partially, utilizing a calibration parameter.

To determine whether these limitations of the models are acceptable, this research compares results of the Matlab program with those of the Vissim program. The Vissim program assumes probabilistic arrival distribution of vehicles and pedestrians. Also, the Vissim program reflects conflicts between vehicles and pedestrians and depicts pedestrians whose movements are based on Social Force Model which are thought to be realistic in that it considers relationship between pedestrians. Furthermore, RTOR can be implemented in the Vissim program.

Parameter values of Vissim program are mostly set to be default values, but pedestrian average speed which has great effect on delay time is set to be 1.3(m/s) as pedestrian average speed of the models.

On the one hand, since pedestrians start to cross crosswalks in flashing green time in the Vissim program, flashing red time is used instead of flashing green time to satisfy the second premise of this research. In order to satisfy the third premise of this research, pedestrian paths are set so that pedestrians cross the shortest path.

A signal intersection where model verification is performed is 4X4 signal intersection where signal system Ⅰ is applied.

Cycle length of signal systems applied to a network of the Vissim program is obtained through the models of the Matlab program.

Simulation is implemented three times, each time being implemented for a period which is corresponding to 30 cycles, and delay time per cycle is averaged from 7 to 24 cycles for three times.

From simulation, vehicle delay times, pedestrian delay times and total delay times before and after installation of scrambled crosswalks can be obtained in the Vissim program.

This research implements verification by model to each model, comparing vehicle delay time, pedestrian delay and total delay time. In verification by model, error rate analysis is implemented. An error rate is calculated from a following equation.

$$Error\,rate = \left| \frac{Exact\,value - approximate\,vlaue}{Exact\,value} \right| \quad (33)$$

A value obtained through the Matlab program is assigned to an approximate value and a value obtained through the Vissim program is assigned to exact value. As real values of delay time can not be obtained easily in reality owing to some research premises, a value of the Vissim program is used to be an exact value. A threshold for verification is assumed to be 15%.

This research implements verification between models by subtracting total delay time after installation of scrambled crosswalks from total delay time before installation of scrambled crosswalks, and then utilizes the contour function of Matlab program to depict a graph with a curve where total delay times before and after scrambled crosswalks are same. In verification between models, two results of the Matlab program and the Vissim program are compared.

5.2 Results by Model

5.2.1 Before Installation

5.2.1.1 Comparison between Vehicle Delay Times

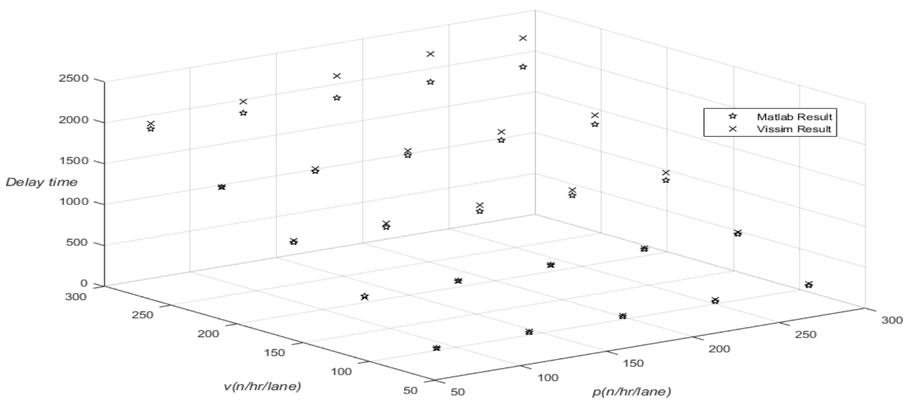
Vehicle delay time of the model obtained through the Matlab program is shown in <Table 9> and that of the Vissim program is shown in <Table 10>.

<Table 9> Vehicle delay time by the Matlab program (sec/cycle)

Veh / Ped (n/hr)	54	108	162	216	270
54	364	364	364	364	364
108	749	749	749	749	749
162	1157	1157	1157	1157	1157
216	1589	1589	1589	1589	1589
270	2048	2048	2048	2048	2048

<Table 10> Vehicle delay time by the Vissim program (sec/cycle)

Veh / Ped (n/hr)	54	108	162	216	270
54	363	369	375	381	382
108	734	745	753	760	764
162	1176	1195	1226	1226	1251
216	1586	1620	1648	1685	1702
270	2112	2188	2313	2388	2399



<Figure 24> Comparison between vehicle delay times

The x-axis in <Figure 24> represents the number of pedestrians per pedestrian traffic flow per hour, and the y-axis represents the number of vehicles per vehicle traffic flow per lane per hour. The z-axis represents the vehicle delay time per cycle. The dots with a pattern '☆' are values of the Matlab program for each combination of vehicle traffic volume and pedestrian traffic volume. The dots with a pattern '×' are values of the Vissim program for each combination.

As can be seen from <Table 9> and <Figure 24>, in a case of Results of the Matlab program, on same traffic volume, vehicle delay time is constant regardless of pedestrian traffic volume. On the contrary, as can be seen from <Table 10> and <Figure 24>, in a case of results of the Vissim program, on same vehicle traffic volume, as pedestrian traffic volume increases, vehicle delay time also increases because of influence of vehicle and pedestrian conflicts which can not be reflected in the model.

A result of error rate analysis is shown in <Table 11>. For all combinations of vehicle traffic volume and pedestrian traffic volume, error rates are under 15%.

<Table 11> Error rate of vehicle delay time

Veh / Ped (n/hr)	54	108	162	216	270
54	0.3%	1.4%	2.9%	4.5%	4.7%
108	2.1%	0.6%	0.5%	1.4%	2.0%
162	1.7%	3.2%	5.7%	5.7%	7.6%
216	0.2%	1.9%	3.6%	5.7%	6.6%
270	3.0%	6.4%	11.5%	14.2%	14.6%

5.2.1.2 Comparison between Pedestrian Delay Times

Both maximum delay time and minimum delay time are used for comparison with values of the Vissim program. Average delay time is used for error rate analysis.

Unlike vehicle delay time, pedestrian delay time is constant regardless of vehicle traffic volume on same pedestrian traffic volume.

<Table 12> Comparison result of pedestrian delay time

Division / Ped	54	108	162	216	270
Max delay time(s)	946	1900	2862	3830	4807
Min delay time(s)	944	1889	2837	3787	4738
Value of Vissim(s)	919	1835	2856	3946	5161
Avg delay time(s)	945	1895	2849	3809	4773
Error rate	2.8%	3.3%	0.2%	3.5%	7.5%

As can be seen from <Table 12>, at 162 pedestrian traffic volume per pedestrian traffic flow per hour, pedestrian delay time of the Vissim program is between maximum pedestrian delay time and minimum pedestrian delay time.

Under 162 pedestrian traffic volume, pedestrian delay time of the Vissim program is under minimum pedestrian delay time. However, over 162 pedestrian traffic volume per hour, pedestrian delay time of the Vissim program is over maximum pedestrian delay time. The reason is that influence of adjacent pedestrians and opposite-side pedestrians makes pedestrians experience more additional delay time as pedestrian traffic volume increases, which can not be reflected in the model. For all pedestrian traffic volumes, error rates are under 15%.

5.2.1.3 Comparison between Total Delay Times

A result of error rate analysis is shown in <Table 13>. For all combinations of vehicle traffic volume and pedestrian traffic volume, error rates are under 15%.

<Table 13> Error rate of total delay time

veh/ped (n/hr)	54	108	162	216	270
54	6.6%	5.3%	1.7%	1.5%	5.3%
108	9.6%	7.3%	3.8%	0.5%	3.4%
162	8.1%	6.3%	2.7%	0.2%	3.6%
216	10.4%	7.8%	4.5%	1.0%	2.4%
270	8.3%	5.1%	0.2%	3.0%	5.3%

5.2.2 After Installation

5.2.2.1 Comparison between Vehicle Delay Times

A result of error rate analysis is shown in <Table 14>. Except seven combinations of vehicle traffic volume and pedestrian traffic volume, error rates are under 15%.

<Table 14> Error rate of vehicle delay time

veh/ped (n/hr)	54	108	162	216	270
54	3.1%	8.0%	8.6%	9.3%	8.9%
108	10.4%	14.5%	15.2%	14.8%	17.1%
162	2.5%	6.0%	6.1%	8.1%	9.8%
216	7.3%	5.9%	6.0%	11.1%	7.4%
270	17.3%	26.1%	22.6%	23.4%	23.5%

An error rate of a case after installation is higher than that of a case before installation in most combinations of vehicle traffic volume and pedestrian traffic volume. The reason is that although the models give buffers to make vehicle traffic flow in a unsaturated state, there are some vehicles which can not pass an intersection in a cycle. A ratio of those vehicles to vehicle traffic flow in a case after installation is higher than that in a case before installation.

5.2.2.2 Comparison between Pedestrian Delay Times

A result of error rate analysis is shown in <Table 15>. For all combinations of vehicle traffic volume and pedestrian traffic volume, error rates are under 15%.

<Table 15> Error rate of pedestrian delay time

veh/ped (n/hr)	54	108	162	216	270
54	5.4%	7.3%	2.3%	3.1%	5.7%
108	0.3%	0.9%	0.8%	0.2%	3.2%
162	2.7%	1.3%	8.7%	3.3%	1.9%
216	5.7%	7.9%	5.1%	5.0%	0.5%
270	10.3%	1.0%	0.6%	0.8%	1.6%

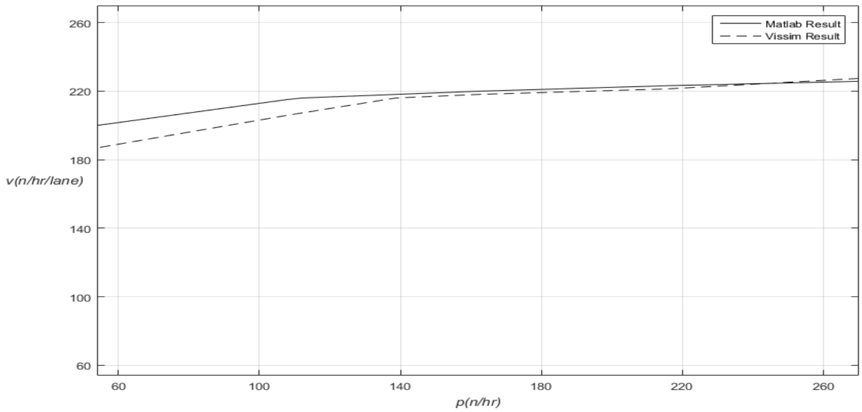
5.2.2.3 Comparison between Total Delay Times

A result of error rate analysis is shown in <Table 16>. Except one combinations of vehicle traffic volume and pedestrian traffic volume, error rates are under 15%.

<Table 16> Error rate of total delay time

Veh / Ped (n/hr)	54	108	162	216	270
54	-0.6%	7.5%	4.2%	4.6%	6.3%
108	7.6%	8.0%	7.6%	6.1%	8.0%
162	1.3%	3.3%	-0.5%	2.1%	3.0%
216	4.9%	1.7%	1.6%	3.7%	3.1%
270	13.5%	19.6%	14.9%	14.4%	13.5%

5.3 Results between Models



<Figure 25> Comparison between appropriate traffic volume areas

The x-axis in <Figure 25> represents the number of pedestrians per pedestrian traffic flow per hour, and the y-axis represents the number of vehicles per vehicle traffic flow per lane per hour. The real line curve means a result of Matlab program and the dotted line curve means that of Vissim program.

The real line curve and the dotted line curve connect dots where total delay times per second before and after installation of scrambled crosswalks are same.

On 54 pedestrian traffic volume per pedestrian traffic flow per hour, installation of scrambled crosswalks is appropriate under 200 vehicle volume per vehicle flow per lane per hour in a case of the Matlab program. In case of a Vissim program, installation of scrambled crosswalks is appropriate under 185 vehicle volume for 54 pedestrian traffic volume. Therefore a gap is 15. As pedestrian traffic volume increases, the gap gets smaller and over about 240 pedestrian traffic volume, relationship is the reverse. Therefore, in scope of this research, the largest gap is 15 vehicle traffic volume for any pedestrian traffic volume which is a component of a combination where total delay time per second before and after installation of scrambled crosswalks are same.

This phenomenon is explained by two reasons. There are some vehicles which can not pass an intersection in a cycle in the Vissim program even though the models give buffers to cycle length in the Matlab program, which increases delay time. Extent of this addition delay time of a case after installation of scrambled crosswalks is larger than that of a case before installation of scrambled crosswalks. Therefore, this research basically overestimates effect of scrambled crosswalks, which makes an appropriate traffic volume area larger. However, as pedestrian traffic volume increases, conflicts between pedestrians and vehicles before installation of scrambled crosswalks increase only in the Vissim program, which makes vehicle delay time before installation of scrambled crosswalks increase. For this reason, overestimation gets smaller, which makes the result that the gap becomes smaller under 240 pedestrian traffic volume and the relationship is the reverse over 240 pedestrian traffic volume.

Due to existence of this gap, in a case of applying an installation criteria which is suggested later, low priority should be given to boundary combinations of vehicle traffic volume and pedestrian traffic volume.

Chapter 6. Discussion

6.1 Comparison with Existing Installation Criteria

The existing Korean installation criteria for scrambled crosswalks is based on the research of Han et al. (2011). Compared to the research, this research brings out a similar result and a different results.

The research of Han et al. (2011) and this research share the result that when the number of signal phase decreases, the appropriate traffic volume area increases. In this research, appropriate areas of signal system Ⅵ, signal system Ⅲ, signal system Ⅱ are from largest to smallest.

However, there is a different result. The research of Han et al. (2011) suggests that a pedestrian effect measure gets better after installation of scrambled crosswalks on same cycle length. However, this research suggests that a pedestrian effect measure can get worse after installation of scrambled crosswalks on same cycle length.

This difference is mainly based on two parts. One part is difference of kinds of effect measures The other part is difference of methods to deal with flashing green time.

The research of Han et al. (2011) uses crossing time which can be calculated from an unique model as a pedestrian effect measure. On the other hand, this research uses pedestrian delay time as a pedestrian effect measure. From the perspective of efficiency of an intersection, delay time is judged to be more reasonable. Also, a same effect measure for vehicle and pedestrian is effective when research deals with vehicle traffic flow and pedestrian traffic flow simultaneously.

The research of Han et al. (2011) deals with flashing green time as time where pedestrians can start crossing. On the other hand, this research deals with flashing green time as time where pedestrians can not start crossing. If flashing green time which is based on length of a crosswalk can be used as time where pedestrians start crossing, difference of length of crosswalks can not be reflected in flashing green time.

Because of these two differences, on same cycle length, total pedestrian delay time can increase after installation of scrambled crosswalks in this research, which means a pedestrian effect measure can get worse. However, because this research reflects change of cycle length before and after installation of scrambled crosswalks unlike the research of Han et al. (2001), an area where pedestrian delay time decreases as pedestrian traffic volume increases exists.

On the one hand, this research and overseas installation criteria share some points. Especially quantitative Australia installation criteria are very similar with results of this research. An Australia installation criterion is about the number of phases. Two phases are requirement for installation of scrambled crosswalks. On this research, a trend is that as the number of phases lowers, appropriate traffic volume area increases. Also, An other Australia criterion is about the number of turning vehicles. The criterion requires some turning vehicles. On this research, as ratio of left-turn vehicles to vehicle traffic flow increases, appropriate traffic volume area also increases.

Also, qualitative criteria of Japan and Australia share some points with results of this research. Some vehicle volume needed, small scale of intersection required and so forth are also found in results of this research.

6.2 Suggestion

The existing Korean criteria for scrambled crosswalks is effective in that a simple criteria is easy to apply to candidates. However, the existing simple criteria reflects effect of signal system only in part, suggesting just the priority criteria. According to this research, effect of signal system is so large that the only priority criteria is not enough.

Therefore, each signal system should have an unique criteria for installation of scrambled crosswalks. Also, criteria should reflect the fact that required pedestrian traffic volume increases as vehicle traffic volume increase.

A criteria for installation of scrambled crosswalks can be suggested by two steps.

First step is to restrict a total traffic volume area to a possible traffic volume area only by vehicle traffic volume per vehicle traffic flow per lane per hour for each signal system. In this step, survey of vehicle traffic volume is only needed.

<Table 17> Criteria by vehicle traffic volume

Signal system	Vehicle Traffic Volume (n/hr/lane)
Ⅰ	Under 250
Ⅱ	X
Ⅲ	Under 140
Ⅳ	Under 250

Second step is to judge whether the possible traffic volume area for each signal system is an appropriate traffic volume area by a combination of vehicle traffic volume and pedestrian traffic volume. In this step, additional survey of pedestrian traffic volume is needed. Graphs which are grounds for this judgement are suggested on the appendix. If a candidate is not fitted in any of the signal intersections which this research encompasses, a criteria for intersection whose number of lanes is just below the number of lanes of the candidate is to be chosen for judgement in signal system Ⅰ and Ⅲ. On the contrary, in signal system Ⅳ, if a candidate is not fitted, a criteria for intersection whose number of lanes is just above the number of lanes of the candidate is to be chosen for judgement.

Also, a following additional priority criteria for signal system Ⅲ can be added.

'As ratio of left-turn vehicles to vehicle traffic flow increase, priority increases'

Chapter 7. Conclusion

Based on the analysis, this research derives two main research results from analysis. Firstly, there is critical vehicle traffic volume above which installation of scrambled crosswalks is not efficient for each combination of signal intersection and signal system. Secondly, appropriate traffic volume areas for installation scrambled crosswalk vary by signal intersection or by signal system and extent of the variation is also different.

From these results, this research suggests the installation criteria which consists of two steps. First step is based on the first result and second step is based on the second result.

There are much research related to installation criteria for scrambled crosswalks. Compared with those research, this research has two main different points. Firstly, this research formulates the delay time models which reflect both vehicle traffic flow and pedestrian traffic flow. Based on the delay time models, optimum cycle length can be obtained. If both vehicle and pedestrian indicators are used to be effect measures of analysis, it is reasonable that a delay time model which is a basis of this analysis should reflect both vehicle and pedestrian indicators. Secondly, this research verifies the models, comparing results of the model with those of the Vissim program.

This research has following advantages. Firstly, this research suggests appropriate traffic volume areas for installation of scrambled crosswalks which can be a basis of an installation criteria. From this result, whether installation of scrambled crosswalks is appropriate is determined by just surveying vehicle traffic volume and pedestrian traffic volume. Secondly, this research suggests a meaningful direction for installation of scrambled crosswalks by setting three research premises.

This research has following shortcomings. Firstly, the second advantage can be a shortcoming in that some of research premises make results different from realty. Therefore some actions need to be preceded to make this research more meaningful. Secondly, this research suggests different criteria for different signal intersections. In other words, this research fails to generalize criteria for installation of scrambled crosswalks.

Future research should focus on following points. Firstly, additional analysis can be conducted for generalization of installation criteria. Dealing with the number of lanes as a variable is one way for generalization. Secondly, future research can reflect stochastic characteristics of arrival in reality. Thirdly, scope of pedestrian traffic volume can be restricted more realistically. This restriction can also give a more realistic criteria for vehicle traffic volume which is closely related to pedestrian traffic volume. For restriction, real pedestrian traffic volume needs to be surveyed and analyzed.

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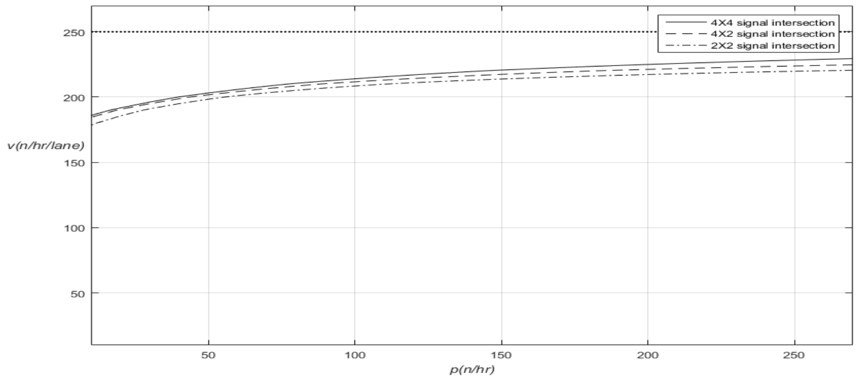
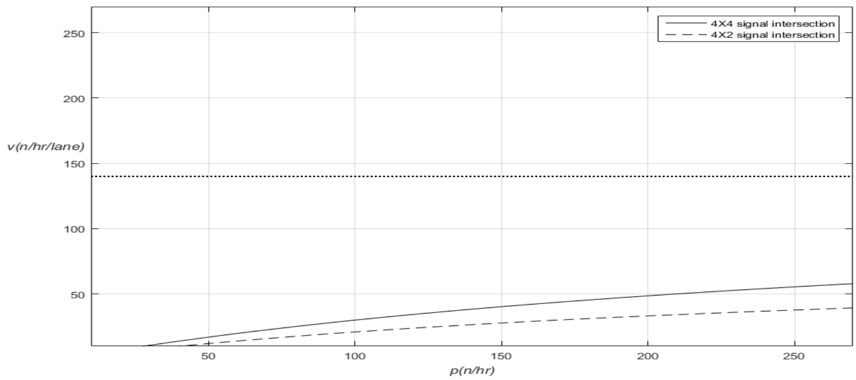
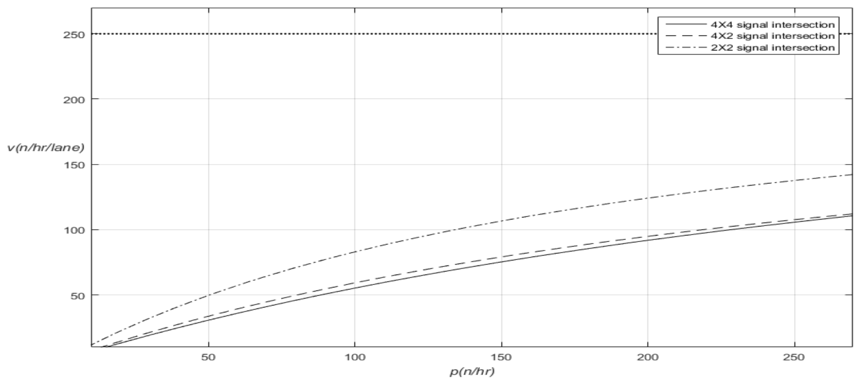
Appendix



<Figure 26> Criteria for signal system Ⅰ



<Figure 27> Criteria for signal system Ⅲ



<Figure 28> Criteria for signal system Ⅳ

국문 초록

차량에 비해 상대적으로 취약한 보행자의 안전에 대한 관심이 증대되고, 횡단보도 상의 보행자 사고에 대한 우려가 팽배해지에 따라 차량과 보행자의 상충을 줄여 보행자의 안전에 기여할 수 있다고 판단되는 대각선 횡단보도 설치가 많이 논의되고, 실제로 설치되는 경우 또한 적지 않다.

그러나 대각선 횡단보도는 모든 차량 교통류들에 적색 신호를 부여하는 전적색 현시를 포함하여야 하기 때문에 필연적으로 주기 당 손실시간이 증가하게 된다. 따라서 대각선 횡단보도 설치에 앞서 효율성 측면에서의 평가가 필요하며 본 연구는 대각선 횡단보도 설치기준을 제시함으로써 교통량과 보행량 조사만으로 대각선 횡단보도 설치 적절성 여부를 판단할 수 있도록 하고자 한다.

본 연구는 교통량과 보행량을 모두 고려한 신호 최적화 모형을 통하여 최적 주기를 도출하고 이를 바탕으로 대각선 횡단보도 설치 전·후 총 지체시간을 비교·분석한다.

분석 결과, 크게 2가지 연구 결과가 도출된다. 첫째, 대각선 횡단보도 설치가 효과적이 될 수 없는 차량 교통량 기준점이 존재한다. 둘째, 신호 시스템별, 신호 교차로별 적정 설치 교통량 영역이 다르며, 그 차이의 정도 또한 상이하다. 이러한 분석 결과를 바탕으로 본 연구는 2가지 단계로 나누어 대각선 횡단보도 설치기준을 제시한다.

주요어 : 대각선 횡단보도, 교통량, 보행량, 신호 최적화, 설치기준
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